A Formal Framework for Specification-Based Embedded Real-Time System Engineering

by

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Abstract

The increasing size and complexity of modern software-intensive systems present novel challenges when engineering high-integrity artifacts within aggressive budgetary constraints. Among these challenges, ensuring confidence in the engineered system, through validation and verification activities, represents the high cost item on many projects. The expensive nature of engineering high-integrity systems using traditional approaches can be partly attributed to the lack of analysis facilities during the early phases of the lifecycle, causing the validation and verification activities to begin too late in the engineering lifecycle. Other challenges include the management of complexity, opportunities for reuse without compromising confidence, and the ability to trace system features across lifecycle phases. The use of models as a specification mechanism provides an approach to mitigate complexity through abstraction. Furthermore, if the specification approach has formal underpinnings, the use of models can be leveraged to automate engineering activities such as formal analysis and test case generation. The research presented in this thesis proposes an engineering framework which addresses the high cost of validation and verification activities through specification-based system engineering. More specifically, the framework provides an integrated approach to embedded real-time system engineering which incorporates specification, simulation, formal verification, and test-case generation. The framework aggregates the state-of-the-art in individual software engineering disciplines to provide an end-to-end approach to embedded real-time system engineering. The key aspects of the framework include:

- A novel specification language, the Timed Abstract State Machine (TASM) language, which extends the theory of Abstract State Machines (ASM). The TASM language is a literate formal specification language which can be applied and multiple levels of abstraction and which can express the three key aspects of embedded real-time systems – function, time, and resources.
Automated verification capabilities achieved through the integration of mature analysis engines, namely the UPPAAL tool suite and the SAT4J SAT solver. The verification capabilities provided by the framework include completeness and consistency verification, model checking, execution time analysis, and resource consumption analysis.

Bi-directional traceability of model features across levels of abstraction and lifecycle phases. Traceability is achieved syntactically through archetypical refinement types; each refinement type provides correctness criteria, which, if met, guarantee semantic integrity through the refinement.

Automated test case generation capabilities for unit testing, integration testing, and regression testing. Unit test cases are generated to achieve TASM specification coverage through the rule coverage criterion. Integration test case generation is achieved through the hierarchical composition of unit test cases. Regression test case generation is achieved by leveraging the bi-directional traceability of model features.

The framework is implemented into an integrated tool suite, the TASM toolset, which incorporates the UPPAAL tool suite and the SAT4J SAT solver. The toolset and framework are evaluated through experimentation on three industrial case studies – an automated manufacturing system, a “drive-by-wire” system used at a major automotive manufacturer, and a scripting environment used on the International Space Station.

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Chapter 1

Introduction

This chapter serves as an "executive summary" of the work presented in this thesis. The chapter contains information about the motivations for the presented research, the contributions of the research, the list of presentations, posters, technical reports and refereed publications related to the research, and the roadmap of the thesis. Each chapter in the thesis follows a template structure, as explained in Section 1.5.

1.1 Motivations

In modern society, software systems can be found everywhere, including in airplanes, in automobiles, and in consumer electronics. The proliferation of software increases the dependency on the correct functioning of software and yields a new set of challenges in the engineering of software-intensive systems. The growing size and complexity of modern software systems exacerbates the difficulty of delivering reliable systems within aggressive budgetary constraints. In various engineering disciplines, the use of models has proven a viable approach to mitigate complexity through abstraction [40]. However, the use of models in the engineering of software is a relatively novel approach to building software systems. The use of models not only helps to control complexity, but if the models have formal underpinnings, the models can be used to automate certain engineering activities such as verification and test case generation.
The research presented in this thesis seeks to address five key challenges in the engineering of embedded real-time systems:

- The high complexity of modern software systems, by providing a model-based approach to software-intensive system engineering.
- The high cost of Verification and Validation (V & V) activities by leveraging the use of models to automate engineering activities.
- The challenges in using formal methods in an engineering context by providing a novel literate specification language and abstracting verification details in a push-button approach.
- The lack of integration between disparate models by providing bi-directional traceability across levels of abstraction.
- The lack of integration of the state-of-the art in individual disciplines by providing an overarching engineering framework.

These five challenges form the base motivation for the research presented in this thesis. These challenges are addressed individually in subsequent chapters. In addressing these challenges, the research presented in this thesis makes a number of research contributions in various areas. These contributions are outlined in the following section.

1.2 Thesis Contributions

The research presented in this thesis makes five key contributions to address the challenges enumerated in the previous section:

- A new specification language for embedded real-time systems, the Timed Abstract State Machine (TASM) language, which extends the theory of Abstract State Machines (ASM). The TASM language integrates the specification of functional and non-functional properties – function, time, and resources.
• A set of verification procedures for automated analysis of models, using generally available analysis engines. The procedures include the analysis of completeness and consistency, the analysis of execution time, and the analysis of resource consumption.

• An approach to traceability of system models that incorporates syntactic change and semantic integrity.

• A generic and extensible approach to automatically generate test cases for unit testing, integration testing, and regression testing.

• An integrated framework for modeling, simulation, verification, and test-case generation for embedded real-time systems.

• An integrated toolset implementing the capabilities of the framework.

1.3 Relevant Publications

The research presented in this thesis has led to presentations and poster sessions presented at the “Real-Time System Symposium (RTSS)” in December 2006 [189], at the “ARTIST Workshop on Tool Platforms for Embedded System Modeling, Analysis and Validation” of the “Computer-Aided Verification Conference (CAV)” in July 2007 [196], at the “Real-Time in Sweden Conference (RTiS)” in August 2007 [197], and at the “Asia-Pacific Software Engineering Conference (APSEC)” in December 2007 [204].

The presented research has also yielded a number of Technical Reports released through the Embedded Systems Laboratory (ESL) at the Massachusetts Institute of Technology [190, 195, 201, 202, 206]. A reference manual for the Timed Abstract State Machine (TASM) language [185], as well as a user guide for the TASM toolset [186] are also available through the Embedded Systems Laboratory [88].

The Timed Abstract State Machine language was presented to the real-time system community at the “Real-Time and Network Systems Conference (RTNS)” in
March 2007 [199] and to the ASM community at the “Abstract State Machines Workshop (ASM)” in June 2007 [198]. A journal article about the TASM language is set to appear in Volume 14 of the Journal of Universal Computer Science (JUCS) in July 2008 [205]. A critical look on how time is treated in modeling languages, motivating the TASM approach to modeling time, was presented at the “Modeling in Software Engineering (MiSE) Workshop” of the “International Conference on Software Engineering (ICSE)” in May 2007 [194].

The case study involving the Electronic Throttle Controller (ETC) was presented at the “Critical System Development using Modeling Languages Workshop (CS-DUML)” of the “Model Driven Engineering Languages and Systems Conference (MoDELS)” in October 2006 [187] and was selected as one of two best papers to appear in Volume 4364 of Lecture Notes in Computer Science (LNCS) entitled “Models in Software Engineering” [188]. The analysis of TASM models using a SAT Solver was presented at the “Model-Based Testing Workshop (MBT)” of the “European Joint Conferences on Theory and Practice of Software (ETAPS)” in May 2007 [192] and appears in Volume 190 of “Electronics Notes in Theoretical Computer Science (ENTCS)” [193]. The TASM toolset was presented at the “Computer-Aided Verification Conference (CAV)” in July 2007 [200].

An overview of the framework will be presented at the “International Symposium on Quality Engineering for Embedded Systems (QEES)” [203], a symposium held jointly with the “European Conference on Model Driven Architecture Foundations and Applications (ECMDA)”, in June 2008. A follow-up article will be submitted to the journal entitled ”Software Tools for Technology Transfer”.

1.4 Thesis Outline

This section provides an overview of the content of each chapter contained in this thesis.

• Chapter 1: Introduction
This Chapter provides an "executive summary" of the thesis and should be read before other chapters.

- **Chapter 2: Background Information**

This chapter provides background information necessary to understand the material contained in the research. This chapter covers a wide range of topics such as information about real-time systems, software engineering, and descriptions of the analysis engines used to implement the framework. The reader is invited to browse sections of this chapter as needed.

- **Chapter 3: Framework Overview**

This chapter provides an overview of the capabilities of the framework as well as the tool architecture used in the implementation of the framework.

- **Chapter 4: The Timed Abstract State Machine Specification Language**

This chapter describes the Timed Abstract State Machine (TASM) Language, its syntax, semantics, and modeling facilities, including how time and resources are treated, hierarchical composition, and parallel composition. Throughout the chapter, illustrative examples are provided to depict the concepts as they are introduced.

- **Chapter 5: Static Analysis**

This chapter presents the types of analysis that can be performed in the framework. The analysis procedures include completeness and consistency analysis, execution time analysis, and resource consumption analysis. This chapter also contains illustrative examples to demonstrate the analysis algorithms. The implementation of the analysis facilities, performed in the TASM toolset, are also described.

- **Chapter 6: Bi-Directional Traceability**
This chapter explains the bi-directional traceability capabilities of the proposed framework. The approach to traceability establishes a relationship between two or more TASM models and combines syntactic change management with notions of semantic equivalence for the models.

• Chapter 7: Test Case Generation

This chapter presents the automated test case generation capabilities of the framework for unit, integration, and regression test case generation. The regression test case generation strategy uses the traceability approach described in Chapter 6. Examples and implementation details are also presented.

• Chapter 8: Case Studies

This chapter contains the results of the three case studies used to evaluate the research presented in this thesis – the production cell case study, an Electronic Throttle Controller (ETC), and the Timeliner Script Executor. The case studies are introduced in Section 2.8 but the models and analysis results are presented in Chapter 8. The complete TASM models for each case study are provided in the appendices.

• Chapter 9: Conclusion

This chapter provides a critical evaluation of the presented research, draws conclusions for the thesis, and describes directions for possible future developments of the research.

• Appendix A: TASM Language Reference

This appendix contains the concepts involved with the implementation of the TASM language in the TASM toolset. These concepts include the complete Context-Free Grammar (CFG) for the TASM language and various implementation topics such as operator precedence and typing.

• Appendix B: Translating TASM Models to SAT
This appendix contains the details of the mapping from the TASM language to \textit{SAT}, for the purpose of static analysis, as explained in Chapter 5, and for test case generation, as explained in Chapter 7.

- **Appendix C: Translating TASM Models to UPPAAL**

  This appendix contains the complete mapping from the TASM language to UPPAAL, for the purpose of timing analysis, as explained in Section 5.3. The mapping to UPPAAL is also used for model checking of functional properties.

- **Appendix D: Production Cell TASM Model**

  This appendix contains the complete TASM model for the production cell case study, explained in Section 2.8.1 and studied in Section 8.1.

- **Appendix E: Electronic Throttle Controller TASM Model**

  This appendix contains the complete TASM model for the electronic throttle controller for the case study, explained in Section 2.8.2 and studied in Section 8.2, in Section 8.3, and in Section 8.4.

- **Appendix F: Timeliner Plant Simulator TASM Model**

  This appendix contains the complete TASM model for the Timeliner case study involving the plant control system, explained in Section 2.8.3 and studied in Section 8.5.

1.5 Chapter Structure

Individual chapters in this thesis follow a common template. At the beginning of each chapter a paragraph explains the information contained in the chapter. The last section of each chapter is named "Segue into Chapter N" and provides a brief summary of the information provided in the current chapter and how it leads to the following chapter. All chapters follow this template except for the appendices. Unlike the thesis chapters, individual appendices do not follow a common pattern. However,
the first paragraph of each appendix contains a brief description of its content. The content of the appendices is summarized in Section 1.4. Appendices do not follow a linear progression and serve as a reference that can be read in any order.

1.6 Notational Conventions

In order to enhance the readability of the thesis, special fonts are used to clarify meaning in certain situations:

- Italic font is used for definitions and when referring to abstract syntax, such as the names of machines or the names of rules.

- Teletype font is used when referring directly to the concrete syntax of a model, such as a variable.

- “Quotation marks” are used to emphasize blocks of text that should be grouped together.

Furthermore, the listings for models expressed in the Timed Abstract State Machine (TASM) language are expressed in teletype font.

1.7 Segue into Chapter 2

This chapter presented an “executive summary” of the content of the thesis. The following chapters expand on this summary. The next chapter, Chapter 2, provides background information about the topics covered throughout the thesis.
Chapter 2

Background Information

This chapter presents background information related to the concepts explained in the following chapters. The information contained in this chapter includes details about the types of systems targeted by the presented research, details about how the current work integrates into software engineering practice, information about the analysis engines used in the framework, and descriptions of the case studies used to evaluate the presented framework.

2.1 Real-Time Embedded Systems

The primary goal of a computer system is to provide value, as defined by a user of the system, by performing a set of functions. More specifically, a computer system must provide a correct response (output) based on a given stimulus (input). The concept of correctness is comprised of multiple facets such as functional correctness and non-functional correctness. The functional correctness of a computer system is defined through a set of requirements that the input-output behavior of the system must satisfy [85]. The requirements describing the functional correctness of a computer system can be described through safety properties, that is, statements about behavior that should never occur, and liveness properties, that is, statements about behavior that should eventually occur [30]. All functional behavior of computer systems can be described in terms of safety and liveness properties [154].
While functional correctness is a critical aspect of all computer systems, certain types of systems also require that non-functional aspects of the system, such as timing behavior, conform to stringent correctness criteria. The research presented in this work addresses the engineering of embedded real-time systems, a class of systems where non-functional properties are central to the system’s value. More specifically, embedded real-time systems represent a special class of computer systems where time plays a critical role in the correctness of the system. In a real-time system, the system must not only produce a correct answer, but must also do so in an adequately bounded amount of time [58]. The amount of time under which the system must produce a response is termed a deadline. If a real-time system provides an answer after a deadline has elapsed, the system is said to have missed a deadline. With regards to correctness, the implications of missing a deadline depends on the type of system. Real-time systems fall into two categories – hard real-time systems, where missing a deadline is unacceptable, and soft real-time systems, where missing a deadline may be acceptable under certain circumstances, depending on performance requirements [155]. Nevertheless, time plays a critical role in defining the correctness of a real-time system since a correct answer provided too late can be as erroneous as providing an incorrect answer [49]. The timing analysis provided by the framework does not make assumptions about whether the system being analyzed is hard or soft. The framework provides generic timing analysis to determine the best and worst case timing behavior, and it is up to the system behavior to decide whether the analysis results are acceptable for the system being engineered.

In practice, real-time systems are also typically reactive, meaning that they do not terminate, but are in continuous interaction with the environment, until the system is switched off. Reactive systems are different than transformational system, where the system terminates after producing an answer. In a reactive real-time system, the timing correctness of the system is defined as the absence of missed deadlines while taking into account the continuous interaction of the system with its environment. The types of systems targeted by the proposed framework are of the mostly periodic nature [164], meaning that they operate in a continuous loop that samples
the environment through sensors, makes a decision on what action the system should take based on the sensor values, and affects the environment by executing the action through an actuator. A sample loop for the systems targeted by the proposed framework is shown in Figure 2-1. It is important to note that which steps of the loop are executed at each iteration is implementation dependent. As will be described in the electronic throttle controller case study, the sampling of the state through sensors could be done at a lower frequency than, for example, the frequency of deciding on the action to be taken by the controller.

![Figure 2-1: High level view of a mostly periodic reactive real-time system](image)

In traditional real-time system theory, the concept of a deadline refers to the Worst-Case Execution Time (WCET) [89] also sometimes called the *worst-case computation time*, that is, the maximum time that can elapse when an individual task or an individual process executes [58]. In this research, the traditional WCET definition is made more general to include system properties. In the remainder of this work, the term WCET is used to denote the maximum amount of time that can elapse when the system completes a path between two states. The definition used in this thesis also stipulates that such a path can consist of *any* two states. In this definition, the notion of *state* can include both the state of the engineering artifact such as the program counter and values of system variables, *and*, the value of environment variables. This definition is more general than the traditional definition and can capture important concepts such as end-to-end latency all the while being able to express the traditional definition. *End-to-end latency* refers to the longest reaction time of a system to an environment stimulus, taking into account system properties such as environment
interaction, task interference, and delay in response. For example, in the loop of Figure 2-1, the value of an environment variable could change while the system is deciding on which action to take. Depending on the frequency of sensor readings, a significant delay could result in the system taking a corrective action since there could be a delay before the change is detected. Figure 2-2 shows a symbolic view of the time that can elapse between an event occurring and the system taking a corrective action. The verification problem to ensure that there are no missed deadlines can be summarized as:

\[ dt = t_2 - t_1 \leq \text{Required Deadline} \]

The response latency, \( dt \), refers to how much time elapses between the event and the response. The proposed framework provides necessary facilities to calculate the maximum value of \( dt \), for any event and action modeled. The Required Deadline is system-dependent and is provided by the performance requirements. It is also the responsibility of the system designer to decide on which course of action to take if the designed system does not meet the required deadline. The proposed system provides only the necessary modeling and analysis facilities. Additional definitions related to execution time are given in Section 5.3.

![Figure 2-2: Delay in system responding to an event of interest](image)

Most real-time systems also fall into the category of embedded systems. Embedded systems represent a special class of real-time systems where the software system is not stand-alone, but is part of a larger system and must work with other components to achieve the system’s goals [155]. Vehicle controllers, such as automotive electronics
and avionics, are typical examples of embedded real-time systems. In an embedded system, resources such as communication bandwidth and memory are typically limited and must be shared across multiple components. Consequently, the correctness of an embedded real-time system is also dependent on the resource usage being adequately bounded. In summary, for an embedded real-time computer system, the correctness of the system is defined in terms of three key aspects – functional correctness, timing behavior, and resource usage. These three aspects form the fundamental motivation of the modeling and analysis capabilities provided by the proposed framework.

2.1.1 The Nature of Time in Real-Time Systems

Since time plays an important role in defining the correctness of a real-time system, it is paramount to understand the role of time in the systems of interest. On a general and global level, the time axis is a monotonic function that is used to order events linearly according to some concept of progression [101]. A large body of research has been devoted to establish that a computer system satisfies a correct ordering of events [49]. This correct ordering of events, also called qualitative time, refers to the ordering of events with respect to one another and is not concerned with the temporal distance between events [212]. For example, in the well-known Simple Mail Transfer Protocol (SMTP), an acknowledgement message (ACK) shall not be received before a synchronization request (SYN) has been emitted. In other words, an ACK must occur after a SYN and never before. However, in real-time systems, timing correctness does not depend only on the ordering of events, but also depends on the numerical distance between events, a concept called quantitative time [155]. For example, in the SMTP protocol, after a SYN has been emitted, a timer is typically started while waiting for the ACK. If, after a prespecified amount of time, the ACK has not been received, the SYN sender might assume that the SYN request was lost. In such a situation, the precise amount of time between the SYN and the ACK is of particular importance, in addition to the messages occurring in the correct order.

Quantitative time appears in real-time system problems either explicitly or implicitly. Examples of where quantitative time appears explicitly include performance
Table 2.1: Examples of sources of explicit quantitative time

<table>
<thead>
<tr>
<th>Source</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirements</td>
<td>The data in the operator console shall be refreshed 10 times per second</td>
</tr>
<tr>
<td>Physics</td>
<td>It takes approximately 5 seconds for a projectile shot straight up in the air at a velocity of 50 m/s to come to rest at its apogee</td>
</tr>
<tr>
<td>Components</td>
<td>Pressure sensors can put data on the system bus at a rate of 10Hz</td>
</tr>
</tbody>
</table>

requirements, local clocks, timeouts, scheduling, the physics of the problem, and constraints of the components of the system. Examples of explicit instances of quantitative time are shown in Table 2.1. Examples where time appears implicitly, as a side-effect, include software execution time and hardware execution time. Listing 2.1 shows a brief example of software code, written in the Timeliner scripting language [61], borrowed from the Timeliner case study. The code represents a sequence used to maintain cabin temperature between 20 and 25 Celsius degrees [238]. In order to determine how long this snippet of Timeliner code takes to execute, many other questions need to be answered. For example, the execution time of the script depends on:

- The properties of the execution platform
- The semantics of the language
- The assumptions on the behavior of the environment

Once the code has been written and the system is implemented, these concerns can typically be addressed to a satisfactory degree of confidence. For example, in [62], precise timing measurements of each statement of the Timeliner language have been measured through laboratory experiments for a specific execution environment. However, determining these execution times a priori remains a challenging endeavor.
Listing 2.1 Sequence TEMP_MONITOR [238]

SEQUENCE TEMP_MONITOR
EVERY 1
  IF TEMPERATURE >= 26 THEN
    SET TRYING_TO_COOL_SYSTEM TO TRUE
    COMMAND COOLING, NEW_STATE=>ON
    WHEN TEMPERATURE <= 22
      SET TRYING_TO_COOL_SYSTEM TO FALSE
      COMMAND COOLING, NEW_STATE=>OFF
    END WHEN
  END IF
  IF TEMPERATURE <= 19 THEN
    COMMAND HEATING, NEW_STATE=>ON
    WHEN TEMPERATURE >= 22
      COMMAND HEATING, NEW_STATE=>OFF
    END WHEN
  END IF
END EVERY
CLOSE SEQUENCE

Even for software and hardware execution, time can also appear implicitly and explicitly. For example, the code in Listing 2.1 contains one explicit timing statement, the “EVERY 1” statement. This statement tells the runtime system that the sequence shall execute at most once per second. Other examples of explicit timing statements include the statements *sleep* and *wait*, which are present in many programming languages such as C++ and Java [239]. In real-time system engineering, the explicit sources of quantitative time, outside of software and hardware, define the timing constraints of the system that is to be built. One of the goals of real-time system engineering is to build a system which meets these constraints.

### 2.2 Systems Engineering

*Systems Engineering* is the aggregation of multiple elements to perform functions that could not be performed by the elements alone [152]. Systems engineering is an overarching discipline which includes aspects bridging people, documentation, software, hardware, and other domains. Systems engineering efforts seek to develop processes, tools, and techniques to ensure that a given engineering artifact satisfies all parties involved throughout the lifetime of a system. In Section 2.1, the types of systems targeted by the presented framework were presented, alongside definitions of the correctness of these systems. The goal of the systems engineering efforts go beyond the
correctness aspects described in Section 2.1 and include concepts related to the stakeholders, potential risks, safety concerns, and other factors affecting the engineering, delivery, and operation of the system [166]. The goal of this section is to situate the applicability of the presented framework in the wider sphere of systems engineering.

Figure 2-3 shows the steps of a generic systems engineering process defined in [19]. The framework presented in this research is applicable in the software and digital hardware engineering facets of real-time systems, during the modeling phases and the integration phases depicted in Figure 2-3.

![Figure 2-3: Systems engineering process [19]](image)

The proposed framework assumes the existence of requirements on the functional, time, and resource aspects of the system. The engineering of software and digital hardware for an embedded system, such as the engineering of an avionics system, will be performed in parallel with other systems engineering activities such as requirements analysis and vehicle design. In the following section, software engineering principles are reviewed as motivations for the presented framework.

### 2.3 Software Engineering

Software engineering is the set of techniques, processes, and tools used to develop computer systems [242]. Typically, software engineering is divided into lifecycle phases that traditionally include requirements engineering, design, implementation, testing, and maintenance [255]. These different phases are carried out in sequence, with a certain amount of overlap depending on the lifecycle model that is used [253]. Validation and Verification (V & V) activities are defined as the process of establishing confidence into the correctness of the system. More specifically, validation refers to
the activities carried out to ensure that the system being engineered will meet the user's needs. **Verification** refers to the activities carried out to ensure that the software behaves in accordance to the correctness criteria expressed as requirements. In practice, these activities comprise a mix of testing, user interviews, mathematical proofs, and various forms of human inspections [99]. V & V activities are typically the large ticket item on software engineering projects and can comprise over 50% of the development costs [39, 255]. The purpose of performing V & V activities is to eradicate defects from the system being engineered. A defect is a facet of the system which does not conform to the user's needs or to the required correctness criteria. V & V activities are typically carried out throughout all phases of the engineering lifecycle. Empirical evaluations of software engineering projects have demonstrated that the cost of finding and fixing a defect in a computer system increases dramatically the later it is found in the lifecycle [38, 39, 255]. Consequently, finding and fixing defects during the early phases of the engineering lifecycle can result in lower defect fixing costs and lower V & V costs. A typical software lifecycle consists of a number of phases that include requirements, design, implementation, testing, and maintenance [38]. A popular example of a popular lifecycle, the "V Lifecycle Model" [242], is depicted in Figure 2-4. In Figure 2-4, the engineering activities typically begin in the top left corner and proceed diagonally toward the bottom and back up toward the top right corner. However, software engineering lifecycle are typically iterative and hence do not follow a strict linear progression, indicated in Figure 2-4 by the arrows linking each phase.

Traditional approaches to software engineering have relied heavily on natural language documents and natural language communication to capture the requirements, design principles, and results of V & V activities relating to the system being engineered [71]. However, since natural language is ambiguous by definition, performing V & V activities based on natural language documents is error-prone and lack the type of repeatability that can be provided through automated analysis [225]. With the growing size and complexity of modern computer systems, relying solely on the intellectual rigor of engineers can lead to unpredictable results [124]. The framework
Figure 2-4: V software lifecycle model [242]
proposed in this research focuses on automating V & V activities, notably formal verification and test case generation, to provide a repeatable and reliable engineering approach that could lead to decreased V & V costs.

2.4 Formal Methods

Various efforts have attempted to remedy the shortcomings of natural language through the formalization of structured natural language [54, 73, 224, 246]. The need for a precise language and the benefits of automated analysis have motivated the development of specification approaches based on mathematics [71]. These attempts, also known as formal methods or formal specification, have yielded specification languages and proof systems that have a wide range of analysis capabilities, mostly through mathematical proofs. These approaches aim to address the lack of rigor of ad-hoc engineering techniques by rooting the engineering in well-founded mathematical principles. However, because many of these languages make use of advanced mathematics, they suffer from a lack of usability and readability without the proper expertise [51, 71]. The benefits and drawbacks of using formal methods have been documented heavily [50, 51, 71]. Cited benefits include the detection of defects early in the engineering cycle [118], precise and concise specifications [248], and the capability for automated analysis [220]. Cited drawbacks include the heavy use of arcane mathematical notations [71], the lack of scalability of most methods [50], and the large investment typically required to use formal methods [51]. Besides the negative connotation that the term formal methods has taken in some circles [124], the benefits of unambiguous specifications and the repeatability of automated analysis, throughout the phases of the lifecycle, have been generally accepted in the software engineering community [37, 179].

The challenges of engineering real-time systems has also led to various efforts to automate lifecycle activities. The lifecycle activities that can be automated include verification [70], validation [98], and test case generation [15, 222]. The automation of these activities is typically centered around a formal specification language or centered around a mathematical formalism. These approaches, also called specification-based
development and *model-based* development, are finding increasing popularity within the industrial community and within the various research communities [179]. The terms *model-based* and *specification-based* are used interchangeably in the literature. In the context of this thesis, these terms are also indistinguishable, but the term *specification* is used to denote the description of behavior that can serve the dual purpose of the documentation of the intended system behavior and a model that can be analyzed. These approaches intersect with formal methods, under a different name, in that they rely on a notation with well-defined formal semantics. However, specification-based approaches focus on engineering activities and less on mathematical proofs, as is the case for formal methods [82]. In the model-based engineering domain, the research community has yielded a large body of languages, approaches, algorithms, and tools to specify, analyze, and automate engineering activities. While there have been key contributions in individual areas, it is currently challenging to incorporate the state-of-the-art in real-time system engineering into a cohesive framework [49] that can be used to engineer systems. These challenges are partly due to the lack of interoperability between existing approaches and tools [49, 179]. This lack of integration creates the need for engineering frameworks that integrate formal methods with specification concepts, such as the framework presented in this thesis. Furthermore, tool support, such as the capabilities provided by the proposed framework, also bridges the integration gap between modeling languages and formal analysis.

### 2.5 Model-Based Software Engineering

Model-based software engineering (MBSE), also called model-driven software engineering (MDSE) and model-driven system engineering, is an approach to software engineering where models play a central role in lifecycle activities [228]. The key point of the approach is the existence of a set of *models*, which are abstractions of the system to be implemented. The models contain information about the desired behavior of the system and are used to drive the lifecycle phases. Some of the ben-
Benefits of having system models include the ability to simulate the prototype system and to perform analysis before implementation begins [257], leveraging the economics of software engineering to uncover defects as early as possible [38]. Model-based engineering approaches typically employ graphical or structured models that can be amenable to simulation and analysis, usually through a computer. As is the case for formal methods, models with well-defined semantics are means to remedy the ambiguity of natural language. A model-based approach is typically composed of a notation, formal or informal, used to express system behavior, and a set of associated methods and processes to ease engineering activities. The true benefits of a model-based approach occur when a literate [151] notation with formal semantics is used, so that the models can serve the dual purpose of an analysis mechanism and of the documentation of intended system behavior [146]. A literate specification language is a language which can be read like the English language and does not contain extraneous symbols aside from basic operators from arithmetic [151]. Furthermore, given the investment required to build models, the ability to automate engineering activities, such as test case generation, can help alleviate the cost of building and maintaining models [173].

Among the proponents of model-based software engineering, two professional organizations have proposed standards for the language and tools to be used for MBSE. The Object Management Group (OMG) has drafted a set of standards to enable model-driven software engineering, especially in the presence of disparate tools [179]. The purpose of the standard is to define information exchange formats so that various models and tools can be incorporated. OMG’s efforts have been focused on using the Unified Modeling Language (UML) [181] as the underlying language of its model-driven efforts. The UML language relies heavily on object-oriented design approaches and has yet to adopt a standard formal semantics [138]. The Society of Automotive Engineers (SAE) preaches a similar model-based approach through the use of the Architecture and Analysis Design Language (AADL) [223], targeted at embedded real-time systems. The AADL language is an Architecture Description Language (ADL) that can be used to express high level component interaction and
information flow. However, at the time of the writing of this thesis, AADL does not contain facilities for specifying component-level behavior.

2.6 Modeling Languages

In order to perform model-based software engineering, models must be expressed using a suitable modeling language. Section 2.1 establishes the correctness criteria of real-time systems, namely function, time, and resources. Furthermore, Section 2.1.1 describes how time is reflected in the engineering of real-time systems. In particular, Listing 2.1 shows an example of software code which expresses explicit and implicit timing behavior. In modeling languages, quantitative time concepts are almost always explicit [144]. The type of modeling addressed in this research is behavioral modeling, to capture the dynamic aspects of the system. Behavioral modeling is in contrast to structural modeling, which captures the static aspects of the system, e.g., a class inheritance hierarchy or a multiplicity relationship [134]. In behavioral modeling, system dynamics are typically represented as some form of transition system where the system transitions from one state to another state based on a set of conditions [144]. Traditional languages to represent state transition systems include finite state automata [232] and statecharts [122]. For most modeling languages, untimed versions of the language exist and time was added as an extension of the language. This is the case for timed automata [5], time/timed Petri nets [60], timed process algebra [159], the Timed Abstract State Machine language (TASM) [199], and the real-time profile of the Unified Modeling Language (UML) [180].

While all of these languages have similarities, they also have significant differences in how they represent and handle time. The two main time models are discrete time and continuous or dense time. In a discrete time model, time progresses in fixed constant steps $dt \in \mathbb{N}^+$. In a continuous time model, time evolves continuously, and any time-related value is taken from the Reals domain ($t \in \mathbb{R}$). Languages also differ on how time evolves. Time can evolve either in states or during transitions. For example, time annotations can be added to Petri nets in places or in transitions or in
both [60]. The difference lies in whether the subject of the description is the duration of an action or the awaiting of an event. An example of a light switch, modeled in the timed automata of UPPAAL [157] is shown in Figure 2-5. The model describes the behavior of a lamp in relation with possible user interactions [24]. If the lamp is off and the switch is pressed, the lamp will turn on to the low setting. If, after the light has been turned on, the switch is pressed again within 5 time units, the lamp increases its intensity to the bright setting. On the other hand, if the lamp is on and the switch is pressed again, but more than five time units have elapsed, the lamp turns off. This example illustrates a model that describes the passage of time between events. In this model, events are instantaneous but the precise timing between events is of utmost importance.

Another way to represent time is to model events or actions as being durative instead of instantaneous. In the Timed Abstract State Machine language (TASM) [189], which will be presented in Chapter 4, time is attached to transitions to simulate durative actions. Listing 2.2 shows the actions of the robot of the production cell system [163], modeled in the TASM language. In the production cell problem, described in Section 2.8.1, a robot takes commands from a controller and executes these commands. When the robot is instructed to pick up a block, the action takes a certain amount of time to complete until the robot is available again to process other commands. In Listing 2.2, the action to pick up a block lasts 1 time unit.

Whether a language predominantly favors time passage or duration of actions in its notation is irrelevant from a pure expressivity perspective since both types of notations can be used to represent both concepts [30]. The differences lie in what paradigm better fits the problem being addressed. For the specification of real-time
Listing 2.2 Partial TASM model of a robot action to pick up a block

R1: Arm B at press, block is available -> pick up block
{
  t := 1;
power := 2000;
  if armbpos = atpress and armb = empty
     and press_block = available then
     press_block := notavailable;
     press := empty;
     armb := loaded;
}

systems, and for the modeling of software in general, the term execution time is used in numerous contexts. Most of the time, this term refers to the time to execute actions or, in other words, to the duration of actions. Verifying the correctness of a real-time system involves establishing that the durations of the actions of the system meet the time constraints of the requirements and of the problem domain.

2.6.1 The Time Paradox: Incorporating Time in High Level Models

Section 2.1.1 explained how time is reflected in real-time systems and Section 2.6 described how modeling languages express time. This subsection explains the paradox encountered when attempting to model system behavior that is closely tied to implementation details. In scheduling theory [63], the task graph [1] is the prevalent modeling formalism. A task graph is a directed graph where nodes represent tasks and edges represent precedence constraints between tasks. Each task is assigned an execution time, that is, a duration. A sample task graph with 7 tasks is shown in Figure 2-6. In Figure 2-6, each node represents a task and the numerical value next to the task represents the execution time of the task. Each arrow represents the precedence constraints, meaning that a task occurring at the beginning of an arrow must complete before the task at the end of the arrow can begin. The scheduling problem is concerned with finding a solution to scheduling the set of tasks on \( n \) processors, while enforcing the precedence constraints [57] and some notion of optimality.

Analogously, the co-synthesis problem concerns itself with optimal allocation of
a task graph to processing elements (e.g., reusable hardware (FPGA), application specific integrated circuits (ASIC), and software) [76]. The similarities between these two problems lie in the existence of a task graph, with known execution times for individual tasks. For the co-synthesis problem, this assumption seems misleading because the execution times will vary depending on which processing element a task is allocated to. On the other hand, for the scheduling problem, the task graph can be derived from an implementation. However, in real-time system engineering, the task graph is an abstraction of an implementation and, conceptually, should be defined before implementation begins. Defining the set of tasks and the dependencies between tasks should be a design decision, not an implementation one. Relying on the set of tasks to naturally emerge during coding causes development to remain an ad-hoc process at best, with little support for predictability. Furthermore, the scheduling problem also assumes that tasks have already been assigned to software, and therefore makes co-synthesis challenging. It is one of the goals of model-driven engineering to remedy ad-hoc system development by structuring engineering activities through the use of models. For real-time systems, can realistic models, such as task graphs, be built before implementing the system?

There are many possible answers to this paradox. Conceptually, design is and has always been an uncertain process where predictions that may or may not come true are made [56]. Nevertheless, design has proved to be a valuable activity in terms of cost and time saving, even in the face of uncertainty [37]. In a model-driven approach
to development, it is highly unlikely that model-driven engineering will be a purely
downstream activity flowing monotonically from model to implementation. More
likely, feedback from downstream activities will be incorporated into upstream activ-
ities, leading to an iterative model-driven approach, where models are being adjusted
as the implementation is being developed. Like any other topic in system engineer-
ing, experience with building models and experience with engineering using models
will dictate the successful use of models in real-time system engineering. Moreover,
rooting development around mature and predictable components, as is often the case
in aerospace systems [234], greatly enhances the predictions that can be made by
models.

At the modeling level, modeling notations are able to capture the uncertainty
involved with annotating models with time. The use of interval semantics for dura-
tions gives a lower bound and an upper bound on durations. An example of a TASM
specification with duration specified using interval semantics is shown in Listing 2.3.

**Listing 2.3 TASM Model of an electronic throttle controller [187] (partial)**

```tasm
R1: Driving Mode
{
  t := [2, 5];

  if controller_mode = driving then
    throttle_v := Driving_Throttle_VO;
}

R2: Limiting Mode
{
  t := [3, 8];

  if controller_mode = limiting then
    throttle_v := Limiting_Throttle_VO;
}
```

Furthermore, the level of abstraction where the modeling occurs determines whether
software times should be included in the model. For system models such as the pro-
duction cell system [163], the physics of the problem and the time constraints on the
system are on a scale much larger (on the order of seconds) than the time scale of
the software (on the order of microseconds). Consequently, as it often happens in
high level models, the software is fast enough given the problem definition and time
does not need to be immediately included for software components in the models.
This is certainly the case in the production cell system where controller actions are approximated to be instantaneous [163].

A model-driven approach should have a notion of refinement [250], that is, a methodology to build models at different levels of abstraction, by gradually adding details to high level models. Furthermore, the refinement approach should have facilities to show a correspondence between two models at different levels of abstraction [17]. If such a notion is present, time estimates from high level models can become constraints on lower level models and, eventually, constraints on implementation. If an implementation cannot satisfy these constraints, the models will need to be adjusted in order to accommodate implementation characteristics. In this view, task graphs can be designed and approximated using high level models, making the scheduling problem and the co-synthesis problem relevant. During the design phase, analyzing schedulability and possible allocations to hardware and software can be useful to drive the implementation. In this research, the notion of refinement, as used in the formal methods community [79], is combined with the notion of traceability, as used in the system engineering community [217]. Traceability has traditionally been used to denote the ability to relate the syntax of disparate artifacts, including models, at different levels of abstraction. For example, in Figure 2-4, the traceability across lifecycle phases is depicted by the gray arrow on the left side of the figure. The benefits of traceability include the documentation of the dependency of various assumptions made throughout lifecycle phases [94]. However, traceability typically involves only the visualization of related artifacts and does not include notions of semantic equivalence that can be enforced through tool support. In contrast, notions of refinement in the formal methods community concern mostly only semantic equivalence between models and do not address the tracking of design assumptions [174]. Uniting these two notions, as performed in the proposed framework, combines the best of both worlds and provides a basis for end-to-end bi-directional traceability from high level models to implementation.
2.7 Analysis Engines

The growing need for more efficient software engineering has led to the development of sophisticated tools for computer-assisted analysis of software artifacts [124]. Among these analysis engines, theorem provers [84, 210], model checkers [30, 67], SAT solvers [175], Satisfiability Modulo Theory (SMT) Solvers [97, 229], and Linear Programming (LP) solvers [96, 218] have attracted large research efforts. All of these solvers support completely automated analysis, except for theorem provers. Because automation of engineering activities is a central goal of the proposed framework, theorem provers are not considered for the present version of the framework. Furthermore, the use of linear programming solvers and SMT solvers are treated as part of Future Work, in Section 9.3. The types and specific instances of analysis engines that are used in the presented research are explained in this section.

In the formal verification realm, model checkers [70] and SAT solvers [175] have been used to perform various types of analysis [140]. The popularity of model checkers and SAT solvers can be attributed to the full automation capabilities of the analysis, combined with the automated generation of a counterexample when a property to be verified does not hold [30]. Furthermore, model checkers and SAT solvers are generally available, and some finely tuned implementations are available in the open source community, including the SAT4J SAT Solver [158] and the NuSMV model checker [65]. A survey of model checkers and other tools for formal verification of real-time systems is provided in [244]. While model checkers and SAT solvers have similarities, their modeling and verification strategies differ significantly. Model checkers and SAT solvers were selected as the analysis engines for the proposed framework because they represent two classes of mature and widely used analysis engines, from two distinct communities.

2.7.1 Model Checkers

Model checkers are a class of analysis engines where the modeling formalism is a variant of finite state automata [232] and the properties to be verified are expressed
using a variant of temporal logic [137]. Model checkers provide reachability analysis facilities to establish liveness and safety properties of transition systems [67]. Model checkers rely heavily on the ability to generate a finite state abstraction of the transition system model, which is then explored in a heuristic or systematic fashion [30]. The parallel combination of finite state automata gives rise to the infamous “state explosion problem”, although the increase in computing power and the improved sophistication in state exploration algorithms has rendered model checkers applicable to problems of industrial size [69]. The popularity of model checkers can be attributed to the complete automation of the verification procedures and to the automated generation of a counterexample if a property of the model does not hold.

**UPPAAL**

The UPPAAL tool suite is a modeling and analysis environment, including model checking, for real-time systems [24, 157, 211]. Like all model checking systems, UPPAAL is composed of a modeling formalism and a temporal logic. The modeling formalism of UPPAAL is a variant of Alur-Dill automata [5]. Alur-Dill automata, also called *timed automata*, are an extension of finite state automata with real-valued clocks to express the passage of time. The timed automata of UPPAAL extends networks of Alur-Dill automata with datatypes, communication channels, and location types [157]. UPPAAL has been used as a verification engine for other formalisms such as Time Petri Nets [100]. The temporal logic [212] used in UPPAAL is a subset of Timed Computation Tree Logic (TCTL) [244], with facilities to express predicates over real-valued clock variables [29]. TCTL is the timed extension of Computation Tree Logic (CTL) [137]. The version of UPPAAL used in this thesis is version 4.0.6, released on March 5th, 2007, and available on the UPPAAL web site (http://www.uppaal.com). The UPPAAL model checker is used in the presented research to verify the timing properties of TASM models, as explained in Section 5.3.
2.7.2 SAT Solvers

The satisfiability problem, also known as SAT for short, is one of the archetypical \textit{NP-Complete} problem in the theory of computation [232]. The problem involves determining whether a Boolean formula is satisfiable. A \textit{Boolean formula} is composed of a set of atomic propositions and operations. Atomic \textit{propositions} are Boolean variables that can take the values \textit{TRUE} or \textit{FALSE}. The propositions are connected using parentheses and the operators NOT, AND, and OR, represented by the symbols $\neg$, $\land$, and $\lor$. A Boolean formula is \textit{satisfiable} if there is an assignment of values to propositions which makes the formula \textit{TRUE}. If no such assignment exists, the formula is \textit{unsatisfiable}. A sample SAT problem is shown below. The proposition $b_i$ represent Boolean variables:

$$(b_1 \lor b_2) \land (b_1 \lor b_3)$$

The SAT problem has found applications in artificial intelligence and in formal verification [140]. The general interest of the SAT problem has led to the development of commercial and academic SAT solvers, which are extremely efficient analytical engines used to determine the satisfiability of Boolean formulas [175]. These solvers are heavily optimized using heuristics that can yield acceptable performance in a number of cases. The standard input format for many SAT solvers requires that the Boolean formula must be in conjunctive normal form (CNF). As for model checkers, SAT solvers rely on the fact that Boolean formulas are finite state. As opposed to model checkers, who are used to verify the properties of a state-transition model by computing a transitive closure of the system, SAT solvers are used to reason about sets of constraints. SAT solvers find a state that satisfies constraints whereas model checkers find a state of the model, reachable from initial conditions. SAT reasoning makes no reference to initial states or to transition rules unless they are included as constraints. SAT solvers have been heavily optimized and have been standardized [140]. SAT solvers have been used for a variety of automated analysis,
including test case generation [149], [213]. Although the SAT problem is known to be NP-Complete, the use of SAT solvers has been shown to be practical in a wide range of cases.

**SAT4J**

The SAT4J SAT solver [158] is an open source solver fully implemented in Java. The solver has a well-documented API such that the solver can be easily integrated into other tools. The solver incorporates the architecture presented in [87] and has performed well in SAT solving competitions. The SAT4J SAT solver is used in the presented research, mostly because of its Java library support and because of its performance. The SAT4J solver is used to verify Completeness and Consistency [123, 125], as explained in Section 5.1, to verify resource consumption, as explained in Section 5.4, and for test case generation, as explained in Chapter 7.

SAT solvers and model checkers show similarities in their benefits, namely automation of the verification procedure and automation of the counterexample generation. SAT solvers and model checkers also show similarities in their drawbacks, namely the potential for state space explosion and the resulting intractability of large state space exploration.

### 2.8 Case Studies

The research presented in this thesis is evaluated using three case studies from three relevant domains. The case studies have been selected to reflect the typical embedded real-time systems that are targeted by the research. The first case study, the Production Cell, comes from the industrial manufacturing domains and is a problem used to evaluate formal methods in the research community. The second case study, an Electronic Throttle Controller (ETC), comes from the automotive domain and is an embedded controller used to optimize fuel consumption in automobiles. The final case study, the Timeliner Script Executor, comes from the aerospace domain and is a scripting environment in use on the International Space Station (ISS). This section
provides background information about these three case studies.

2.8.1 The Production Cell

The production cell system is an industrial case study that has been used to evaluate formal methods [163]. The functional aspects of the system have been modeled and analyzed in details using Abstract State Machines (ASM) in [45]. However, the time and resource behavior have not been modeled using ASM. The system is based on an industrial metal processing plant near Karlsruhe in Germany. The production cell consists of a series of components that need to be coordinated to achieve a common goal of stamping metal blocks. Blocks come into the system as raw and must leave the system as stamped. The schematic view of the production cell system is shown in Figure 2-7. Blocks are introduced into the system via the loader, which puts blocks on the feed belt. The feed belt carries blocks from one end of the belt to the other. Once a block reaches the end of the feed belt, the robot can pick up the block and insert it into the press, where the block is stamped. Once a block has been stamped, the robot can pick up the block from the press and unload it on the deposit belt, at which point the stamped block is carried out of the system.

All components operate concurrently and must be synchronized to achieve the system’s goals. The robot has two arms, arm a and arm b, which are perpendicular, move in tandem and can pick up and drop blocks in parallel. For example, the robot can drop a block in the press while picking up a block from the feed. To pick up or drop a block, the robot arms must extend and magnets attached to each arm must be turned on and off. A controller coordinates the actions of the system by using actuators to operate the various components. The original problem definition includes various safety requirements with respect to the actuators. For example, blocks must be dropped only in the press and on the deposit belt and nowhere else. The safety requirements of the original definition are listed in Section 8.1.2.

To make the TASM model easier to grasp, some simplifications and extensions have been made to the original problem definition from [163]. For example, the elevating rotatory table has been omitted. The traveling crane has been replaced by
Figure 2-7: Top view of the production cell
<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>motor_press</td>
<td>electric motor</td>
<td>operate the press</td>
</tr>
<tr>
<td>motor_arma</td>
<td>electric motor</td>
<td>extend and retract arm a</td>
</tr>
<tr>
<td>motor_armb</td>
<td>electric motor</td>
<td>extend and retract arm b</td>
</tr>
<tr>
<td>magnet_arma</td>
<td>electromagnet</td>
<td>pick up and drop arm a</td>
</tr>
<tr>
<td>magnet_armb</td>
<td>electromagnet</td>
<td>pick up and drop arm b</td>
</tr>
<tr>
<td>motor_robot</td>
<td>electric motor</td>
<td>rotate robot</td>
</tr>
<tr>
<td>motor_feed</td>
<td>electric motor</td>
<td>activate and deactivate feed belt</td>
</tr>
<tr>
<td>motor_deposit</td>
<td>electric motor</td>
<td>activate and deactivate deposit belt</td>
</tr>
</tbody>
</table>

Table 2.2: List of actuators used in the production cell system

a loader, which is a component that simply puts a finite number of blocks on the feed belt. We describe every component in details in following subsections. The controller reads the state of the various components through a set of sensors and commands the various components through actuators. The set of sensors is shown in Table 2.4 and the set of actuators is shown in Table 2.2.

Electromagnet actuators can be on/off. Motor actuators can also be on/off but also have a binary direction, called polarity. The polarity of the motors determines the direction of the actuation. For example, setting the polarity of the motor\_arma motor to negative and starting the motor will retract arm a. The combination of polarities for the motors are shown in Table 2.3.

The switch and photoelectric cell sensors are discrete binary sensors that give true/false information. The potentiometer sensors return a numerical value. The model remains faithful to the reality of sensors, actuators, and components. The controller uses only sensors and internal variables to make decisions. Furthermore, the controller uses only actuators to command the components. Sensors are read-only for the controller and actuators are read/write. Each component, other than the controller, update the values of sensors. Actuators are commanded only by the controller. This convention is congruent with the controller-environment separation principle [208].

The original example has been extended to reflect the reality that certain actions are durative, that is, they take a finite amount of time to complete. For example, the time that it takes for the press to stamp a block is 11 time units. The example has also been extended to include a resource, power consumption. For example, turning
<table>
<thead>
<tr>
<th>Name</th>
<th>Polarity</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>motor_press</td>
<td>positive</td>
<td>operate the press</td>
</tr>
<tr>
<td>motor_press</td>
<td>negative</td>
<td>operate the press</td>
</tr>
<tr>
<td>motor arma</td>
<td>positive</td>
<td>extend arm a</td>
</tr>
<tr>
<td>motor arma</td>
<td>negative</td>
<td>retract arm a</td>
</tr>
<tr>
<td>motor armb</td>
<td>positive</td>
<td>extend arm b</td>
</tr>
<tr>
<td>motor armb</td>
<td>negative</td>
<td>retract arm b</td>
</tr>
<tr>
<td>motor robot</td>
<td>positive</td>
<td>rotate robot counterclockwise</td>
</tr>
<tr>
<td>motor robot</td>
<td>negative</td>
<td>rotate robot clockwise</td>
</tr>
<tr>
<td>motor feed</td>
<td>positive</td>
<td>activate feed belt in the direction loader to robot</td>
</tr>
<tr>
<td>motor feed</td>
<td>negative</td>
<td>activate feed belt in the direction robot to loader</td>
</tr>
<tr>
<td>motor deposit</td>
<td>positive</td>
<td>activate deposit belt in the direction out of system to robot</td>
</tr>
<tr>
<td>motor deposit</td>
<td>negative</td>
<td>activate deposit belt in the direction robot to out of system</td>
</tr>
</tbody>
</table>

Table 2.3: Behavior of actuators based on polarity

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>robot angle</td>
<td>potentiometer</td>
<td>the position of the robot</td>
</tr>
<tr>
<td>press.status</td>
<td>switch</td>
<td>whether the press is busy or not</td>
</tr>
<tr>
<td>arma.position</td>
<td>potentiometer</td>
<td>how far has arm a extended</td>
</tr>
<tr>
<td>armb.position</td>
<td>potentiometer</td>
<td>how far has arm b extended</td>
</tr>
<tr>
<td>feed.begin</td>
<td>photoelectric</td>
<td>is there a block at the beginning of the feed belt</td>
</tr>
<tr>
<td>feed.end</td>
<td>photoelectric</td>
<td>is there a block at the extreme end of the feed belt</td>
</tr>
<tr>
<td>deposit.begin</td>
<td>photoelectric</td>
<td>is there a block at the beginning of the deposit belt</td>
</tr>
<tr>
<td>deposit.end</td>
<td>photoelectric</td>
<td>is there a block at the extreme end of the deposit belt</td>
</tr>
</tbody>
</table>

Table 2.4: List of sensors used in the production cell system
Table 2.5: Durative actions

<table>
<thead>
<tr>
<th>Component</th>
<th>Action</th>
<th>Duration</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loader</td>
<td>Put a block on the belt</td>
<td>2</td>
<td>200</td>
</tr>
<tr>
<td>Feed</td>
<td>Move block</td>
<td>5</td>
<td>500</td>
</tr>
<tr>
<td>Deposit</td>
<td>Move block</td>
<td>7</td>
<td>500</td>
</tr>
<tr>
<td>Robot</td>
<td>Rotate 30°</td>
<td>2</td>
<td>1000</td>
</tr>
<tr>
<td>Robot</td>
<td>Extend arm</td>
<td>3</td>
<td>1200</td>
</tr>
<tr>
<td>Robot</td>
<td>Retract arm</td>
<td>2</td>
<td>1100</td>
</tr>
<tr>
<td>Robot</td>
<td>Drop a block</td>
<td>2</td>
<td>800</td>
</tr>
<tr>
<td>Robot</td>
<td>Pickup a block</td>
<td>3</td>
<td>1000</td>
</tr>
<tr>
<td>Press</td>
<td>Stamp a block</td>
<td>11</td>
<td>3000</td>
</tr>
</tbody>
</table>

on the press motor consumes 1500 units of power per time unit while the press stamps a block. The list of durative actions, with their power consumptions, are shown in Table 2.5.

All other actions are assumed to be instantaneous and are assumed to consume no power. The controller actions are assumed to be instantaneous. While these assumptions do not reflect reality, it is nevertheless reasonable because the timing of the software is fast enough in relation to the timing of other components. The software operates on the order of micro seconds while the hardware components operate on the order of tenths of a second. This simplification is part of the original case study definition in [163].

Loader

The behavior of the loader is to put blocks on the feed belt. The design of the loader puts blocks on the belt either continuously or loads a specific number blocks and stops after the blocks have been loaded. The loader is used as the environmental component which drives the system. The behavior of the loader is to put a block on the feed belt as soon as the feed belt is empty, that is, as soon as the robot picks up a block from the feed belt. This behavior ensures that a block will be available to the robot as soon as possible so that the robot doesn't have to wait indefinitely. The loader also communicates whether or not it is done putting blocks on the belt so that the controller can take appropriate action.
Feed Belt

The feed belt is a simple component that takes a block from the loader to the robot. The feed belt is activated by the `motor_feed` motor. If the `motor_feed` motor is turned on and its polarity is positive, the belt moves from the feed to the robot (left to right in Figure 2-7). The belt contains two sensors, one to determine whether there is a block at the beginning of the belt (`feed_begin`) and one to determine whether there is a block at the end of the belt (`feed_end`). Some of the requirements of the belt is that it be stopped before the loader puts a block on it and that it be stopped before the robot picks up a block from it.

Robot

The robot is made up of 3 components which operate in parallel - the base, arm a, and arm b. The base can rotate clockwise and counter clockwise depending on the polarity of the `motor_robot` actuator. If the polarity of the `motor_robot` actuator is negative, the robot rotates in a clockwise direction in Figure 2-7. The positive polarity rotates the robot counter clockwise. Requirements on the robot rotation are such that it shouldn't rotate while the arms are extended in order to avoid collisions with the press and the belts.

The rotation of the robot can be controlled at the same time as the two arms. The two arms can be extended and retracted and their respective magnets can be turned on and off. The arms differ in their height such that only arm a can pick up from the feed belt and only arm b can drop blocks on the deposit belt. Furthermore, only arm a can drop a block in the press and only arm b can pick up a block from the press. These restrictions are congruent with the original problem definition [163]. The arms are operated using a motor whose polarity influences the behavior. For example, arm a can be extended by turning `motor_arma` on with its polarity set to positive. Arm a can be retracted by reversing the polarity. Arm b can be operated in a similar fashion. The magnets are used to pick up and drop blocks. For example, if arm a is extended at the feed belt, a block is available at the feed belt, and `magnet_arma` is
turned on, the block is to be picked up by arm a and the feed belt becomes empty. Blocks remain picked up as long as the magnet is on. Once the magnet is turned off, the block is dropped. Requirements on the robot arms is that blocks should not be dropped in places other than the press and the deposit belt.

Press

The press is a simple component that is either busy stamping a block or idle. The press will begin stamping a block when the motor_press is turned on. The polarity of the motor does not affect the behavior of the press. The press also contains a sensor to indicate whether a block is ready or not. While the press is busy stamping a block, the block is notfinished and the press is loaded. Once the press has finished stamping the block, the block is finished and the press is loaded. There are no safety requirements on the press other than it should not be turned on when it is empty.

Deposit Belt

The deposit belt is identical to the feed belt, except that its polarity is reversed and the deposit belt is longer than the feed belt. In the model, the deposit belt is assumed to “magically” remove blocks from the system once they reach the end of the belt. The belt should not be turned on when it is empty and blocks should not be dropped on it when the belt is on. The belt can be turned on using the motor_deposit motor. When the motor has negative polarity, the deposit belt operates from the robot to out of the system (right to left in Figure 2-7). If the polarity is reversed, the belt operates in the opposite direction.

Controller

The controller uses the sensors and the actuators to operate the various components of the system. There are three core situations that the controller needs to handle. The first situation is the beginning of simulation, where there are no blocks in the system. In this situation, the robot shall wait with arm a at the feed belt until a block enters the system. Once a block enters the system, it should be picked up as soon as
possible and loaded in the press. The second situation occurs when there is a block in the press. In this situation, the robot shall wait for another block to enter the system through the feed belt. The robot shall also wait for the press to be finished stamping the block. Arm a shall pick up a block at the feed and arm b shall pick up the block from the press. When this situation is met, the robot shall be rotated such that arm a will drop its block in the press and arm b will drop its block on the deposit belt. Once this has been achieved, the robot returns to the feed and the cycle resumes. The third situation occurs when there is a block in the press and the loader is no longer loading blocks into the system. When this situation occurs, the robot shall wait for arm b to pick up the block from the press and immediately unload it on the deposit belt. After this situation has occurred, the robot shall return with arm a at the feed belt and wait indefinitely until the first situation is encountered.

The controller can command all actuators in parallel and read the sensors at any point. The assumption that the controller actions are instantaneous is fair since the major concern is to ensure that the controller behavior is safe. Adding time to the controller actions would reduce the parallelism of the controller. The production cell case study is analyzed using the framework, and the results are provided in Section 8.1. The TASM model for the case study is provided in Appendix D.

2.8.2 Electronic Throttle Controller

The Electronic Throttle Controller (ETC) is a “drive-by-wire” system that is currently in use at a major automotive company. The ETC was initially modeled by Griffiths [111] as a hybrid system using Mathworks’ Simulink and Stateflow [167]. The ETC is used to optimize fuel consumption based on a set of criteria, including environmental conditions such as temperature and altitude, the state of the vehicle such as engine RPM and speed, and driver inputs such as cruise control and gas pedal angle [48]. The throttle controller is a piece of software which sits between the operator and the engine and replaces the mechanical linkage between the gas pedal and the engine throttle. The software interprets driver input and operating conditions, through sensors, to decide on the desired angle of the engine throttle for optimal fuel
efficiency.

The throttle angle governs how much air can enter the engine and, consequently, how much power is produced by the engine. The relationship between throttle angle and fuel consumption is intuitive. The angle of the engine throttle determines how much air can go in the cylinder, and hence controls the volume of the charge. Consequently, the throttle position governs the amount of torque produced. The fueling system is responsible for injecting an amount of fuel so that, immediately before combustion takes place, the Air-to-Fuel Ratio (AFR) is optimized. More specifically, the AFR should be stoichiometric (i.e., as close to 14.7:1 as possible for regular fuel) in order to allow for complete combustion, resulting in optimal efficiency. In order to optimize fuel efficiency, there are two main parameters to control: the angle of the throttle and the AFR as commanded by the fuel injectors. The ETC uses these two outputs to control the behavior of the engine.

Figure 2-8 shows the top level of the ETC model in Simulink, with the two key outputs – desired current (desired_current) and desired rate of fuel mass (dMfc). The angle of the throttle is controlled by the amount of current fed to the throttle servo. The desired current affects the position of the throttle and is determined based on the position of the gas pedal (as activated by the operator) and other external parameters (e.g., vehicle speed, $O_2$ concentration in the exhaust, engine speed, and temperature). The other controller output is the rate of fuel mass (dMfc). The dMfc value controls how much gas is sprayed in the combustion chamber. That value needs to be dynamically adjusted to maintain a stoichiometric combustion. The transfer function that characterizes the relationship between these two quantities (desired current and dMfc) is non-linear, and the model considered in this case study controls both factors independently.

The throttle controller uses modes to decide the control laws that govern the throttle actuation. For example, the throttle controller operates under different modes that have a priority ordering, depending on environmental conditions such as engine revolution, traction, cruise control settings, and driver input. The modes define the desired throttle angle, commanded through a current output from the throttle
Figure 2-8: High level Simulink model of the ETC
During nominal operation, the major modes of the controller are grouped into “driving modes” and “limiting modes”. The limiting modes, defined as undesirable environment conditions, take precedence over driving modes. Limiting modes include “traction control”, where the wheels rotate with too little friction, and “revolution control”, where the engine operates over a predefined threshold of rotations per minute. The driving modes include “human control”, where the throttle is commanded via the gas pedal, and “cruise control”, where the throttle is commanded based on the desired vehicle speed. The different modes are shown in Figure 2-9, adapted from [111], represented visually as a Statechart variant. The “XOR” label indicates mutual exclusion between modes and the “AND” label indicates parallel composition of modes. The transitions to the “failure detected” mode are not shown in Figure 2-9 to keep the figure simple. In each mode, a transition to the “failure detected” is possible. The detection of failure takes precedence over all other modes and the behavior of the ETC is to gradually decrease the vehicle speed until shutdown is possible.

![Figure 2-9: ETC modes](image)

The modes of the throttle controller determine the desired throttle angle and, consequently, the amount of current output from the controller. The mode switching logic, as well as the calculation of the desired current represent the functional
behavior of the ETC, dictating what the output should be based on various inputs. Because the calculation of the dMfc is completely isolated from the rest of the system, it is omitted from the case study. The study of the electronic throttle controller functional behavior, as well as the functional requirements for the ETC are explained in Section 8.2.

The ETC represents an interesting case study for the proposed framework because the functional behavior is implemented using a set of tasks and a scheduler. The ETC implementation is achieved using 3 tasks - a manager task, which sets the major and minor modes of the ETC, a monitor task, which periodically appraises the health of the system, and a servo task, which calculates and outputs the desired current based on the controller mode and the health of the system. The tasks have different periods and are driven by a scheduler with a 1 ms clock, as shown in Figure 2-10.

![Figure 2-10: ETC tasks and scheduler](image)

The scheduler does not support preemption and the tasks have fixed priority. The monitor task has the highest priority, followed by the monitor task, followed by the servo task. The scheduling strategy is modeled and analyzed using the framework in Section 8.3. The model in Section 8.3 contains only the scheduler and tasks and does not contain any functional behavior. Modeling the system in this way enables the verification of the scheduling strategy and the functional behavior strategy separately. In Section 8.4, the functional model and the tasking model are combined into a composite model through a series of refinements. The traceability approach described in Chapter 6 is used to demonstrate that properties that were proved separately about both the functional model and the tasking model are preserved through the combination. The three TASM models corresponding to these three views of the ETC are provided in Appendix E.
The ETC case study is used to exercise all aspects of the framework. Safety and liveness properties are verified according to the requirements expressed in [111]. Timing properties relating to the scheduling facets of the system are also studied. The model also contains 2 resources, power consumption and memory, which are analyzed for their best case and worst case conditions. Test case generation is performed based on the functional model and the tasking model. Finally, the traceability approach is exercised when combining the functional and tasking models, and is also used for regression test case generation. The ETC proves to be an interesting case study because it combines two types of models, functional and time, and utilizes all features of the framework.

2.8.3 Timeliner Script Executor

The Timeliner system [61] has been developed by the Charles Stark Draper Laboratory, in conjunction with the National Aeronautics and Space Administration (NASA), as a scripting environment to automate procedural tasks typically performed by human operators [177]. The system is composed of a high level input language, a compiler, a run-time system, and a user interface. The system is currently in use on the International Space Station (ISS) to automate a variety of tasks traditionally performed by astronauts, including spacecraft operations, subsystem checkouts, and failure detection [61].

The first component, the Timeliner language, was designed to allow easy definition of sequencing and control for complex systems. The Timeliner language is a high level scripting language with control flow based on time conditions and general Boolean conditions. Programs written in the Timeliner language are called scripts, and are organized hierarchically in bundles, sequences, and statements. Each step or decision point in a script is expressed as a series of Timeliner statements. These statements are grouped together into a Timeliner sequence, and a series of related sequences are grouped together into a Timeliner Bundle. The statement, sequence, and bundle groupings provide an organizational structure, as well as a control structure for an operator interacting with the system, as shown in Figure 2-11. A Timeliner
script contains one or more bundles. A bundle contains one or more sequences and
a sequence contains one or more statements. Bundles and sequences can be active
or inactive. During execution, the Timeliner run-time system executes all active se-
quenues in all active bundles. If a bundle is inactive, its sequences are not executed.
In the Timeliner language, there are six general types of statements:

- Block declaration statements – these define the boundaries of bundles, se-
quenues, and subsequences

- Timing control statements – these affect timing or flow of execution

- Conditional control statements and their modifier clauses – these allow for spe-
cific conditions that control execution based on general system values

- Action statements – these are used to carry out actions affecting the target
system and support interaction with the operator

- Bundle/Sequence Control statements – these are used to manage bundles and
to control sequence execution

- Non-executable statements – these are used for definitions of symbols and re-
serving of local storage.

A sample script is given in Listing 2.1 and other example scripts are given in
Section 8.5. The complete Timeliner language is documented in [177].

On the International Space Station, the Timeliner script executor shares processor
usage with other tasks. The script executor is given a fixed slice of time in which
to execute sequences. One round of Timeliner execution is called a pass. In a pass,
the script executor will sequentially execute all active sequences in all active bundles.
Each sequence executes in round-robin fashion, until a blocking statement is encoun-
tered. Once a blocking statement is encountered, the execution for that sequence
will resume in the next pass, at the blocking statement. Blocking statements include
\textit{EVERY}, \textit{WHEN}, and \textit{WHenever} statements [177]. The execution times of
various Timeliner statements have been heavily studied by the Charles Stark Draper
Laboratory [62]. The measures were performed using the Timeliner Testbed, with version CI.024 of the Timeliner Executor, using an embedded real-time 16MHz Intel 80836sx VME board with an 80387 floating point coprocessor. The execution times contained in document [62] are used to model the scripts in the TASM language.

![Operator Commands]

Figure 2-11: Timeliner script organization [61]

The second component, the compiler, translates an ASCII representation of the language into a form that the Timeliner execution engine can consume. The compiler additionally supports the independent definition of system data object and command information, such that Timeliner bundles can interact with a physical system without the details of the system data formats needing to be embedded within the language. Lastly, the compiler and the execution engine, known as the Executor, are designed for ease of portability to different platforms. The third component, the Executor, provides real-time monitoring and control based on the commands and conditions defined in the Timeliner sequences. A compiled bundle may be installed, executed and removed independently of execution environment software build. The Executor supports parallel execution and independent control of multiple bundles, which themselves may contain sequences that execute in parallel. This execution may be in either an asynchronous or synchronous manner. The Executor works together with the final component, the user interface, to provide the ability to precisely track, view, annotate, and interactively control an executing Timeliner script. Through the displays, an operator can also monitor the status of and receive messages from executing scripts. Hence sequences can be executed completely autonomously or via more interactive control.
Analysis

Traditionally, the Best-Case Execution Time (BCET) and Worst-Case Execution Time (WCET) of one pass of the Timeliner script execution were obtained through manual analysis and through systematic testing. However the timing properties of Timeliner scripts can be obtain through static analysis. The purpose of using the TASM language and framework is to determine the BCET and WCET for one pass of the script executor, for a given script, by taking into account the execution of all sequences and their potential interference. Determining these times will ensure that a proper time slice can be selected for the script executor. The selected time slice should be large enough to handle the worst-case scenario, but small enough to ensure optimal processor usage. To analyze the execution times of the Timeliner script executor, a set of sample scripts is modeled in the TASM language. These scripts stem from a plant controller application. The plant controller application was selected because it is simple enough to clearly explain the analysis approach but complex enough to verify interesting properties of the scripts. The details of the plant controller are detailed in the following section.

Plant Controller

The Plant Controller is a simple Timeliner application where sequences are used to maintain the cabin pressure and the ambient temperature of a plant between predefined thresholds. A logical view of the application is shown in Figure 2-12. The Timeliner script, which contains two sequences, has been obtained from [238]. The first sequence, TEMP_MONITOR, is used to maintain the temperature of the cabin between 20 and 25 Celsius degrees. The second sequence, HUMIDITY_MONITOR, is used to maintain the humidity of the cabin between 40 and 60 percent. The TEMP_MONITOR sequence is shown in Listing 2.1 and the HUMIDITY_MONITOR is shown in Listing 8.24. When the temperature is greater than 25 Celsius degrees, the sequence will command the cooling system to start. When the temperature is below 20 Celsius degrees, the sequence commands the heating system to start. The
variable `TRYING_TO_COOL_SYSTEM` is used to notify the HUMIDITY_MONITOR sequence not to turn off the cooling system if the TEMP_MONITOR sequence needs it to cool the cabin. The HUMIDITY_MONITOR sequence uses the cooling system to reduce the humidity of the cabin and shares usage of the cooling system with the TEMP_MONITOR sequence.

![Temperature Humidity](image)

Figure 2-12: Timeliner plant application

This Timeliner script is fairly straightforward, but it is useful to demonstrate the capabilities of the TASM language and framework, notably in terms of execution time analysis. The analysis of the plant controller scripts is provided in Section 8.5. The complete TASM model of the scripts is documented in Appendix F.

### 2.8.4 Motivations for the Case Studies

The three case studies provide an adequate basis to evaluate the proposed framework. The case studies come from three different domains and serve to illustrate the versatility of the TASM language in modeling different applications from multiple domains. Furthermore, the combination of the three case studies provides modeling and analysis of both functional properties and non-functional properties. The production cell case study provides an application of medium size where the modeling of the hardware components remove the need to model the time behavior of the software
controller. As explained in Section 2.6.1, this situation occurs because the hardware components operate on the order of seconds, while the software operates on the order of microseconds.

The ETC, on the other hand, does not model the time behavior of the environment. Consequently, the time-based behavior of the controller can be modeled and analyzed, at the task level. The ETC provides an application of industrial size that stretches the limits of the analysis capabilities, as explained in Section 8.4.7. Since the application is adapted from Mathworks' Simulink and Stateflow, it also serves to demonstrate that the TASM language can capture the semantics of Stateflow and some of the Simulink semantics. The ETC also contributes to demonstrate the modeling of scheduling and tasking alongside functional behavior.

Finally, the Timeliner case study serves to demonstrate modeling at the implementation code level, with precise timing behavior for individual code statements. In the Timeliner case study, the time-based behavior of the environment is also abstracted away and only non-deterministic changes in environment conditions are modeled. The Timeliner case study is a case study of modest size, but serves to illustrate the test case generation strategy and how it can be related to implementation code.

2.9 Segue into Chapter 3

This chapter presented background information related to the concepts used in the subsequent chapters of this thesis. Included in this chapter was information about real-time embedded systems, software engineering, and the case studies used to evaluate the presented research. Extended descriptions of the case studies, with detailed models and analysis results, are presented in Chapter 8. In the next chapter, Chapter 3, the various components of the engineering framework are presented, alongside the tool architecture used to implement the framework.
Chapter 3

Framework Overview

This chapter presents an overview of the different components of the framework. Section 3.1 provides the motivations for the features of the framework, in light of the objectives described in Section 1.1 and in light of the target systems described in Section 2.1. Overviews of the different components of the framework are given in Section 3.3. Each component of the framework is treated in detail in subsequent chapters. This chapter also provides a description of the tool architecture that is used to implement the framework. This chapter focuses on the capabilities, motivations, and tool support of the framework while subsequent chapters describe in details the language and algorithms used to achieve the capabilities of the framework.

3.1 Introduction

The proposed framework provides a specification-based approach to system engineering by rooting engineering activities in a formal yet readable specification language. The benefits of a specification-based or model-based approach are explained in Section 2.3. Furthermore, as explained in Section 2.1, the systems targeted by the proposed framework are reactive embedded real-time systems. The aspects of interest of these systems include function, time, and resources. Consequently, the proposed framework provides the necessary facilities to model and reason about these three aspects. Moreover, the proposed framework aims to reduce the high cost of V &
V activities by integrating and automating formal verification and test case generation. The framework also addresses the inherent design paradox of model-based approaches, described in Section 2.6.1, by providing bi-directional traceability of system models from high level models down to the implementation level. The integration of a formal yet literate specification language, adequate for the target systems, formal verification, test case generation, and bi-directional traceability provide a unique set of features not available in other engineering frameworks. As explained in Section 1.1 and in Chapter 2, these features are paramount to tackle the increasing complexity and associated challenges encountered when engineering the target systems. In the following section, related frameworks are reviewed, in light of the capabilities of the framework presented in this thesis.

3.2 Related Work

The need and benefits of model-based development have prompted a variety of languages and approaches to model embedded systems, as outlined in [49, 230, 231]. In this section, related tool-supported approaches to real-time system engineering are reviewed. The comparison between competing offerings and the proposed framework is performed in the context of high level engineering capabilities. It is important to note that if a given framework does not currently provide certain capabilities, it is not necessary due to a shortcoming of the offering, but it is most likely due to the goals of the given framework and the community to which it belongs. For example, in the Ptolemy project [55], the focus is put on integrating different computation models for real-time systems and to provide an overarching simulation environment. Consequently, it is not surprising that PTOLEMY does not support code generation since it is not meant as a complete systems engineering solution. Nevertheless, popular tool-supported engineering aids, however specialized they may be, are included in this section for comparison with the proposed framework. Offerings which are not tool-supported and which are not specifically targeted at real-time systems are omitted. The offerings are compared along different dimensions, and the results are
shown in Table 3.1. The specifics of each offering are compared with the offerings of the proposed framework in subsequent chapters. For example, all of the reviewed offerings are rooted in a modeling language. These modeling languages are reviewed as part of the related work in Chapter 4, where the TASM language is described. In the remainder of this section, competing approaches to the proposed framework are reviewed, in alphabetical order.

The CHARON language and associated framework and toolkit provide a rich environment to incorporate continuous and discrete dynamics for hybrid systems modeling and simulation [3]. The input language of CHARON is a variant of Statecharts [120], extended with continuous dynamics and the framework provides facilities for hierarchical modeling [6]. The CHARON suite of tools provides rich facilities for simulation of hybrid systems, including graphing facilities to visualize time-dependent behavior of continuous dynamics. The CHARON tool suite also includes a verifier, called requiem, which is used to explore the state space of CHARON models [4] in a model checking fashion. The primary focus of CHARON is the modeling, simulation, and verification of hybrid systems. HyTech is a symbolic model checker for linear hybrid automata [127]. HyTech’s focus is primarily on modeling and verification through symbolic manipulation techniques.

The IF toolset [52] is an integrated toolset for the design and analysis of real-time systems. The IF toolset uses the Unified Modeling Language (UML) and the System Design Language (SDL) as its input specification language. The toolset translates the input languages to their own version of timed automata for analysis purposes. Recent developments have included the development of semantics for both UML and the real-time profile of UML [182] as part of the Omega project [178]. The IF toolset contains facilities for test case generation and for code generation and provides an offering similar to the framework presented in this thesis. The core differences revolve around the input languages, which are compared in Section 4.1, and in the lack of traceability and refinement concepts. Furthermore, the analysis capabilities of the IF toolset do not include execution time analysis and resource consumption analysis. Mathworks’ Matlab, Simulink, and Stateflow provide a rich set of facilities for modeling and
simulating hybrid systems [167]. Matlab is one of the success story of model-based engineering since it is heavily used in the embedded system industry. One of the drawbacks of Matlab is its lack of analysis capabilities beyond simple syntax verifying, type checking, and model completeness.

The PTOLEMY project and associated tool environment aims to develop a generic environment for simulation of timed systems [55]. The input language of Ptolemy can incorporate disparate computation models for the sake of hybrid system modeling and simulation. While PTOLEMY enables the integration of disparate computing models, its focus is not on system engineering. On the other hand, the Specification Tools and Requirements Methodology (SpecTRM) [160] is a suite of tools that incorporate notions of safety engineering, system engineering, and intent specification [161]. At the time of the writing of this thesis, SpecTRM contained rich facilities of system level modeling and simulation in the form of requirements, but did not yet contain facilities for software engineering activities. Consequently, the framework proposed in this thesis could represent a suitable complement to SpecTRM.

In the modeling and analysis of embedded real-time systems, the visual formalism Statecharts [120] and its associated tool STATEMATE [122] represent one of the early formalisms applied to real-time system engineering [91]. Statecharts have been heavily used in various domains and numerous semantics have been suggested and adopted in different communities [122]. STATEMATE has transitioned to industry and has become a rich tool suite for embedded systems engineering, which contains facilities for test case generation and for code generation [121]. STATEMATE does not contain refinement and traceability facilities and its input language, Statecharts, belongs to a difference class of languages than the TASM language. The two languages are compared in Section 4.1.

The Timed Input Output Automata (TIOA) is a language and mathematical framework for the modeling and analysis of hybrid systems [147]. The framework has been implemented through a set of tools using the PVS theorem prover and the UPPAAL tool suite for analysis [171]. More recently, the Tempo language and associated toolkit have been developed on top of the TIOA formalism [165]. The
main focus of the TIOA framework and associated language and toolset has been on
the composition semantics and proof methods to ensure correctness of TIOA models,
their composition, and their refinements. TIOA's rich semantics and flexible analysis
capabilities could serve as an analytical basis for integrating continuous behavior with
the TASM language. By expressing TASM semantics using TIOA, hybrid systems
modeling and verification could be incorporated in the framework. This option is
investigated in Chapter 9 as part of future work. At the time of this writing, the
TIOA toolkit and the Tempo toolset did not contain facilities for test case generation
or code generation.

The UPPAAL tool suite utilizes a variant of networks of Alur-Dill automata ex-
tended with finite variables, data structures, communication channels, and urgent
and committed locations [29]. The UPPAAL tool suite is comprised of an editor, a
simulator, and a sophisticated verifier which explores the state space of the timed
automata networks using TCTL [24]. Efforts have been undertaken to develop en-
gineering solutions on top of UPPAAL, namely the TIMES toolset, which is a toolset
to describe a scheduler and a set of tasks that can be analyzed for schedulability
and synthesized to an implementation in C [9]. Furthermore, the COVER toolset is
a tool to generate test cases based on networks of timed automata [128]. However,
these separate offerings are not integrated into a cohesive offering and UPPAAL remains
largely an analysis engine, a model checker for timed automata, with various special
purpose tools developed on top of it.

3.3 Capabilities

This section provides an overview of the capabilities of the presented framework.
The capabilities include modeling and simulation facilities for the target systems,
static analysis of system models, bi-directional traceability of model features, and
automated test case generation. Each subsequent section provides an overview of the
different capabilities and provides forward pointers to following chapters describing
the features in details.
### Table 3.1: Comparison of the proposed framework with other frameworks for embedded real-time systems engineering

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<th>Other Analysis</th>
<th>Traceability</th>
<th>Refinement</th>
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</tr>
</tbody>
</table>

#### 3.3.1 Modeling and Simulation

The proposed approach to real-time system engineering promotes the use of models in all phases of the engineering lifecycle. More specifically, models are used as the primary abstraction to capture desired system behavior. During different lifecycle phases, modeling occurs at different levels of abstraction, as depicted in Figure 2-4. Consequently, an appropriate modeling language should be versatile enough to express system behavior at different levels of abstraction. Furthermore, the notion of *system* is a generic notion which can include environment behavior depending on where the system boundary is drawn. As a result, an appropriate modeling language should also include facilities to define the system boundary arbitrarily, depending on the system being engineered, and to include the modeling of environment behavior as needed. In the rest of this thesis, the term *system* is used to describe the behavior captured in the specification of the system, which may or may not include a subset of the behavior of the environment.

In the proposed framework, models are expressed using the Timed Abstract State Machine (TASM) language, a novel specification language whose syntax and semantics are described in Chapter 4. The TASM language is an extension of the theory of Abstract State Machines (ASM) [42], adapted for the specification of embedded real-time systems. ASMs provide a readable specification language that can model behavior at various levels of abstraction [41], and includes a generic theory of re-
finement [43]. ASMs provide a flexible and generic computing model that can easily be tailored to suit a particular purpose. The TASM language extends the theory of Abstract State Machines by adapting the language to the specification of the target systems.

Because the systems targeted by the research are embedded real-time systems, functional and non-functional properties are an integral part of the system's correctness, as explained in Section 2.1. Consequently, the modeling of non-functional properties is an important feature of the proposed framework. The non-functional properties that can be expressed in the TASM language are time and resource consumption, two concepts which are added to the theory of ASMs. Because the TASM language describes behavior as the computing steps of an abstract machine, models expressed in the TASM language are executable by definition, a desirable property of system models [98]. The simulation capabilities of the proposed framework include the specification of environment behavior, encoded in the TASM language. Furthermore, scenarios depicting different initial conditions are an integral part of the simulation strategy. The details of the TASM language, alongside illustrative examples, are given in Chapter 4.

While the modeling and simulation of system behavior provides a practical and insightful approach to system engineering, using solely modeling and simulation to gain insight into system behavior can be error-prone since it relies heavily on the intellectual prowess of the user [135]. Consequently, the ability to perform analysis of system models is an important companion to simulation. The proposed framework provides a rich set of verification capabilities, as explained in the following section.

### 3.3.2 Static Analysis

The modeling facilities of the framework and the TASM language center around the expression of functional behavior, time, and resource consumption. The analysis capabilities include automated analysis of functional behavior in the form of completeness and consistency, two important properties of system specifications [123, 125]. These two properties are formally defined in Section 5.1 in the context of the TASM lan-
guage and a verification approach is provided to automatically analyze the completeness and consistency of TASM specifications. Furthermore, because the verification approach includes model checking facilities [67], verification of functional properties using temporal logic formulas [212] is provided by the framework. More specifically, formal verification of the safety and liveness of TASM specifications, using a subset of Timed Computation Tree Logic (TCTL) [244], is achieved by reusing the UPPAAL tool suite, as explained in Section 5.2.

The framework provides a rich set of analysis capabilities for functional properties, but also addresses the analysis of time and resource consumption. The analysis of timing properties includes the automated derivation of Best Case Execution Time (BCET) and Worst Case Execution Time (WCET), using an approach called iterative bounded liveness, as explained in Section 5.3. The analysis of resource consumption properties includes the automated derivation of best case and worst case resource bounds for a given TASM model. Together, the analysis facilities comprise a set of algorithms and approaches to verify properties of the three key aspects of target systems, namely function, time, and resources. The complete analysis capabilities of the presented framework are explained in Chapter 5.

### 3.3.3 Bi-Directional Traceability

Because modeling typically happens at different levels of abstraction, ensuring consistency between different models can greatly enhance model maintenance [138]. Furthermore, the benefits of traceability between levels of abstraction has been discussed in Section 2.6.1, in terms of visualizing the propagation of design assumptions and the propagation of changes, and in terms of ensuring notions of equivalence between models. The traceability approach provided by the framework integrates notions of syntactic change with facilities to ensure semantic integrity between models. The integration of these two properties is an often overlooked problem in pure theories of refinement [43]. The bi-directional traceability capabilities provided by the framework supply a set of common refinement types that can explain the differences between two models. The two models are related syntactically by mapping the features of the mod-
els, achieving traditional notions of traceability [217]. The traceability approach can be used to track syntactic changes between models and to follow the propagation of changes and assumptions.

Furthermore, the traceability approach provided by the framework complements pure syntactic mappings with notions of semantic equivalence. For each type of refinement used to explain the differences between models, a set of correctness criteria are provided. If these correctness criteria hold for the refinement, a notion of semantic equivalence is guaranteed between the two models. The specific notions of semantic equivalence are explained in Section 6.2.2, for each type of refinement. The key idea behind the semantic equivalence approach is to reduce the verification activities. More specifically, if verification was performed on a given model, and this model is refined and traced using the proposed approach, verification results will hold in the refined model if the correctness criteria are met for the refinement. Consequently, verification performed on models before they are refined does not need to be repeated in refined models, reducing the total amount of verification that needs to be performed. In summary, the proposed approach to traceability provides bi-directional traceability so that the effects of assumptions and changes can be propagated top-down or bottom-up, verification results can be reused, and regression test cases can be generated, as explained in the following section. The traceability approach is explained in Chapter 8.

3.3.4 Test Case Generation

Simulation and static analysis of system models provide practical and insightful means to gain insight into system behavior. However, model simulation relies on the intellectual discipline of the end-user to provide all necessary scenarios to exercise the relevant system behavior. This situation can lead to important simulation scenarios being overlooked. Furthermore, while formal analysis provides mathematical guarantees that a model has certain properties, scalability remains a hurdle of automated formal analysis approaches such as model checking [69, 117, 124]. Consequently, simulation could lead to error-prone validation and formal verification might not be
feasible on complex models. Nevertheless, simulation provides a lightweight and intuitive approach to validation while automated formal analysis is desirable when it can be applied. Given the limitations of simulation and of formal analysis, other means of ensuring confidence into the system are necessary as a complement. In the engineering community, the main V & V activity remains testing, in the form of unit testing, integration testing, and regression testing [242]. For safety-critical systems, testing is mandatory for certification and requires that the testing approach exercises the system to a given level of coverage [216].

In a sense, testing resembles simulation since it involves devising a scenario and observing the response of the system. However, the construction of test cases can be done systematically, to exercise the system under test to a certain degree of confidence. The presented framework provides facilities for the automated generation of test cases for unit testing, integration testing, and regression testing. The approach to automatically generate test cases uses novel algorithms that utilize TASM models to derive test cases for unit and integration testing, using the rule coverage criterion from the ASM community [103], as explained in Section 7.2. Furthermore, the framework uses the bi-directional traceability approach to identify the effects of changes at different modeling levels, so that regression testing can be automated, as explained in Section 7.6. The approach to generate test cases is described in Chapter 7.

3.4 Tool Architecture

The features of the framework are implemented in the TASM toolset [200]. The TASM toolset uses literate and graphical facilities to create, edit, simulate, and analyze TASM specifications. The toolset is comprised of multiple components, divided into front-end components, back-end components, and 3rd party analysis engines, as depicted in Figure 3-1. The TASM toolset is completely written in the Java programming language, and uses the Eclipse [183] graphical libraries for the Graphical User Interface (GUI). The TASM toolset can be used on Windows XP and Vista and on Linux. The TASM toolset is an open source project which is available, free of charge,
from the TASM web site [88].

3.4.1 Front-End Components

The front-end components of the toolset include facilities for creating and editing TASM specifications, through the TASM Editor. The editor enables the specification of functional and non-functional behavior, with standard facilities for syntax highlighting and syntax checking. The TASM Simulator enables the graphical visualization of the dynamic behavior expressed in the specification in a step-by-step
fashion. Because time and resources can be specified using intervals, that is, using a lower bound and an upper bound, the simulation can use different semantics for time durations and resource consumption. For example, a given simulation can use the worst-case time (upper bound) for all steps, to visualize the system behavior under the longest running times. Other options include best-case time, average-case time, and using a time non-deterministically selected from the specified interval. The same semantics can be selected for the resource consumption behavior.

The TASM Analyzer is the component of the TASM toolset that performs analysis of specifications. The analyzer can be used to verify basic properties of TASM specifications such as consistency and completeness [123]. In the TASM language, completeness ensures that for all classes of monitored variable values, a rule will be enabled. Consistency ensures that for all classes of monitored variable values, one and only one rule is enabled. In other words, verifying consistency means verifying that the rules of a given machine are mutually exclusive. Both completeness and consistency are verified at the machine specification level. The analyzer GUI provides intuitive feedback to the user so that if a machine is incomplete or inconsistent, a witness counterexample is automatically generated from the back-end components and displayed to the user. The analyzer also provides the ability to export the completeness and consistency problems to a flat file, using the DIMACS file format, which is a standardized file format for SAT solver input [158].

The TASM analyzer also provides graphical facilities to verify the execution time of TASM models. The execution time is verified by mapping TASM specifications to the timed automata formalism of UPPAAL. The analyzer also provides facilities for exporting the generated UPPAAL model so that the model can be used for further analysis such as functional verification using temporal logic formulas. The derivation of minimum and maximum resource consumption is also provided by the TASM analyzer through a GUI.
3.4.2 Back-End Components

The back-end components of the TASM toolset provide most of the facilities available in the Graphical User Interface (GUI). The parser is responsible for loading and saving the TASM model to disk, using the "*.tasm" file format whose context-free grammar is available in Appendix A. The syntax verifier is used to ensure that errors in the models can be easily identified in the TASM editor through syntax highlighting and detailed error messages. Once the syntax has been verified to be free of errors, the simulator can explore various behaviors of the TASM model, through step-by-step analysis and different initial conditions specified through the TASM simulator. The simulator provides a rich interface, including the list of generated update sets, the history of resource consumption, and the values of internal and external state components.

The analyzer is the bridge between the GUI and the 3rd party engines. The analyzer provides all of the necessary facilities so that a user of the toolset is unaware that 3rd party engines are used in the analysis procedure. The analyzer provides a rich interface to the TASM analyzer GUI so that feedback can be provided to the toolset user in an intuitive fashion. The back-end analyzer achieves its tasks by translating TASM models through the back-end translator. The translator is the back-end component used to map between the TASM syntax to the syntax of 3rd party engines. The translator understands the 4 main file formats used in the TASM toolset, namely the TASM file format (*.tasm), the DIMACS file format (*.sat), the UPPAAL model file format (*.xml), and the UPPAAL query file format (*.q). The DIMACS file format is the standard input format of SAT solvers, including the SAT4J SAT solver. The UPPAAL tool suite uses its own version of XML as its input format and saves temporal logic formulas in a separate file, called the query file (*.q). The translator juggles these different formats to provide the necessary facilities to the back-end analyzer and to provide import/export capabilities to the analyzer front-end.

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3.4.3 3rd Party Engines

The analysis of completeness and consistency is achieved by translating machine rule guard expressions into a Boolean formula in conjunctive normal form [192]. The Boolean formula can then be verified for satisfiability using a SAT solver. The TASM toolset uses the SAT4J solver, an open source SAT solver [158]. The completeness and consistency problem is formulated in such a way that an incomplete or inconsistent specification leads to a satisfiable Boolean formula. Formulating the problem this way ensures that the SAT solver can automatically generate a counterexample if the specification is inconsistent or incomplete. The SAT4J solver is a Java-based solver which can be integrated seamlessly into any Java application. The TASM toolset provides the option to solve the completeness and consistency problems directly, without requiring the user to know that the specification is being translated to SAT. Because the input format of SAT solvers is standardized, the TASM toolset provides the capability to export the generated SAT problem, so that the problem can be analyzed and solved outside of the toolset. The mapping SAT4J SAT solver is also used to obtain minimum and maximum resource consumption.

The analysis of execution time is achieved with the UPPAAL tool suite. The UPPAAL tool suite is also written in Java, but is not an open source project. Furthermore, the UPPAAL tool suite does not have a public interface that can be used to manipulate UPPAAL models programmatically. However, UPPAAL contains an official library to manipulate the XML model file. The UPPAAL verifier is the component of UPPAAL used to explore the state space of the timed automata model and contains a published interface to load connect, load models, and execute temporal logic queries against the model.

3.5 Segue into Chapter 4

In this chapter, an overview of the framework was presented, including high level descriptions of each component of the framework. Furthermore, the tool architecture used to realize the framework was presented. Each component of the framework is
treated in-depth in the following chapters. The next chapter, Chapter 4, describes
the language that is used as the specification basis for the framework, the Timed
Abstract State Machine (TASM) language.
Chapter 4

The Timed Abstract State Machine Specification Language

This chapter describes the Timed Abstract State Machine (TASM) language, the modeling language which serves as the specification basis for the presented framework. The TASM language an extension of Abstract State Machines (ASM) to include facilities for specifying time and resource consumption. This chapter presents the motivations for the choices of the concepts included in the language, in light of target systems and related work. The syntax and semantics of the TASM language are presented, accompanied by an illustrative example to explain the concepts as they are introduced. The descriptive example concerns the behavior of a light and fan controller and is detailed in Section 4.1.5.

4.1 Related Work

This section presents a large body of related work concerning the design of the TASM language. The following subsection presents a review of usability concepts for specification and modeling languages, as support for the usability potential of the TASM language. Since the TASM language is an extension of ASM, a brief overview of ASM is presented, with related work concerning the inclusion of time in the ASM formalism. An overview of the main features of the TASM language are provided, in
order to qualify the differences between TASM, ASM, and related formalisms. The overview serves as an introduction to the motivations and features of the TASM language before the language is explained in details in Section 4.2 and in Section 4.3. Finally, this section concludes with a comparison of TASM with other popular formalisms used for the modeling and analysis of embedded real-time systems, for the frameworks presented in Section 3.2.

4.1.1 Usability of Specification Languages

The term “Formal Methods” has historically been used to designate an approach to system specification based on rigorous mathematical principles with an associated proof system to mathematically reason about properties of the system under design [225, 248]. The benefits of formal methods have been heavily documented, including specifications which are unambiguous and the ability to uncover defects during the early phases of the engineering lifecycle [50, 117]. However, the mathematical nature of early efforts in the formal methods community have yielded a set of languages and proof systems that were challenging to use by practitioners not versed in mathematics or computer science [71, 124]. But the benefits of unambiguous specifications, combined with the ability to detect defects early in the engineering cycle have provided a value proposition attractive to practitioners. Consequently, efforts have been made to combine the rigor of formal methods with a specification language that can be readily used by practitioners [162].

The topic of “usability” of a specification language is a highly subjective subject and depends heavily on the experience of the specifier and on the quality of the tool supporting the specification activities. Nevertheless, some basic notions of readability of specification languages have been established in the literature [146]. The term literate is used to denote a specification that can be read, like the English language [151]. Textual languages are traditionally more readable than graphical notations such as statecharts, which can become cluttered, counterintuitive, and have no clear starting point and end point for reading purposes [258]. The TASM language was designed with readability in mind by avoiding the use of special symbols,
keeping the syntax minimal, and providing abstraction mechanisms to structure specifications \[124, 146, 240\]. Furthermore, in terms of real-time system specification, the language makes the expression of timing concepts explicit, a desirable property of real-time languages \[254\]. While no controlled experiments were conducted to investigate the usability of the TASM language, the principles of literate specifications were maintained during the design of the language. Furthermore, since the TASM language is based on ASM, the usability of TASM can be inferred from the past successes of ASM in terms of readability \[41\]. Experience with industrial contacts, with fellow undergraduate and graduate students, and with presentations of the TASM language in various communities have served to reinforce the assumption that the TASM language is a literate specification language which can be used and understood by almost anyone who has basic programming proficiency \[42\].

4.1.2 Abstract State Machines

Abstract State Machines (ASM) provide an approach to specify, analyze, and verify hardware and software systems at different levels of abstraction \[42\]. The motivations and benefits of using Abstract State Machines (ASM), formerly known as evolving algebras, for hardware and software design have been documented in \[41\]. On the practical-side, ASMs have been used successfully on a wide range of applications, ranging from hardware-software systems to high level system design \[42, 47\]. ASMs have also been shown to be scalable to industrial size systems \[46\]. Furthermore, there is enough evidence to believe that ASMs provide a literate specification language, that is, a language that is understandable and usable without extensive mathematical training \[71\], as explained in Section 4.1.1. The preliminary evidence supporting the ease-of-use of ASMs revolves around the small size of the syntax, the simplicity of the semantics, and the avoidance of extraneous mathematical symbols. Moreover, the semantic distance, that is, the amount of effort required to translate between one model to another, for example between a design specification and an implementation, appears to be “small” for ASMs. The term “small” is used in comparison to other formalisms that are predominantly visual (e.g., timed automata) \[258\] or that make
heavy use of mathematical symbols (e.g., process algebra).

On the theoretical side, ASMs have well-defined formal semantics, which makes ASM specifications unambiguous and subjectable to formal analysis. ASM specifications are also independent of a specific verification method and can be verified either through manual proofs or through automated tools [249]. Furthermore, ASM theory was developed as a methodology for high level system design [42]. Consequently, refinement, or the process of gradually adding details to a system design, is an integral part of the theory, which makes ASMs applicable at various levels of abstraction. Finally, ASM specifications are executable, a useful property in the construction and validation of specifications [98]. The anecdotal evidence supporting the success of the ASM method [41] suggests that tailoring the formalism to the area of embedded real-time systems could achieve similar benefits. Abstract State Machines have also been used to automate engineering activities, including verification using model checkers [249] and test case generation [110].

The TASM language is an extension of Abstract State Machines (ASM), with facilities to specify time and resource consumption. The subset of ASM included in the TASM language is the same as explained in [249], which includes conditional statements and assignments, but excludes the \texttt{forall} construct and the \texttt{choose} construct. The \texttt{forall} statement is excluded because the duration of this construct depends on dynamic conditions and cannot be statically assigned. The \texttt{choose} construct is omitted for similar reasons because it is counterintuitive to assign a static duration to non-deterministic choice. The TASM language also excludes the \texttt{import} construct because safety-critical real-time systems discourage dynamic allocation. The omission of these three constructs is not too restrictive since many ASM specifications have not used these constructs, e.g., the production cell system in [45]. The concepts of Abstract State Machines (ASM) revolve around the concepts of an abstract machine and an abstract state. For an ASM, behavior is specified as the computing steps of the abstract machine and its effects on the abstract state. More specifically, the dynamic behavior is expressed through the machine executing a \textit{step}, which corresponds to a group of atomic updates made to global state. An \textit{update set} is the term used
to describe the set of atomic updates that are associated with a single step. A *run* of an ASM, is a sequence of steps, that is, a sequence of update sets. The global state after each step can be obtained by applying individual update sets sequentially.

The syntactical structure of a machine in the TASM language is an ASM in *canonical form*, also called an ASM in *block form* [110]. In this form, a machine is structured into a finite set of rules, written in precondition-effect style. Conceptually, block form is convenient for structuring specifications and analysis but it is not necessary since any ASM can be converted to block form by introducing a program counter variable [110]. For an ASM that contains *n* rules, a machine in block form has the following structure:

\[
\begin{align*}
R_1 & \equiv \text{if } G_1 \text{ then } E_1 \\
R_2 & \equiv \text{if } G_2 \text{ then } E_2 \\
& \vdots \\
R_n & \equiv \text{if } G_n \text{ then } E_n
\end{align*}
\]  

The guard *G_i* is the condition that needs to be enabled for the effect of the rule, *E_i*, to be applied to the environment. The effect of the rule is grouped into an *update set*, which is applied atomically to the environment at each computation step of the machine. In the ASM community, ASMs have been used to model specific examples of real-time systems [44, 72]. Some extensions have been proposed to the ASM theory to include timing characteristics [221] but the extensions make no mention of how time is to be specified (only the theoretical semantics are proposed) and do not address concurrency. Related work from the ASM community concerning using ASM to specify and analyze embedded real-time systems is reviewed in the following section.

**Time in Abstract State Machines**

The proposed approach to incorporate time in the Abstract State Machine (ASM) formalism incorporates concepts from a variety of previous approaches from the ASM
community. In the ASM community, related work has revolved around two main paradigms: instantaneous actions with time constraints, also called timed ASMs [72], and durative actions [44]. In timed constrained ASMs, all actions are instantaneous but rule guards can contain predicates over an external function called \textit{currt ime}, which denotes a wall clock. The \textit{currt ime} function is a monotone function which takes no argument and returns a value from the Reals domain. This approach has been used to specify and analyze real-time concurrent algorithms such as the railway crossing problem [22] and the Kermit protocol [136]. This approach is well-suited for declarative specification and for event-based systems where the temporal duration between events is the primary representation of timed-based behavior. However, the systems targeted by the TASM language are naturally specified using a duration paradigm. The approach presented in this thesis also contains a function analogous to the \textit{currt ime} function, called \textit{now}, but the function is not an external function, motivating the use of a different name. The underlying semantics of the \textit{currt ime} function are highly dependent on the moves of agents being durative since time progression is determined through agent actions. In timed ASMs and related approaches, the concept of time is an external function that is not part of the system behavior [114]. The progression of time is dependent on the rule guards and not on the actions of the specified system.

In contrast, the TASM language provides facilities to specify the duration of actions performed by the specified system. A similar approach using durative actions has been used in [44] to analyze Lamport’s bakery algorithm. In this approach, an untimed version of the algorithm is presented and is refined with durative actions. The refinement is shown to preserve the correctness of the untimed version. The approach is based on asynchronous ASM and the notion of partially ordered runs [115]. The durative moves are specified to occur during an open real interval \((a, b)\) where \(a\) and \(b\) are time values on the global time axis. Using the time specification, the moves of agents are ordered linearly and the requirements of partially ordered runs are extended to include conditions for overlapping moves. The approach presented in [44] provides no structured syntax to capture the duration of actions and the analysis of
the specification relies on creative proof methods. Furthermore, the moves of agents are specified on the global time axis instead of in terms of relative duration of moves, as used in TASM.

The approach adopted in the TASM language follows a durative action paradigm but specifies moves of agents in terms of relative durations of moves. The duration of a run is thus related to the summation of the moves of agents. Furthermore, the concurrency semantics in the TASM approach is related to synchronous multi-agent ASMs [47] since the moves of agents are synchronized using a global system clock. In the TASM language, there are no external functions that are not controlled by an agent of the specification. External functions are included into the behavior of agents that represent the environment. While the lack of external functions might seem counterintuitive to model embedded controllers, the external functions have been replaced by functions controlled by agents representing the environment. In this way, the system can be simulated completely without the need to hardcode the values of external functions since the values in the environment can depend on the behavior of the system. The TASM approach resembles the real-time controller ASM approach where runs are extended with state changes that occur at computationally significant real-time moments [72]. However, the computation of the significant real-time moments is a result of the actions of agents and is not determined a priori, as is the case in [72].

The key difference between the Timed Abstract State Machine (TASM) language and ASM is that steps are durative in TASM. In ASM, machine steps are instantaneous. Furthermore, in TASM, durative steps can consume a finite amount of resources. In the case of single agent specifications, the durative steps of the agent dictate the progression of time in the specification. In the case of multi-agent specifications, the durative steps are used to synchronize agents with respect to one another. In TASM, a step is the execution of a rule, which produces an update set. The update set is applied atomically to global state. For the single agent case, the duration of the step, reflected in the update set obtained through a rule execution dictates the progression of time. At the completion of a step, the environment is updated by
applying the update set once the step duration has elapsed.

The concept of step is fundamental in the definition of ASM and in computation theory in general since a step defines the atomic unit of progression of an abstract machine. In TASM, the concept of step is augmented with a duration and a set of resources consumed during the step execution to capture the physical reality of embedded real-time systems. This abstract model adequately captures the physical reality of computer systems where steps are typically rarely instantaneous. The durations and resource consumptions can be easily modified to capture behavior at different levels of abstraction, to document system assumptions, and to relate models at different levels of abstraction, including non-atomic refinement. In concrete computer systems, the notion of step varies depending on the level of abstraction. For example, a step could be considered a clock cycle, a machine operation, or a statement execution in a high level programming language. Throughout this chapter, the terms step, rule execution, move of an agent, and action of an agent are used interchangeably.

The composition extensions for ASMs presented in this chapter are based on the XASM language [10]. However, the XASM language does not include time or resource specification and only deals with single agent ASMs. The specification of resource consumption has not been addressed in the ASM community.

The systems that are targeted by the TASM language are embedded real-time systems. These systems include embedded controllers that monitor the environment periodically, through sensors, and take action on the environment through actuators. The important characteristics of such systems is that the values of sensors as read by the system are directly related to the actions taken by the system. Consequently, the behavior of the environment, typically represented as external functions in previous ASM approaches [72], cannot be hardcoded a priori since they depend on the actions of the controller. More information about target systems is available in Section 2.1.
4.1.3 The TASM Language

At a high level, the concrete syntax of the TASM language extends the block form of equation 4.1 to include time and resource consumption. The specification of time and resource consumption is achieved through annotations of individual rules. The concrete syntax of TASM resembles the ASM syntax presented in [104], with extensions for time and resource annotations. To illustrate these concepts, a sample rule of a block TASM is shown in Listing 4.1, expressed in the concrete syntax of the TASM language. The rule describes the behavior of the feed belt from the production cell case study [163]. For a description of the production cell system and a graphical representation of its layout, the reader is referred to Section 2.8.1. The feed belt carries blocks from the loader to the robot. According to the description of the system, moving a block from the loader to the robot takes 5 time units and consumes 500 units of power. Listing 4.1 shows the rule with the time and resource annotations. The line numbers are not part of the specification and are added to ease the description of the listing.

Listing 4.1 Rule 1 of machine Feed

<table>
<thead>
<tr>
<th>Line</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R1: Block goes to end of belt</td>
</tr>
<tr>
<td>2</td>
<td>{</td>
</tr>
<tr>
<td>3</td>
<td>t := 5;</td>
</tr>
<tr>
<td>4</td>
<td>power := 500;</td>
</tr>
<tr>
<td>5</td>
<td>if feed_belt = loaded and feed_begin = True and</td>
</tr>
<tr>
<td>6</td>
<td>motor_feed = on and motor_feed_p = positive then</td>
</tr>
<tr>
<td>7</td>
<td>feed_begin := False;</td>
</tr>
<tr>
<td>8</td>
<td>feed_end := True;</td>
</tr>
<tr>
<td>9</td>
<td>}</td>
</tr>
</tbody>
</table>

In Listing 4.1, line 1 contains the name of the rule, line 3 contains the time annotation, line 4 contains a resource annotation, line 6 and 7 contain the guard $G$ of the rule, and lines 8 and 9 contain the effect expression $E$ of the rule. Semantically, rule $R_1$ will be enabled when the guarding condition evaluates to True and when the machine is not busy executing a rule. When rule $R_1$ is executed, the machine will be blocked from executing other rules for 5 time units, at which point the effect of executing the rule will be applied to the environment. Furthermore, during the 5 time units of
the rule execution, 500 units of power will be consumed. While a machine is "busy" executing a rule, other parallel machines, if present, can execute rules in overlapping time intervals and the durations of their rule executions determine the synchronization of parallel update sets. The semantics of rule execution are such that a rule is executed based on the state at the beginning of the rule execution. These semantics are congruent with the target systems described in Section 2.1, which "cache" the state read through sensors before making a decision about the output. Furthermore, the TASM language uses relative duration at its time specification paradigm, in the form of rule execution times. While the semantics of the TASM language could be expressed using timed constrained ASM [114], the TASM language provides a concise and readable notation to express the desired behavior of the target system. A mapping between the TASM language and ASM is provided in Section 4.4. The syntax of the TASM language is explained in detail in Section 4.2 and the semantics are explained in Section 4.3.

4.1.4 Other Specification Formalisms

In the academic community, numerous mathematical formalisms have been proposed to specify and analyze real-time systems. The most popular formalisms developed in academia can be classified into three main families: automata, process algebra, and Petri nets [33]. These three families are reviewed and the languages of the related frameworks described in Section 3.2 are compared to the TASM language, with comparison results presented in Table 4.1.

In the automata family, timed automata are finite state automata extended with real-valued clocks and communication channels [5]. The formalism has been used on a variety of applications and is the formalism used in the UPPAAL tool suite [157]. The formalism is well-suited for analysis by model-checking, but the lack of structuring mechanisms makes abstraction and encapsulation difficult to achieve [34]. Statecharts and the associated tool STATEMATE [122] augment automata with structuring mechanisms (superstates). Statecharts also include time concepts through the use of delays and timers. Statecharts have been heavily studied in various com-
munities and many different semantics exist to describe the behavior of statechart models [23, 122].

In the Petri net family, a large number of variations on the traditional Petri net model have been developed, including various models of time [60]. Non-determinism is an essential part of Petri nets, which makes Petri net unsuitable for the specification of safety-critical real-time systems where predictability is of highest importance [34].

In the process algebra family, various offsprings of Communicating Sequential Processes (CSP) [31] and the Calculus of Communicating Systems (CCS) [170] have been defined, including multiple versions of timed process algebra [31]. However, in this formalism, it is difficult to express non-functional properties other than time (e.g., resource consumption). Timed LOTOS (ET-LOTOS) [31] is an example of a language from the process algebra family. Other well known formalisms include the Synchronous languages ESTEREL and LUSTRE [34].

In the industrial community, especially in the aerospace and automotive industries, the Unified Modeling Language (UML) [181] and the Architecture Analysis and Design Language (AADL) [223] have come to dominate notational conventions. At its onset, UML did not have formal semantics and remained a graphical language with limited support for automated analysis. Since its inception, many tools have defined their own semantics for UML, but the international standard [181] still does not contain a standard definition of the formal semantics. In the UML community, two real-time profiles have been proposed, the UML profile for “Schedulability, Performance, and Time Specification (SPT)” [180] and the UML profile for “Modeling and Analysis of Real-Time and Embedded Systems (MARTES)” [182]. The MARTES profile is the latest profile that corresponds to version 2.0 of UML. While both profiles contain a large amount of syntax, the lack of a consistent semantics, as well as disagreements among community leaders create challenges for widespread adoption of the profiles [93, 107]. Furthermore, UML is predominantly tied to object-oriented approaches [105, 108]. AADL contains formal semantics but is still in the early development stage. It is unclear whether AADL can be used to specify low level functional behavior. In its current form, AADL remains an Architecture Description Language
(ADL) and cannot express component-level behavior.

When comparing specification languages, numerous dimensions can be utilized for the comparison, including usability [162], composition models, communication model [144], and whether a language is graphical or textual. The comparison of related languages to the TASM language is performed using the categories in the headings of Table 4.1. These categories were selected based more on usability issues and less on semantic richness [162]. For example, it was argued in Section 2.1 that time specification using a duration paradigm is well-suited for the specification of the desired behavior of the systems of interest. Furthermore, a textual representation obeys the principles of literate specifications [146] while hierarchical composition is paramount to structure specifications and for reuse [35]. One of the main differences between the TASM language and languages like CHARON [4], TIOA/Tempo [147], and Simulink and Stateflow [167] is that TASM does not currently have facilities for specifying continuous behavior such as dynamics described by a differential equation. This difference is debatable since the behavior of a software system is inherently discrete. Continuous dynamics need to be included only when considering issues of performance such as stability and steady-state error [218]. Nevertheless, verification engines and notations that do not include continuous dynamics have proved useful in specifying and analyzing systems, such examples include Uppaal [24] and UML [179]. In the frameworks described in Section 3.2 the language SDL is not included in Table 4.1 because that language is primarily applied to telecommunication protocols [172], a type of system not targeted by the TASM language. Furthermore, UML uses a variant of statecharts, as does STATEMATE [121].

4.1.5 Light Switch Example

Throughout this chapter, a small example is presented to illustrate the features of the TASM language. The example contains a light bulb, a fan, two switches and two abstract state machines that operate in parallel and control the status of the light and fans depending on the state of the switches. A schematic view of the application is shown in Figure 4-1. This example is used throughout this chapter to
illustrate concepts as they are introduced. Different versions of the example are used to illustrate different concepts. For example, version 1 of the example, in Listing 4.2, contains only the control for the light bulb, one switch, and the light bulb (the fan components are omitted). The presented example also contains two resources, memory and power, that the machines can use to perform their functions. While the presented example is quite simple, it is useful to illustrate the concepts of the TASM language. More substantial examples of TASM models are available in Chapter 8.

Table 4.1: Comparison of the features of the TASM language with other languages for embedded real-time system specification

<table>
<thead>
<tr>
<th>Name</th>
<th>Continuous Dynamics</th>
<th>Hierarchical Composition</th>
<th>Parallel Composition</th>
<th>Representation</th>
<th>Time Approach</th>
<th>Communication Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>TASM</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Textual</td>
<td>Duration</td>
<td>Shared Vars</td>
</tr>
<tr>
<td>Simulink/Stateflow</td>
<td>x</td>
<td>x</td>
<td></td>
<td>Graphical</td>
<td>Timers</td>
<td>Channels</td>
</tr>
<tr>
<td>Statecharts</td>
<td></td>
<td>x</td>
<td></td>
<td>Graphical</td>
<td>Timers</td>
<td>Channels</td>
</tr>
<tr>
<td>TIOA/Tempo</td>
<td>x</td>
<td></td>
<td></td>
<td>Textual</td>
<td>Diff. Eq.</td>
<td>I/O</td>
</tr>
<tr>
<td>Timed Automata</td>
<td></td>
<td>x</td>
<td></td>
<td>Graphical</td>
<td>State</td>
<td>Channels</td>
</tr>
<tr>
<td>SpecTRM-RL</td>
<td>x</td>
<td></td>
<td>x</td>
<td>Text, Tabular</td>
<td>Timers</td>
<td>I/O</td>
</tr>
</tbody>
</table>

Figure 4-1: Light switch example
4.2 The Timed Abstract State Machine (TASM) Language: Syntax

This section describes the syntax of the TASM language. In Section 4.2.1, the syntax of the ASM formalism is expressed with discrete mathematics concepts, in so-called abstract syntax. The sample specification given in Listing 4.2 is expressed concrete syntax of the ASM language, that is, the syntax that can be implemented in a toolset and input via a keyboard. In this section, the same convention is followed – the TASM concepts are introduced using abstract syntax and illustrated in examples using concrete syntax. The syntax used in Listing 4.2 and used in subsequent listings is the syntax implemented in the TASM toolset. A complete description of the concrete syntax of the TASM language is available in Appendix A.

4.2.1 Basic ASM Specification

The term specification is used to denote the document that results from the process of writing down a system design. The term specification is used interchangeably with the term model throughout this chapter. This section introduces specifications that contain only a single abstract state machine, also known as basic or single-agent ASMs in the ASM community [47]. This section provides the basis for expressing the syntax and semantics of the TASM language by providing a simple definition of a specification. The specification described is equally applicable to ASM or to TASM because it does not utilize any of the features that distinguish TASM from ASM. Consequently, the material presented in this section can be interpreted as a formulation of ASM, in terms that will be useful to describe the features of the TASM language.

A basic abstract state machine specification is made up of two parts - an abstract state machine and an environment. The machine executes steps based on values in the environment and modifies values in the environment. The environment consists of two parts - the set of environment variables and the universe of types that vari-
ables can have. In the TASM language all variables are strongly typed. The machine consists of three parts - a set of monitored variables, a set of controlled variables, and a set of rules. The *monitored* variables are the variables in the environment that affect the machine execution. The *controlled* variables are the variables in the environment that the machine affects. The set of *rules* are named predicates, written in precondition-effect style, that express the state evolution logic. Formally, a specification *ASMSPEC* is a pair:

\[
\text{ASMSPEC} = \langle E, ASM \rangle
\]

Where:

* $E$ is the environment, which is a pair:

\[
E = \langle EV, TU \rangle
\]

Where:

- $EV$ denotes the *Environment Variables*, a set of typed variables
- $TU$ is the *Type Universe*, a set of types that includes:
  * Reals: $RVU = \mathbb{R}$
  * Integers: $NVU = \{ \ldots, -1, 0, 1, \ldots \}$
  * Boolean constants: $BVU = \{ True, False \}$
  * User-defined types: $UDVU$

* $ASM$ is the machine, which is a triple:

\[
ASM = \langle MV, CV, R \rangle
\]

Where:

- $MV$ is the set of *Monitored Variables* = \{ $mv \mid mv \in EV$ and $mv$ is read-only in $R$ \}
- CV is the set of Controlled Variables = \{cv \mid cv \in EV \text{ and } cv \text{ is read-write in } R\}

- R is the set of Rules = \{(n, r) \mid n \text{ is a name and } r \text{ is a rule of the form } \text{if } C \text{ then } A \text{ where } C \text{ is an expression that evaluates to an element in } BVU \text{ and } A \text{ is an action}\}

An action A is a sequence of one or more updates to environment variables, also called an effect expression, of the form \( v := vu \) where \( v \in CV \) and \( vu \) is an expression that evaluates to an element in the type of \( v \).

Updates to environment variables are organized in steps, where each step corresponds to a rule execution. In the rest of this chapter, the terms step execution and rule execution are used interchangeably. A rule is enabled if its guarding condition, C, evaluates to the Boolean value True. The update set for the \( i^{th} \) step, denoted \( U_i \), is defined as the collection of all updates to controlled variables for the step. An update set \( U_i \) will contain 0 or more pairs \((cv, v)\) of assignments of values to controlled variables.

An update set is said to be consistent if there are no conflicting updates in the set, that is, no variable is updated twice with different values. That is, an update set \( U \) is consistent if:

- For all two update pairs \((cv1, v1), (cv2, v2)\) in \( U \):
  - if \( cv1 = cv2 \) then \( v1 = v2 \)

A run of a basic ASM is defined by a sequence, potentially infinite, of update sets. For an ASM that terminates after \( n \) steps, a run would yield a sequence of update sets at each step:

\[ U_1, U_2, \ldots, U_n \]

The state progression can be obtained by applying the update set at each step. For an ASM that terminates after \( n \) steps, the state progression the run of the ASM yields \( n \) states:
\[ S_0, S_1, S_2, \ldots, S_n \]

The state \( S_0 \) denotes the initial values of the environment at the beginning of the machine execution. The operator \( o \) is introduced to denote the application of an update set to the current state to yield a successor state. More specifically:

\[ S_i = S_{i-1} \circ U_i \quad (i > 0) \]

The complete reference about ASM theory is available in [47].

4.2.2 Light Switch Example Version 1

Version 1 of the example contains only the light bulb and the corresponding switch. Listing 4.2 shows a basic ASM specification describing the logic for switching the light "on" or "off" based on whether the switch is "up" or "down". The specification is divided into sections, identified by capital letters followed by a colon. Comments in the specification are preceded by the escape sequence "//".

A sample run with the initial environment \(((\text{light, OFF}), (\text{switch, UP}))\) yields one update set:

\[ U_1 = ((\text{light, ON})) \]

The run of the machine becomes:

- \( S_0 = ((\text{light, OFF}), (\text{switch, UP})) \)
- \( U_1 = ((\text{light, ON})) \)
- \( S_1 = S_0 \circ U_1 = ((\text{light, OFF}), (\text{switch, UP})) \circ ((\text{light, ON})) = ((\text{light, ON}), (\text{switch, UP})) \)

After the step has finished executing, the environment becomes: \(((\text{light, ON}), (\text{switch, UP})))\). At this point, since the machine no longer has enabled rules, the machine terminates.
Listing 4.2 Light switch example version 1

ENVIRONMENT:

USER-DEFINED TYPES:
    light_status := {ON, OFF};
    switch_status := {UP, DOWN};

VARIABLES:
    light_status light := OFF;
    switch_status switch := DOWN;

----------------------------------------

MAIN MACHINE:

MONITORED VARIABLES:
    switch;

CONTROLLED VARIABLES:
    light;

RULES:

R1: Turn On
{
    if light = OFF and switch = UP then
        light := ON;
}

R2: Turn Off
{
    if light = ON and switch = DOWN then
        light := OFF;
}
4.2.3 Time

The TASM approach to time specification is to specify the duration of a rule execution. In the TASM world, this means that each step will last a finite amount of time before an update set is applied atomically to the environment. Syntactically, time gets specified for each rule in the form of an annotation. The annotation is specified as an interval \([t_{\text{min}}, t_{\text{max}}]\). The lack of a time annotation for a rule is assumed to mean \(t = 0\), an instantaneous rule execution. Semantically, a time annotation is interpreted as a closed interval over \(\mathbb{R}_{\geq 0}\). For a given run, a rule execution will last an amount \(t_i\) where \(t_i\) is taken non-deterministically from the interval \([t_{\text{min}}, t_{\text{max}}]\). The approach uses relative time between steps since each step will have a finite duration. The total time for a run of a given machine is simply the summation of the individual step times over the run.

Because time is used as a synchronization mechanism and because the specification denotes the behavior of reactive systems, a special keyword can be used in time annotations. This keyword, called \texttt{next}, is used with time specification, e.g. \(t := \texttt{next}\), to denote that the duration of a rule execution will be determined by the application of an update set generated by a parallel entity. For example, when a machine executes a rule with the \(t := \texttt{next}\) annotation, the update set produced by the rule will be applied at the time of the next state change, dictated by the update set of another machine. This time annotation can be used to synchronize parallel entities who are waiting for a handshake. Furthermore, this special time annotation can be used to denote that a given machine will wait for a state change before executing a rule. This construct could be used to specify that the machine will not do any "useful" work until some outside party alters the value of one of its monitored variables. The \texttt{next} construct essentially states that time should elapse until an event of interest occurs and is used to keep the machine "live" and prevent termination or infinite loops.
4.2.4 Resources

The specification of non-functional properties includes timing characteristics as well as resource consumption properties. A resource is defined as a global quantity that has a finite size. Power, memory, and communication bandwidth are examples of resources. Resources are used by the machine when the machine executes a rule. Similarly to time specification, syntactically, each rule specifies, as an annotation, how much of a given resource it consumes. The annotation is specified as an interval \([rr_{\text{min}}, rr_{\text{max}}]\). The omission of a resource consumption annotation is assumed to mean zero resource consumption. Semantically, a resource annotation is interpreted as a closed interval over \(\mathbb{R}_{\geq 0}\). For a run, for each resource, a rule execution will consume an amount \(rr_i\) where \(rr_i\) is taken non-deterministically from the interval \([rr_{\text{min}}, rr_{\text{max}}]\). The semantics of resource usage are assumed to be volatile, that is, usage lasts only through the step duration. For example, if a rule consumes 128 kilobytes of memory, the total memory usage will be increased by 128 kilobytes during the step duration and will be decreased by 128 kilobytes after the update set has been applied to the environment. Time elapses and resources are consumed only when a rule is executed. Determining whether a given rule is activated is instantaneous and consumes no resources.

Formally, a rule \(R\) of a machine ASM, described in Section 4.2.1, is extended to reflect time and resource annotations:

\[
R = (n, t, RR, r)
\]

Where:

- \(n\) and \(r\) keep the same meaning
- \(t\) denotes the duration of the rule execution is a closed interval over \(\mathbb{R}_{\geq 0}\)
- \(RR\) is the set of resources used by the rule where each element is of the form \((rr, ra)\) where \(rr \in ER\) is the resource name and \(ra\) is the resource amount consumed, specified as a closed interval on \(\mathbb{R}_{\geq 0}\)
4.2.5 Light Switch Example Version 2

The light switch example from Section 4.2.1 is extended with time annotations and resource annotations. The sample resources are memory and power. Memory has a maximum size of 16,000 units and power has a maximum size of 100 units. The extended environment, as well as the extended machine specification are shown in Listing 4.3. In Listing 4.3, the rules specify that the execution of the first rule of the machine, rule \( R_1 \), lasts between 4 and 10 time units. Furthermore, execution of rule \( R_1 \) consumes 200 units of memory and 25 units of power. The semantics of this example, including sample runs, are given in Section 4.3.4. Listing 4.3 introduces the special \( \text{else rule} \), which is enabled when no other rule is enabled. The else rule is used to prevent the machine from terminating when no other rule is enabled.

4.2.6 Hierarchical Composition

In complex systems, structuring mechanisms are required to partition large specifications into manageable blocks [6]. The partitioning enables bottom-up or top-down construction of specifications and creates opportunities for reuse. Furthermore, modularity enables separation of concerns and can help mitigate verification complexity [4]. The composition mechanisms included in the TASM language are based on the XASM language [10]. In the XASM language, an ASM can use other ASMs in rules in two different ways - as a \( \text{sub ASM} \) or as a \( \text{function ASM} \). A \( \text{sub ASM} \) is a machine that is used to structure specifications hierarchically, similar to a \( \text{Turbo ASM} \) [42]. A \( \text{function ASM} \) is a machine that takes a set of inputs and returns a single value as output, similarly to a function in programming languages, and similar to an ASM \( \text{macro} \) [42]. These two concepts enable abstraction of specifications by hiding details inside of auxiliary machines. In the TASM language, the definition of a sub machine is similar to the previous definition of machine ASM given in Section 4.2.1:

\[
SASM = (n, MV, CV, R)
\]

Where \( n \) is the machine name, unique in the specification, and the other tuple...
Listing 4.3 Light switch example version 2 – time and resource annotations

ENVIRONMENT:

USER-DEFINED TYPES:
  light_status := {ON, OFF};
  switch_status := {UP, DOWN};

RESOURCES:
  memory := [0, 16000];
  power := [0, 100];

VARIABLES:
  light_status light := OFF;
  switch_status switch := DOWN;

MAIN MACHINE:

MONITORED VARIABLES:
  switch;

CONTROLLED VARIABLES:
  light;

RULES:

R1: Turn On
{
  t := [4, 10];
  memory := 200;
  power := 25;
  if light = OFF and switch = UP then
    light := ON;
}

R2: Turn Off
{
  t := 6;
  memory := 100;
  power := 15;
  if light = ON and switch = DOWN then
    light := OFF;
}

R3: Else
{
  else then
    skip;
}


members keep the same definitions given in previous sections. The execution and termination semantics of a sub ASM are different than those of a main ASM. When a sub ASM is invoked, one of its enabled rules is selected, it yields an update set, and it terminates.

The definition of a function ASM is slightly different. Instead of specifying monitored and controlled variables, a function ASM specifies the number and types of the inputs and the type of the output:

$$FASM = (n, IV, OV, R)$$

Where:

- $n$ is the machine name, unique in the specification
- $IV$ is a set of named inputs $(ivn, it)$ where $ivn$ is the input name, unique in $IV$, and $it \in TU$ is its type.
- $OV$ is a pair $(ovn, ot)$ specifying the output where $ovn$ is the name of the output and $ot \in TU$ is its type.
- $R$ is the set of rules with the same definition as previously stated, but with the restriction that it only operates on variables in IV and OV.

A function ASM cannot modify the environment and must derive its output solely from its inputs. The only side-effect of a function ASM is time and resource consumption. A specification, $ASMSPEC$, is extended to include the auxiliary ASMs:

$$ASMSPEC = (E, AASM, ASM)$$

Where:

- $E$ is the environment
- $AASM$ is a set of auxiliary ASMs (both sub ASMs and function ASMs)
• ASM is the main machine

The auxiliary machines are purely syntactic construct to ease reuse and structuring of specifications. As Theorem 4.1 and Theorem 4.2 state, the hierarchical composition can be eliminated without modifying the semantics. A description of the semantics of the concepts introduced in this section is available in Section 4.3.

4.2.7 Light Switch Example Version 3

The light switch example is extended to illustrate the use of auxiliary machines. The example has been extended with a function machine called TURN_ON and a sub machine called TURN_OFF. Sample runs for this example are given in Section 4.3.6.

Listing 4.4 Light switch example version 3 – hierarchical composition

<table>
<thead>
<tr>
<th>FUNCTION MACHINE: TURN_ON</th>
<th>SUB MACHINE: TURN_OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT VARIABLES:</td>
<td></td>
</tr>
<tr>
<td>switch_status ss;</td>
<td></td>
</tr>
<tr>
<td>OUTPUT VARIABLE:</td>
<td></td>
</tr>
<tr>
<td>light_status ls;</td>
<td></td>
</tr>
<tr>
<td>RULES:</td>
<td></td>
</tr>
<tr>
<td>R1: Turn On</td>
<td>R1: Turn Off</td>
</tr>
<tr>
<td>{</td>
<td>{</td>
</tr>
<tr>
<td>t := [4, 10];</td>
<td>t := 6;</td>
</tr>
<tr>
<td>memory := 128;</td>
<td></td>
</tr>
<tr>
<td>if ss = UP then</td>
<td>if switch = DOWN then</td>
</tr>
<tr>
<td>ls := ON;</td>
<td>light := OFF;</td>
</tr>
<tr>
<td>}</td>
<td>}</td>
</tr>
<tr>
<td>R2: Else</td>
<td>R2: Else</td>
</tr>
<tr>
<td>{</td>
<td>{</td>
</tr>
<tr>
<td>else then</td>
<td>else then</td>
</tr>
<tr>
<td>ls := OFF;</td>
<td>skip;</td>
</tr>
<tr>
<td>}</td>
<td>}</td>
</tr>
</tbody>
</table>

The two modified rules of the main machine from Listing 4.3 are shown in Listing 4.5. The remainder of the specification remains unchanged from Listing 4.2 and Listing 4.3.
4.2.8 Parallel Composition

To enable specification of multiple parallel activities in a system, the TASM language allows parallel composition of multiple abstract state machines. Parallel composition is enabled through the definition of multiple top-level machines, called main machines, analogous to multiple agents in [42]. Formally, the specification ASMSPEC is extended to include a set of main machines $MASM$ as opposed to the single machine $ASM$ for the basic ASM specification of Section 4.2.1:

$$ASMSPEC = <E, AASM, MASM>$$

Where:

- $E$ is the environment
- $AASM$ is a set of auxiliary ASMs (both sub ASMs and function ASMs)
- $MASM$ is a set of main machines $ASM$ that execute in parallel

The definition of a main machine $ASM$ is the same as the definition given in Section 4.2.3. Other definitions also remain unchanged.
4.2.9 Light Switch Example Version 4

In version 4 of the light switch problem, the example is extended to include an extra main machine that operates in parallel. The extra machine is used to control the fan. Listing 4.6 gives the environment definition, including the resources and the extra variables corresponding to the fan control. The main machine for the light control is shown in Listing 4.7. The main machine for the fan control is shown in Listing 4.8. The fan control machine contains time and resource annotations. The semantics of the parallel execution, as well as the consumption of resources are given in Section 4.3.8.

Listing 4.6 Environment definition for resources and parallel composition

ENVIRONMENT:

USER-DEFINED TYPES:
- component_status := \{ON, OFF\};
- switch_status := \{UP, DOWN\};

RESOURCES:
- memory := [0, 16000];
- power := [0, 100];

VARIABLES:
- component_status light := OFF;
- switch_status light_switch := DOWN;
- component_status fan := OFF;
- switch_status fan_switch := DOWN;

4.3 The Timed Abstract State Machine (TASM) Language: Semantics

The semantics of the TASM language are expressed using the notions of step, state, and update set introduced in Section 4.2.1. The TASM language extends the update set concept with time and resource consumption. Updates to environment variables are organized in steps, where each step corresponds to a rule execution. In this section, the terms step execution and rule execution are used interchangeably. A rule is enabled if its guarding condition, \( C \), evaluates to the Boolean value True. The
Listing 4.7 Light control main machine definition for resources and parallel composition

MAIN MACHINE:
   LIGHT_CONTROL

MONITORED VARIABLES:
   light_switch;

CONTROLLED VARIABLES:
   light;

RULES:

R1: Turn On
{
   t := [4, 10];
   memory := 300;
   power := 25;
   if light = OFF and light_switch = UP then
      light := ON;
}

R2: Turn Off
{
   t := 6;
   memory := 100;
   power := 15;
   if light = ON and light_switch = DOWN then
      light := OFF;
}

R3: Else
{
   t := next;
   else then
      skip;
}
Listing 4.8 Fan main machine definition for resources and parallel composition

MAIN MACHINE:
FAN_CONTROL

MONITORED VARIABLES:
fan_switch;

CONTROLLED VARIABLES:
fan;

RULES:

R1: Turn On
{
  t := [1, 8];
  memory := 100;
  power := 35;
  if fan = OFF and fan_switch = UP then
    fan := ON;
}

R2: Turn Off
{
  t := 2;
  memory := 200;
  power := 25;
  if fan = ON and fan_switch = DOWN then
    fan := OFF;
}

R3: Else
{
  t = next;
  else then
    skip;
}
update set for the $i^{th}$ step, denoted $U_i$, is defined as the collection of all updates to controlled variables for the step. An update set $U_i$ will contain 0 or more pairs $(cv, v)$ of assignments of values to controlled variables. A run of a basic ASM is defined by a sequence of update sets.

### 4.3.1 Update Set

In TASM, when a machine executes a step, the update set that is produced contains the duration of the step, as well as the amounts of resources that are consumed during the step execution. The special symbol $\bot$ is used to denote the absence of an annotation, for either a time annotation or a resource annotation. Update sets are extended to include the duration of the step, $t \in \mathbb{R}_{\geq 0} \cup \{\bot\}$ and a set of resource usage pairs $rc = (rr, rac) \in RC$ where $rr$ is the resource name and $rac \in \mathbb{R}_{\geq 0} \cup \{\bot\}$ is a single value denoting the amount of resource usage for the step. If a resource is specified as an interval, $rac$ is a value non-deterministically selected from the interval.

The symbol $TRU_i$ is used to denote the timed update set, with resource consumptions, of the $i^{th}$ step of a machine, where $t_i$ is the step duration, $RC_i$ is the set of consumed resources, and $U_i$ is the set of updates to variables:

$$TRU_i = (t_i, RC_i, U_i)$$

The structure of the update set is explained in the following subsections by extending the update set presented in Section 4.2.1.

### 4.3.2 Time

When a time annotation is included in a rule, the specified time denotes possible duration of the update set, specified as relative time between steps. The total time of a run of a single machine is simply the summation of the individual step times over the run. The update set concept is extended to include the duration $t_i$ of the update set:
The set of variable updates, $U$, is unchanged from Section 4.2.1. A run of a machine that terminates after $n$ steps becomes:

$$TU_1, TU_2, \ldots, TU_n$$

The state concept is also extended to reflect the value of time for the given state. While the time values in the update sets are relative to the previous steps, the time values in the state are absolute. A given run starts execution at time $t = 0$. The Timed State, $TS_i$, where $gt_i$ denotes the global time is defined as:

$$TS_i = (gt_i, S_i)$$

The state $S_i$ is unchanged from Section 4.2.1. Given this definition of timed state, the sequence of states for a run that ends after $n$ steps:

$$TS_1, TS_2, \ldots, TS_n$$

The $\circ$ operator is extended for the new definitions of state and update set:

$$TS_i = TS_{i-1} \circ TU_i = (gt_{i-1}, S_{i-1}) \circ (t_i, U_i) = (gt_{i-1} + t_i, S_{i-1} \circ U_i)$$

For a run that ends after $n$ steps, the total time of the run would be $gt_n$ and would be defined as the summation of the step times over the run:

$$gt_n = \sum_{i=1}^{n} t_i$$

### 4.3.3 Resources

Update sets are also extended to reflect resource consumption at each step. Each update set is extended to include a set of resource usage pairs $rc = (rr, rac) \in RC$
where \( rr \) is the resource name and \( rac \) is a single value denoting the exact amount of resource usage for the step. If a resource is specified as an interval, \( rac \) is a value taken from the interval. The symbol \( TRU_i \) is used to denote the timed update set, with resource usage, of the \( i^{th} \) step, where \( t_i \) is the step duration, \( RC_i \) is the set of consumed resources, and \( U_i \) is the update set:

\[
TRU_i = (t_i, RC_i, U_i)
\]

The execution semantics are also extended to reflect resource usage. Because resources are limited quantities, if an executing ASM utilizes more than a resource’s limits, execution halts. Execution is well-defined only if resource utilization falls below the boundaries of the available resources. Resource usage is slightly different than time in that the resource utilization for a given update set starts with the time of the previous update set and lasts through the rule completion. The consumption of a resource for an update set \( TRU_i \) lasts during an open interval \( (gt_{i-1}, gt_i] \). The state definition is also extended to reflect resource consumption:

\[
TRS_i = (gt_i, SRC_i, S_i)
\]

The sequence of states for a run that ends after \( n \) steps:

\[
TRS_0, TRS_1, TRS_2, \ldots, TRS_n
\]

For update sets with time and resources, the \( \circ \) operator is defined as follows:

\[
TRS_i = TRS_{i-1} \circ TRU_i = (gt_{i-1}, RC_{i-1}, S_{i-1}) \circ (t_i, RC_i, U_i)
\]

\[
= (gt_{i-1} + t_i, RC_i, S_{i-1} \circ U_i)
\]

\[
= (gt_i, RC_i, S_i)
\]

For all \( gt \) in the open interval \( (gt_{i-1}, gt_i] \), the state \( TRS \) will be \( (gt, RC_i, S_{i-1}) \). This definition reflects the behavior that resource consumption will begin with the
start of a rule execution and will last until the rule execution is finished.

Concurrent resource usage by multiple components is assumed to be additive. For example, if two components, \( x \) and \( y \) use the same resource \( A \) concurrently, where \( x \) uses amount \( a_x \) and \( y \) uses amount \( a_y \), then the total resource usage amount is \( a_x + a_y \). For the remainder of this chapter, the term *update set* refers to an update set of the \( TRU_i \) form and the term *state* refers to a state of the \( TRS_i \) form.

### 4.3.4 Light Switch Example Version 2 Revisited

The semantics of a basic specification with time and resource annotations can be illustrated using a sample run of the machine in Listing 4.3.

Three sample update sets for different initial conditions of variable values are shown below:

- **Initial condition: ((light, OFF), (switch, UP))**
  
  Update set: \((5, ((\text{memory, 200}, (\text{power, 25})), ((\text{light, ON}))))\)

- **Initial condition: ((light, ON), (switch, DOWN))**
  
  Update set: \((6, ((\text{memory, 100}, (\text{power, 15})), ((\text{light, OFF}))))\)

- **Initial condition: ((light, OFF) (switch, DOWN))**
  
  Update set: \((0, ((\text{memory, 0}, (\text{power, 0})), \emptyset))\)

Formally, the behavior and state progression of the first set of initial conditions can be expressed as follows:

- \( TRS_0 = (0, ((\text{memory, 0}, (\text{power, 0})), ((\text{light, OFF}), (\text{switch, UP})))) \)

- \( TRU_1 = (5, ((\text{memory, 200}), (\text{power, 25})), (\text{light, ON})) \)

- \( TRS_1 = TRS_0 \circ TRU_1 = (5, ((\text{memory, 200}), (\text{power, 25})), ((\text{light, ON}), (\text{switch, UP}))) \)

For all times \( gt \) in the open interval \([0, 5)\), the state \( TRS \) is \((gt, ((\text{memory, 200}), (\text{power, 25})), S_0)\). The same logic can be applied to the other two sample runs.
Mapping the above update set and state on the time axis yields the following states over time:

- $t < 5$: $(((\text{memory}, 200), (\text{power}, 25)), ((\text{light}, \text{OFF}), (\text{switch}, \text{UP})))$
- $t = 5$: $(((\text{memory}, 200), (\text{power}, 25)), ((\text{light}, \text{ON}), (\text{switch}, \text{UP})))$
- $t > 5$: $(((\text{memory}, 0)), ((\text{light}, \text{ON}), (\text{switch}, \text{UP})))$

The duration of 5 time units was non-deterministically selected from the interval $[4, 10]$. The sample run illustrates the execution semantics of interval duration. In the Listing 4.3, the rule duration is specified using an interval, $t := [4, 10]$. In a run, the update set contains a single figure for the duration of the step. For a run to be well-defined, the duration of the rule application for the step corresponding to this rule must be in the interval. For the sample run, the duration of 5 time units was selected non-deterministically and any value in the interval could have been used. The 200 units of memory resource are consumed from the beginning of the rule execution to the completion of the rule execution. This execution model is simple and intuitive and allows the specifier to explore various potential behaviors.

### 4.3.5 Hierarchical Composition

Semantically, hierarchical composition is achieved through the composition of update sets. A rule execution can utilize sub machines and function machines in its effect expression. Each effect expression produces an update set, and those update sets are composed together to yield a cumulative update set to be applied to the environment.

To define the semantics of hierarchical composition, the semantic domain $\mathbb{R}_{\geq 0} \cup \{\bot\}$ is utilized. The special value $\bot$ is used to denote the absence of an annotation, for either a time annotation or a resource annotation.

Two composition operators are defined, $\otimes$ and $\circ$, to achieve hierarchical composition. The $\otimes$ operator is used to perform the composition of update sets produced by effect expressions within the same rule:
\[
TRU_1 \otimes TRU_2 = (t_1, RC_1, U_1) \otimes (t_2, RC_2, U_2) \\
= (t_1 \otimes t_2, RC_1 \otimes RC_2, U_1 \cup U_2)
\]

The \( \otimes \) operator is commutative and associative. The semantics of effect expressions within the same rule are that they happen in parallel. This means that the time annotations will be composed to reflect the duration of the longest update set:

\[
t_1 \otimes t_2 = \begin{cases} 
  t_1 & \text{if } t_2 = \perp \\
  t_2 & \text{if } t_1 = \perp \\
  \max(t_1, t_2) & \text{otherwise}
\end{cases}
\]

The composition of resources also follows the semantics of parallel execution of effect expressions within the same rule. The \( \otimes \) operator is distributed over the set of resources:

\[
RC_1 \otimes RC_2 = (rc_{11}, \ldots, rc_{1n}) \otimes (rc_{21}, \ldots, rc_{2n}) \\
= (rc_{11} \otimes rc_{21}, \ldots, rc_{1n} \otimes rc_{2n}) \\
= ((rr_{11}, rac_{11}) \otimes (rr_{21}, rac_{21}), \ldots, \\
  (rr_{1n}, rac_{1n}) \otimes (rr_{2n}, rac_{2n})) \\
= ((rr_{11}, rac_{11} \otimes rac_{21}), \ldots, \\
  (rr_{1n}, rac_{1n} \otimes rac_{2n}))
\]

In the TASM language, resources are assumed to be additive, that is, parallel consumption of amounts \( r_1 \) and \( r_2 \) of the same resource yields a total consumption \( r_1 + r_2 \):
Intuitively, the cumulative duration of a rule effect will be the longest time of an individual effect, the resource consumption will be the summation of the consumptions from individual effects, and the cumulative updates to variables will be the union of the updates from individual effects.

The operator is used to perform composition of update sets between a parent machine and a child machine. A parent machine is defined as a machine that uses an auxiliary machine in at least one of its rules' effect expression. A child machine is defined as an auxiliary machine that is being used by another machine. For composition that involves a hierarchy of multiple levels, a machine can play both the role of parent and the role of child. To define the operator, the subscript $p$ is used to denote the update set generated by the parent machine, and the subscript $c$ to denote the update set generated by the child machine:

$$TRU_p \oplus TRU_c = (t_p, RC_p, U_p) \oplus (t_c, RC_c, U_c)$$

$$= (t_p \oplus t_c, RC_p \oplus RC_c, U_p \cup U_c)$$

The $\oplus$ operator is not commutative, but it is associative. The duration of the rule execution will be determined by the parent, if a time annotation exists in the parent. Otherwise, it will be determined by the child:

$$t_p \oplus t_c = \begin{cases} 
t_c & \text{if } t_p = \bot \\
t_p & \text{otherwise} \end{cases}$$
The distribution of the $\oplus$ operator over the set of consumed resources is the same as for the $\otimes$ operator:

$$RC_p \oplus RC_c = (rc_{p1}, \ldots, rc_{pn}) \oplus (rc_{c1}, \ldots, rc_{cn})$$

$$= (rc_{p1} \oplus rc_{c1}, \ldots, rc_{pn} \oplus rc_{cn})$$

$$= ((rr_{p1}, rac_{p1}) \oplus (rr_{c1}, rac_{c1}), \ldots ,$$

$$\quad (rr_{pn}, rac_{pn}) \oplus (rr_{cn}, rac_{cn}))$$

$$= ((rr_{p1}, rac_{p1} \oplus rac_{c1}), \ldots ,$$

$$\quad (rr_{pn}, rac_{pn} \oplus rac_{cn}))$$

The resources consumed by the rule execution will be determined by the parent, if a resource annotation exists in the parent. Otherwise, it will be determined by the child:

$$rac_p \oplus rac_c = \begin{cases} rac_c & \text{if } rac_p = \perp \\ rac_p & \text{otherwise} \end{cases}$$

Intuitively, the composition between parent update sets and child update sets is such that the parent machine overrides the child machine. If the parent machine has annotations, those annotations override the annotations from child machines. If a parent machine doesn’t have an annotation, then its behavior is defined by the annotations of the auxiliary machines it uses. These semantics enables the abstraction of timing analysis common in the real-time community [89] where program units, such as function calls, are annotated with timing bounds without analyzing the underlying behavior of the units. Furthermore, these semantics enable bottom up construction of specifications where the timing behavior can be defined by as the sum of the parts. The hierarchical composition semantics maintain the semantics of ASM where everything that occurs within a step happens in parallel. As in the case of ASM,
conflicting updates to variables yield update set inconsistency.

Figure 4-2 shows a hierarchy of machines for a sample rule execution. Each numbered square represents a machine. Machine “1” represents the rule of the main machine being executed; all other squares represent either sub machines or function machines used to derive the update set produced by the main machine. Machine “3” is an example of a machine that plays the role of parent (of machine “7”) and child (of machine “1”).

![Figure 4-2: Hierarchical composition](image)

Each machine generates an update set $TRU_i$, where $i$ is the machine number. The derivation of the produced update set is done in a bottom-up fashion, where $TRU_{ret}$ is the update set returned by the main machine:

$$TRU_{ret} = TRU_1 \oplus (TRU_2 \oplus (TRU_5 \otimes TRU_6)) \otimes (TRU_3 \oplus TRU_7) \otimes TRU_4$$

### 4.3.6 Light Switch Example Version 3 Revisited

The semantics of hierarchical composition are illustrated using the example from Listing 4.4 and Listing 4.5. Two sample runs are shown to illustrate the invocation of a sub machine and of a function machine. The first step of two sample runs are shown below:

- Initial environment: ((light, OFF), (switch, UP))
Update set: (1, ((memory, 128)), ((light, ON)))

- Initial environment: ((light, ON), (switch, DOWN))
  Update set: (6, ((memory, 1024)), ((light, OFF)))

The first sample run invokes the function ASM and obtains the step duration from the main ASM definition and the resource consumption from the function ASM. The second sample run obtains the variable updates and rule duration from the sub ASM and the resource consumption from the main ASM.

The first sample run can be detailed as follows:

- \( TRS_0 = (0, ((memory, 0)), ((light, OFF), (switch, UP))) \)

- Update set from function ASM: \( FTRU_1 = (5, ((memory, 128)), \emptyset) \)

- Update set from main ASM: \( RTRU_1 = (1, ((memory, \bot)), ((light, ON))) \)

- Combined update set: \( TRU_1 = RTRU_1 \oplus FTRU_1 = (1 \oplus 5, ((memory, \bot)) \oplus ((memory, 128)), ((light, ON)) \cup \emptyset) = (1, ((memory, 128)), ((light, ON))) \)

- \( TRS_1 = TRS_0 \circ TRU_1 = (0, ((memory, 0)), ((light, ON), (switch, UP))) \circ (1, ((memory, 128)), ((light, ON))) = (1, ((memory, 128)), ((light, ON), (switch, UP))) \)

The second sample run can be detailed as follows:

- \( TRS_0 = (0, ((memory, 0)), ((light, OFF), (switch, UP))) \)

- Update set from sub ASM: \( STRU_1 = (6, ((memory, \bot)), ((light, OFF))) \)

- Update set from main ASM: \( RTRU_1 = (\bot, ((memory, 1024)), (\emptyset)) \)

- Combined update set: \( TRU_1 = RTRU_1 \oplus STRU_1 = (\bot \oplus 6, ((memory, 1024)) \oplus ((memory, \bot)), \emptyset \cup ((light, OFF))) = (6, ((memory, 1024)), ((light, OFF))) \)
- \( TRS_1 = S_0 \circ TRU_1 = (0, ((\text{memory}, 0)), ((\text{light}, \text{OFF}), (\text{switch}, \text{UP}))) \circ (6, ((\text{memory}, 1024)), ((\text{light}, \text{OFF}))) = (6, ((\text{memory}, 1024)), ((\text{light}, \text{OFF}), (\text{switch}, \text{UP}))) \)

The same operators can be used to detail the first sample run, which uses the function machine.

### 4.3.7 Hierarchical Composition and Expressivity

While hierarchical composition facilities are necessary in practice to enable reuse and to ease the management of complex models, hierarchical composition does not affect algorithmic expressivity. As Theorem 4.1 and Theorem 4.2 state, the hierarchical composition facilities of the TASM language could be eliminated without modifying the semantics of the language.

In the proof of Theorem 4.1, the following notation is used: the function machine is treated symbolically as “\( f(\text{params}) \)” where “\( f \)” is the name of the function machine and “\( \text{params} \)” is the list of parameters passed to the machine. The symbols “\( \{\text{exp} \ \backslash \ \text{val}\} \)”, reused from programming language semantics, are used to denote “the resulting expression where symbols in \( \text{exp} \) are replaced by values in \( \text{val} \)”. More specifically, it is used to replace the parameters in the function machine definition with the passed-in parameters in the function machine call. A parameterized version of a function machine, used in the proof of Theorem 4.1, is shown below:

\[
FR_1 \equiv \text{if } FG_1 \text{ then } out \_ \text{var} := out \_ \text{exp}_1; \\
FR_2 \equiv \text{if } FG_2 \text{ then } out \_ \text{var} := out \_ \text{exp}_2; \\
\vdots \\
FR_n \equiv \text{if } FG_n \text{ then } out \_ \text{var} := out \_ \text{exp}_n; 
\]

Where \( out \_ \text{exp}_i \) represents an expression used to compute the output value of the function machine. With these definitions, Theorem 4.1 can be stated and proved.
Theorem 4.1. For every machine that uses a function machine, there is an equivalent machine that does not use the function machine.

Proof. The theorem is proved by construction, by providing an equivalent machine without the function machine. For a machine that uses a function machine, the function machine can occur in either the rule guard $G_i$ or in the rule effect $E_i$. Both cases are considered separately:

- Case 1: Function machine in rule guard

If the function machine occurs in the rule guard, the guard will be of the form:

$$if \ g_{li} \circ var = f(params) \circ g_{ri} then E_i$$

Where $\circ$ represents a logical connective, $g_{li}$ represents the part of the guard to the "left" of the expression where the function machine occurs, and $g_{ri}$ represents the part of the guard to the "right" of the expression where the function machine occurs. The function machine call could be part of a complex expression but the simplified version $f(params)$ is used in the proof and can be easily generalized to any expression.

The equivalent machine can be constructed in the following way by replacing the rule where the function call occurs with $n$ new rules that are constructed in the following way:

$$if \ g_{li} \circ var = \{\text{out.exp}_1 \ \backslash \ params\} \circ g_{ri} \land \{FG_1 \ \backslash \ params\} then E_i$$

$$if \ g_{li} \circ var = \{\text{out.exp}_2 \ \backslash \ params\} \circ g_{ri} \land \{FG_2 \ \backslash \ params\} then E_i$$

$$\vdots$$

$$if \ g_{li} \circ var = \{\text{out.exp}_n \ \backslash \ params\} \circ g_{ri} \land \{FG_n \ \backslash \ params\} then E_i$$

It can be easily seen that the guards of each of these new rules will be enabled exactly when the function machine guards are enabled and when the guard of the original rule is enabled. And by replacing the invocation of the function machine with
the return expression of the function machine definition ensures that the semantics aren't changed. Since evaluating rule guards does not consume time or resources, annotations occurring in the function machine can be discarded.

- **Case 2: Function machine in effect expression**

If the function machine occurs in the rule effect, the rule where the function machine call occurs will be of the form:

\[
\text{if } G_i \text{ then } e_{\text{li}}; \text{ var } := f(\text{params}); e_{\text{ri}};
\]

Where \( e_{\text{li}} \) represents the part of the effect expression to the "left" of the function machine expression, \( e_{\text{ri}} \) represents the part of the effect expression to the "right" of the function machine expression, and \( f(\text{params}) \) represents the function machine expression. The function machine call could be part of a complex expression but the simplified version \( f(\text{params}) \) is used in the proof and can be easily generalized to any expression.

The equivalent machine can be constructed in the following way by replacing the rule where the function machine call occurs with \( n \) new rules in the machine definition:

\[
\begin{align*}
\text{if } G_i \wedge \{FG_1 \setminus \text{params}\} \text{ then } e_{\text{li}}; \text{ var } := \{\text{out.exp}_1 \setminus \text{params}\}; e_{\text{ri}}; \\
\text{if } G_i \wedge \{FG_2 \setminus \text{params}\} \text{ then } e_{\text{li}}; \text{ var } := \{\text{out.exp}_2 \setminus \text{params}\}; e_{\text{ri}}; \\
&\quad \vdots \\
\text{if } G_i \wedge \{FG_n \setminus \text{params}\} \text{ then } e_{\text{li}}; \text{ var } := \{\text{out.exp}_n \setminus \text{params}\}; e_{\text{ri}};
\end{align*}
\]

It can be easily seen that the guards of each of these new rules will be enabled exactly when the function machine guards are enabled and when the guard of the original rule is enabled. And by replacing the invocation of the function machine with the return expression of the function machine definition ensures that the semantics aren't changed. For function machines occurring in effect expressions, time and resources can be consumed. How the annotations from the function machine
are included in the equivalent “flattened” machine follows the rules of hierarchical composition of update sets described in Section 4.2.6.

These two cases can be generalized to any expression containing function machines by being applied to all expressions containing function invocations.

\[ \square \]

A parameterized version of a sub machine, used in the proof of Theorem 4.2, is shown below:

\[
\begin{align*}
SR_1 & \equiv if \ SG_1 \ then \ SE_1; \\
SR_2 & \equiv if \ SG_2 \ then \ SE_2; \\
& \quad \vdots \\
FR_n & \equiv if \ SG_n \ then \ SE_n;
\end{align*}
\]

Equipped with this definition, Theorem 4.2 can be stated.

**Theorem 4.2.** For every machine that uses a sub machine, there is an equivalent machine that does not use the sub machine.

**Proof.** This theorem is also proved by construction. Since sub machine invocations can only occur in effect expressions, only one case needs to be considered. An effect containing a sub machine call will be of the form:

\[
if \ G_i \ then \ e_{ri}; \ SUB\_MACHINE( ); \ e_{ri};
\]

The construction of the equivalent machine is even simpler than it is for the proof of Theorem 4.1 since sub machines do not take in parameters. The equivalent machine, without the sub machine call, can be constructed in the following way:
if $G_i \land SG_1$ then $e_{i1}; SE_{1i}; e_{ri};$

if $G_i \land SG_2$ then $e_{i1}; SE_{2i}; e_{ri};$

: 

if $G_i \land SG_n$ then $e_{in}; SE_{ni}; e_{ri};$

It can be easily seen that the guards of each of these new rules will be enabled exactly when the sub machine guards are enabled and when the guard of the original guard is enabled. The time and resource annotations from the sub machine are included in the "flattened" equivalent machine following the rules of hierarchical composition of update sets described in Section 4.2.6.

\[ \square \]

4.3.8 Parallel Composition

Because concurrency is an integral part of most real-time systems, the specification formalism must be able to specify concurrent behavior. In the abstract state machine world, this is achieved through multiple machines running in parallel. In the ASM literature, concurrency is termed multi-agent ASMs [47]. There are two varieties of multi-agent ASMs - synchronous and asynchronous. In the synchronous case, two or more machines execute a single step in parallel and the resulting update sets are checked for consistency, merged, and applied instantaneously to global state. In other words, for $m$ machines executing concurrently, each executing $n$ steps, all groups of step update sets, $U_{ij}$, must be consistent. $U_{ij}$ denotes the $i^{th}$ step of the $j^{th}$ machine:

$$(((U_{11}, U_{12}, \ldots, U_{1m}), \ldots, (U_{n1}, U_{n2}, \ldots, U_{nm})))$$

If a group of update sets is consistent for a given step, the updates sets are collected into a single update set and applied atomically to global state. The process is repeated for each step. In the asynchronous case, there is no prespecified order in
which a machine executes a step. In fact, any ASM can perform any number of steps at a given time. This lack of ordering enables the system designer to define the exact semantics of parallel execution.

The semantics of parallel composition regards the synchronization of the main machines with respect to the global progression of time. The global time of a run, \( t_b \), is defined as a monotonically increasing function over \( \mathbb{R}_{\geq 0} \). Machines execute steps that last a finite amount of time, expressed through the duration \( t_i \) of the produced update set. The time of generation, \( t_{gi} \), of an update set is the value of \( t_b \) when the update set is generated. The time of application, \( t_{ai} \), of an update set for a given machine is defined as \( t_{gi} + t_i \), that is, the value of \( t_b \) when the update set will be applied. A machine whose update set, generated at global time \( t_{gp} \), lasts \( t_p \) will be busy until \( t_b = t_{gp} + t_p \). While it is busy, the machine cannot perform other steps. In the meantime, other machines who are not busy are free to perform steps. This informal definition gives rise to update sets no longer constrained by step number, but constrained by time. Parallel composition, combined with time annotations, enables the specification of both synchronous and asynchronous systems.

The operator \( \odot \) is defined for parallel composition of update sets. For a set of update sets \( TRU_i \) generated during the same step by \( i \) different main machines:

\[
TRU_1 \odot TRU_2 = (t_1, RC_1, U_1) \odot (t_2, RC_2, U_2)
\]

\[
= \begin{cases} 
(t_1, RC_1 \odot RC_2, U_1) & \text{if } t_1 < t_2 \\
(t_2, RC_1 \odot RC_2, U_2) & \text{if } t_1 > t_2 \\
(t_1, RC_1 \odot RC_2, U_1 \cup U_2) & \text{if } t_1 = t_2
\end{cases}
\]

The operator \( \odot \) is both commutative and associative. The parallel composition of resources is assumed to be additive, as in the case of hierarchical composition using the \( \oplus \) operator:
\[ RC_1 \odot RC_2 = (r_{c11}, \ldots, r_{c1n}) \odot (r_{c21}, \ldots, r_{c2n}) \]
\[ = (r_{c11} \odot r_{c21}, \ldots, r_{c1n} \odot r_{c2n}) \]
\[ = ((rr_{r11}, rac_{11}) \odot (rr_{r21}, rac_{21}) \ldots, \]
\[ (rr_{r1n}, rac_{1n}) \odot (rr_{r2n}, rac_{2n})) \]
\[ = ((rr_{r11}, rac_{11} \odot rac_{21}), \ldots \]
\[ ((rr_{r1n}, rac_{1n} \odot rac_{2n})) \]

The parallel composition of resources is assumed to be additive, as in the case of hierarchical composition using the \( \otimes \) operator:

\[
rac_1 \odot rac_2 = \begin{cases} 
  rac_1 & \text{if } rac_2 = \bot \\
  rac_2 & \text{if } rac_1 = \bot \\
  rac_1 + rac_2 & \text{otherwise}
\end{cases}
\]

At each global step of the simulation, a list of pending update sets are kept in an ordered list, sorted by time of application. At each global step of the simulation, the update set at the front of the list is composed in parallel with other update sets, using the \( \odot \) operator and the resulting update set is applied to the environment. Once an update set is applied to the environment, the step is completed and the global time of the simulation progresses according to the duration of the applied update set.

The concurrency semantics of the TASM language reduce to the concurrency semantics of synchronous and asynchronous multi-agent ASMs. For a TASM specification where all machine steps have the same duration \( dt \neq 0 \), the specification is essentially a synchronous multi-agent ASM specification with linear time progression. For a TASM specification where all machine steps have the same duration \( dt = 0 \), the specification is essentially an asynchronous multi-agent ASM specification. In TASM, time plays the role of delaying moves of a machine until the delay of the rule.
execution has elapsed and acts as a synchronization mechanism.

Parallel composition also introduces contention between machines for resource consumption. In the TASM language, no machine is preempted from using a resource. However, if the resource is exhausted, an exception is thrown and results in update set inconsistency. The shared resource model is simple and useful to model many resource types. Concurrent resource usage is additive. For example, if, in a time interval, two different machines use the same resource (in amounts $r_1$ and $r_2$ respectively), the total amount used would be $r_1 + r_2$. A more extensive application of the $\circ$ operator is shown to demonstrate the parallel composition of two update sets produced by two main machines that yield update sets with different durations:

- Update set by machine 1: $TRU_1 = (t_1, RC_1, U_1)$
- Update set by machine 2: $TRU_2 = (t_2, RC_2, U_2)$
- State when update set is produced: $TRS_i = (gt_i, RC_i, S_i)$
- if $t_1 = t_2$
  - Combined update set: $TRU = TRU_1 \circ TRU_2 = (t_1, RC_1 + RC_2, U_1 \cup U_2)$
  - $TRS_{i+1} = TRS_i \circ TRU = (gt_i + t_1, RC_i + RC_1 + RC_2, S_i \cup (U_1 \cup U_2))$
- if $t_1 > t_2$
  - Combined update set: $TRU_i = TRU_1 \circ TRU_2 = (t_1, RC_1 + RC_2, U_1)$
  - Combined update set: $TRU_{i+1} = TRU_1 \circ TRU_2 = (t_2 - t_1, RC_1, U_2)$
  - $TRS_{i+1} = TRS_i \circ TRU_i = (gt_i + t_1, RC_i + RC_1 + RC_2, S_i \cup U_1)$
  - $TRS_{i+2} = TRS_{i+1} \circ TRU_{i+1} = (gt_i + t_2, RC_i + RC_2, S_{i+1} \cup U_2)$
- if $t_1 < t_2$
  - Combined update set: $TRU_i = TRU_1 \circ TRU_2 = (t_2, RC_1 + RC_2, U_2)$
  - Combined update set: $TRU_{i+1} = TRU_1 \circ TRU_2 = (t_1 - t_2, RC_2, U_1)$
4.3.9 Light Switch Example Version 4 Revisited

In Listing 4.6 and Listing 4.8, the light switch example is further extended to illustrate the semantics of parallel composition. An extra main machine is added to represent the control logic for a fan, operating in parallel with the light. The logic for the fan and the light both utilize memory and power. For the initial environment \(((\text{light\_switch}, \text{UP}), (\text{light}, \text{OFF}), (\text{fan\_switch}, \text{UP}), (\text{fan}, \text{OFF}))\), the trace of update sets is shown below. Each machine will execute a single step that modifies the environment. The update sets for the step of each machine are shown below:

- Step 1 of machine LIGHT\_CONTROL: (4, ((memory, 300), (power, 25)), ((light, ON)))
- Step 1 of machine FAN\_CONTROL: (1, ((memory, 100), (power, 35)), ((fan, ON)))

This example shows how steps from different machines can take a different amount of time. The value of 4 time units for machine LIGHT\_CONTROL and the value of 1 time units for machine FAN\_CONTROL were taken non-deterministically from the intervals. The beginning of these steps happen at the same time, but the different durations illustrate the semantics of parallel composition. The time values of interest can be broken into five different intervals:

- \(t < 1\): Execution of step 1 of both machines
- \(t = 1\): Completion of step 1 of machine FAN\_CONTROL
- \(1 < t < 4\): Continued execution of step 1 of machine LIGHT\_CONTROL
- \(t = 4\): Completion of step 1 of machine LIGHT\_CONTROL
- \(t > 4\): Waiting for a change in the environment
The combined update sets for each time interval are shown below. The execution of both machines overlaps only in the interval $t < 1$. In the other intervals, the behavior is that of individual machines. Updates to the environment are produced only at the end of the step:

- $t < 1$: $\left(\left(\text{memory, } 400\right), \left(\text{power, } 60\right), \emptyset\right)$
- $t = 1$: $\left(\left(\text{memory, } 400\right), \left(\text{power, } 60\right), \left(\text{fan, } \text{ON}\right)\right)$
- $1 < t < 4$: $\left(\left(\text{memory, } 300\right), \left(\text{power, } 25\right), \emptyset\right)$
- $t = 4$: $\left(\left(\text{memory, } 300\right), \left(\text{power, } 25\right), \left(\text{light, } \text{ON}\right)\right)$
- $t > 4$: $\left(\left(\text{memory, } 0\right), \left(\text{power, } 0\right), \emptyset\right)$

Formally, the state evolution can be tracked through the following stages:

- $TRS_0 = (1, \left(\text{memory, } 0\right), \left(\text{power, } 0\right), \left(\text{light, OFF}\right), \left(\text{fan, OFF}\right))$
- $TRU_{\text{FAN\_CONTROL},1} = (1, \left(\text{memory, } 100\right), \left(\text{power, } 35\right), \left(\text{fan, ON}\right))$
- $TRU_{\text{LIGHT\_CONTROL},1} = (4, \left(\text{memory, } 300\right), \left(\text{power, } 25\right), \left(\text{light, ON}\right))$
- $TRU_1 = TRU_{\text{FAN\_CONTROL},1} \circ TRU_{\text{LIGHT\_CONTROL},1} = (1, \left(\text{memory, } 400\right), \left(\text{power, } 60\right), \left(\text{fan, ON}\right))$
- $TRU_2 = TRU_{\text{FAN\_CONTROL},1} \circ TRU_{\text{LIGHT\_CONTROL},1} = (3, \left(\text{memory, } 300\right), \left(\text{power, } 25\right), \left(\text{light, ON}\right))$
- $TRS_1 = TRS_0 \circ TRU_1 = (1, \left(\text{memory, } 400\right), \left(\text{power, } 60\right), \left(\text{light, OFF}\right), \left(\text{fan, ON}\right))$
- $TRS_2 = TRS_1 \circ TRU_2 = (4, \left(\text{memory, } 300\right), \left(\text{power, } 25\right), \left(\text{light, ON}\right), \left(\text{fan, ON}\right))$

The time history of variable values and resource consumption for the run is also shown in Figure 4-3.
4.3.10 Summary and Other Extensions

From the point of view of the effects on the environment, there is no difference whether or not an update set is generated from a single main ASM or through multiple parallel main ASMs. The composition of main machines and the use of sub and function machines is indistinguishable to the environment. The environment only sees a single update set, that is produced at each "step" of the system. Once the composition has been achieved, the composed system behaves as a single main ASM with no composition. The difference occurs in the internal merging of update sets. In the case of hierarchical composition, that is, update sets produced by sub ASMs and function ASMs, the $\otimes$ and $\oplus$ operators are used to obtain the resulting update set from the use of auxiliary ASMs. For parallel composition, that is, multiple update sets produced by main ASMs, the $\odot$ operator is used to obtain the resulting update set that is to be applied to the environment. The update set operators are listed in table 4.2.
Termination Semantics

As described in Section 2.1, the types of systems targeted by this research are reactive real-time systems, that is, systems which continuously interact with their environment in an infinite loop fashion [164]. In this model, the environment could be modified outside of the machine's control. To enable this behavior the first extension to the ASM theory is to introduce the Else Rule construct. The Else Rule construct, denoted by the else keyword as a rule guard, is used to indicate that the machine will continue execution, even if no other rule is enabled. Furthermore, the use of the skip keyword is used to denote that an empty update set is produced but that execution should still continue.

A sample loop of such systems iterates through three stages. The first stage involves inferring the state of the environment, typically through sensors. The second stage involves taking some action, based on logic from the inferred state of the environment. The third and final stage involves affecting the state of the environment, typically through actuators. This loop will run continuously until the system is stopped by an outside source such as an operator or a failure. Applications using these types of loops are common in process controllers such as avionics and automobile electronics. The ASM metaphor, through the concepts of monitored variables, controlled variables, and steps reflects the behavior of reactive systems.

The assumption of termination when an empty update set is produced is not valid for reactive systems. The assumption may be valid for sequential algorithms, but, as can be observed in the light switch example, the controller should continuously monitor the state of the switch because the state of the switch could be altered outside of the machine's control.

Special Rule Durations

Since relative durations defines the underlying progression of time in the model, a special annotation can be used to specify that a given machine will "wait" until something meaningful happens in the environment. This annotation is used to denote that
the machine will not execute any rules until something changes in the environment. This special annotation is the “t := next” construct. When a rule containing this time annotation is executed, the duration of the rule is “indeterminate” and the update set will be applied once another rule in another machine is executed.

Non-Determinism

While the TASM language does not include the choose construct from ASM, non-determinism is intrinsic to the TASM language. For example, time and resource annotations can vary non-deterministically. Input/Output non-determinism, in terms of assignments to variables, can occur in TASM if one or more rules are enabled simultaneously for a given step of a given machine. In this case, a rule is chosen non-deterministically from the enabled rules and it is executed. This type of non-determinism differs from ASM where multiple enabled rules are executed within the same step and the update sets are combined. In the TASM language, such semantics would be confusing since durations would have to be added. Furthermore, the ability to non-deterministically chose an enabled rule is convenient when modeling the environment to capture different simulation scenarios. The environment is inherently non-deterministic [208] and modeling this behavior is paramount to achieve realistic simulation scenarios.

The “Else” Rule

In the syntax of a TASM specification, the “Else” rule is used as shorthand notation for “a rule that is enabled is no other rule is enabled”. While the simple keyword else is straightforward to write and understand, the special “Else” rule does not augment the semantics of the language. A machine definition containing an “Else” rule could be rewritten without the “Else” rule, without affecting the semantics. If a machine has \( n \) rules \( R_i \), whose guards are \( G_i \) and where \( R_n \) is the “Else” rule, the guard of rule \( R_n \) is equivalent to the following guard:
\[ G_n \equiv \neg(G_1 \lor \ldots \lor G_{n-1}) \]

Showing that these two guards are equivalent by definition because the "Else" rule is enabled whenever no other rules are enabled, which is exactly the definition of the negation of the disjunction of the guards of all the other rules. This substitution of the "Else" rule for a predicate over variables is important because in the rest of this thesis, the "Else" rule does not need to be treated differently than any other rule. Consequently, the "Else" rule is mentioned only where it is not evident from context that it could be replaced by a predicate over variables.

**Internal State**

In the presented discussion and examples, all variables are global. Extending individual machines with internal state enables encapsulation by limiting the scope of variables. A new section is added to each ASM definition, the "INTERNAL VARIABLES" section. This section is used to define the name and types of variables internal to the ASM.

**Constructors**

Reuse of specifications can be beneficial, especially for the specification of redundant systems. ASM definitions are extended with a "CONSTRUCTOR" section. The section lists variables whose values must be specified before a specific instance of the ASM specification can be used. This construct enables the creation of parameterized specifications to empower reuse.

The constructor concept introduces a new type of ASM, the template ASM. The template ASM is defined like any other ASM except that it contains an extra section, the CONSTRUCTOR section. Like a function ASM, the constructor section specifies the name and value types of arguments. Main machines can be defined based on template ASMs by using the machine name as constructor in the following fashion:
Global Clock

Individual machines can obtain the current value of time by accessing the global clock. The global clock can be accessed through the special keyword “now” that returns a value denoting the current time, in the context of the querying machine. The value returned by “now” is the time value before the execution of a rule, based on the semantics of parallel composition from section 4.3.8.

Runs of Multi-Agent TASM Specifications

In [47], runs of synchronous and asynchronous multi-agent ASMs are described through ordering of agent moves. Synchronous multi-agent ASMs runs are defined through a total ordering of agent moves while runs of asynchronous multi-agent ASMs are defined through a partial ordering of agent moves. In the TASM language, time plays a key role in the synchronization of moves of agents. As mentioned in Section 4.3.8, depending on the nature of the time annotations, multi-agent TASM specifications can express both synchronous and asynchronous multi-agent ASMs. Consequently, the TASM language can be considered a more general model that can express both asynchronous and synchronous behavior, without modifying the underlying concurrency model.

The requirements of runs of multi-agent TASM specifications can be described in terms of partially ordered runs [115]. The ASM conditions on partially ordered runs contains 3 criteria – finite history, sequentiality of agents, and coherence [47] (p. 209). These three conditions also apply to runs of TASM specifications but the ordering relation is extended to include durations. The partially ordered set $(M, \prec)$ of moves $m$ is extended to include the timestamp of the move completion, $t_c$. The set is ordered with respect to $t_c$ and with respect to a partial order for moves whose timestamps are
the same. Using this ordering relation, the *sequentiality of agents* and the *coherence* conditions follow naturally.

The complete description of the TASM language is available in [185]. The concrete syntax of the TASM language as well as descriptions of the logical objects of the language, as implemented in the TASM toolset, is available in Appendix A.

### 4.4 Relation to Timed ASM

In [114], the authors present a specification and verification of the railroad crossing problem using a combination of ASM and the *currttime* external function (most recently called *now*). The algebra presented in [114] provides a general approach to timed system modeling. In order to demonstrate that TASM provides a more concise notation, the semantics of the TASM language are expressed using Timed ASM. In order to map a TASM specification into the Timed ASM language, two domains are introduced, namely *DTASM* and *DASM* to denote the domains of specifications expressed in the TASM language and the ASM language respectively. A function called *Desug* that maps a TASM specification into an ASM specification is also introduced. The “desugaring” function is defined for all individual elements of the TASM language (specifications, variables, types, rules, etc.) and maps the TASM elements into elements of the ASM language.

\[
Desug : DTASM \rightarrow DASM
\]

Each resource definition, *Rdef*, in the environment is desugared into a global shared dynamic function:

\[
Desug[Rdef] = \text{shared } Rdef
\]

Type definitions, *Tdef* get desugared into static finite domains:

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\[ \text{Desug}[[T \text{def} ]] = \text{static domain } T \text{def} \]

Controlled and monitored variables inside of machines get desugared into nullary controlled and dynamic functions, respectively.

The desugaring of the rules is the most complex desugar in the TASM language, because this is where time and resource utilization play a role. To illustrate the desugaring of rules, the following abstract syntax for a rule definition is utilized:

- \( \text{Rules} = (R_i^+) \)
- \( R_i = (t_i \ r_i^* \ i f \ cond_i \ then \ effect_i) \)

In the TASM, the set of rules for a given machine is implicitly mutually exclusive. In the ASM language, the mutual exclusion is explicit. The desugaring introduces two variables, one to keep the time when the rule application will finish executing and one to denote that the machine is “busy” doing work. These two variables are denoted by \( t\text{comp}_{\text{fresh}} \) and \( m\text{busy}_{\text{fresh}} \). The \( fresh \) underscore is used to indicate that the variable name is introduced by the desugaring and enforces that it does not clash with existing names. Both of these variables also desugar into controlled dynamic functions:

\[
\text{Desug}[[ t\text{comp}_{\text{fresh}} ]] = \text{controlled } t\text{comp} \text{ initially } -1 \\
\text{Desug}[[ m\text{busy}_{\text{fresh}} ]] = \text{controlled } m\text{busy} \text{ initially } False
\]

Conceptually, once a rule is triggered, a machine sets the \( m\text{busy} \) variable to \text{True} and will not do anything until the rule duration has elapsed. Once the rule duration has elapsed, the machine will generate the appropriate update set atomically and will be free to execute another rule. The desugaring of a rule is expressed as:
Desug[[ Rule ]] = Desug[[ (t_i, r_i^* if cond_i then effect_i) ]]
= if/else if cond_i \land \neg mbusy_{fresh} then
  mbusy_{fresh} := True;
  tcomp_{fresh} := now + getDuration(t_i);
  r_{i_{fresh}} := getResourceConsumption(r_i);
else if now = tcomp_{fresh} \land mbusy_{fresh} then
  effect_i;
  mbusy_{fresh} := False;
  tcomp_{fresh} := -1;
  r_{i_{fresh}} := 0;
...

The function \textit{getDuration} is a macro that is created using the condition and
the time annotation of the rule. It returns the duration of the rule by selecting a
duration non-deterministically from the rule annotation. The introduction of the two
auxiliary variables and the time conditions will guarantee that the machine will not
produce any update sets and that no other rules will be enabled while the machine is
executing a rule. This behavior is exactly the desired behavior to simulate “durative”
actions. Function machines are desugared as macros and sub machines are desugared
just like main machines and they are “inlined” inside the rule where they are invoked.
The desugaring of the “\(t := \text{next}\)” construct is fairly straightforward albeit tedious. It
involves caching the state at the beginning of the rule execution and creating an extra
rule which compares the cached state to the current state. If there is a mismatch, the
machine immediately resumes executing rules. If there is no mismatch, the machine
simply waits until there is a mismatch.

The one area that remains to be formally specified is the execution semantics of
resources. For each resource that is defined in the environment, an agent is created
that is used to sum up all of the resources used by other agents. These new agents, symbolically depicted in Listing 4.9, are used to ensure that resource usage falls within the specified bounds.

**Listing 4.9 Machine to compute resources**

```plaintext
Agent RESOURCE_i
  controlled last_fresh initially 0
  controlled totalresource_i_fresh initially 0

  if now = last_fresh + dt then
    totalresource_i_fresh := sum(r_i)
  else
    if totalresource_i_fresh > resource_{max} then
      RESOURCE_EXHAUSTED
```

The role of the sum macro is to sum up all of the resource annotations from executing agents. The `RESOURCE_EXHAUSTED` macro simply halts execution to note that a given resource has been exhausted.

### 4.5 Segue into Chapter 5

This chapter described the Timed Abstract State Machine (TASM) language through its syntax and semantics. The following chapter, Chapter 5, describes the types of automated analysis that can be performed on models expressed in the TASM language. More specifically, Chapter 5 describes how functional, timing, and resource consumption behavior of TASM models can be statically analyzed using the framework.
Chapter 5

Static Analysis

This chapter describes the analysis of models that can be performed using the framework. The analysis that can be performed using the proposed framework include Completeness and Consistency, Safety and Liveness, Execution Time, and Resource Consumption. These four types of analyses are included in the four sections of this chapter. The analysis is performed with readily available analysis engines, namely the UPPAAL tool suite [157] and the SAT4J SAT solver [158]. The analysis is achieved by mapping TASM models to the input language of these engines. Summaries of the translation algorithms are given in this chapter but a complete version of the translation to SAT is available in Appendix B and a complete version of the translation to UPPAAL is given in Appendix C.

5.1 Functional Analysis: Completeness and Consistency

Consistency and completeness were identified as useful properties of specifications in [123] and in [125]. In the context of the specification of embedded systems, completeness of the specification is defined as the specification having a response for every possible class of inputs. In the same context, consistency is defined as the specification being free of contradictory behavior, including unintentional non-determinism [125].
Formal definitions of these properties, in the context of TASM specifications, are given in Section 5.1.2 and in Section 5.1.3. Traditionally, verifying these properties was accomplished manually by system specifiers, through inspection of specifications [66]. Because a specification is likely to evolve during the engineering lifecycle, the ability to verify these properties automatically can ease and shorten the analysis process [124]. Language-specific verification algorithms have been proposed in [123] in the context of the RSML requirement language and in [125] in the context of the SCR requirement language. In contrast, the analysis approach proposed in this chapter is not language specific and can be reused for other languages. The proposed approach achieves verification by translating specifications to formulas in propositional logic, formulating completeness and consistency as a Boolean satisfiability problem (SAT) [232], and automating the verification procedure by using a generally available solver, a SAT solver [175].

More specifically, the verification is achieved by mapping TASM specifications to Boolean formulas in Conjunctive Normal Form (CNF). The specified mapping is derived using the structural properties of the specification and does not require the generation of a global reachability graph, thereby avoiding the infamous state space explosion problem [125]. The proposed mapping could also be applied to specifications in other languages expressed using transition systems, such as ASM specifications, because the mapping does not consider the time or resource annotations of the TASM language. The mapping to Boolean formulas in CNF allows for automated verification using any SAT solver which conforms to the “DIMACS” format [158]. Using a standard input format provides flexibility in the choice of specific solver as optimizations and heuristics are constantly improving [229]. The mapping from TASM to a Boolean formula is achieved in such a way that consistency and completeness are expressed as unsatisfiability of the Boolean formulas. If the TASM specification is incomplete or inconsistent, the SAT solver will generate an assignment which makes the Boolean formula satisfiable. This assignment serves as the counterexample to exercise the incompleteness or inconsistency of the specification. Throughout this section, the “block form” of TASM from Equation 4.1 is used to define the concepts
5.1.1 Related Work

The definition and automated verification of completeness and consistency of specifications were originally introduced in [123] and in [125]. In [123], the RSML language, a hierarchical state-based language, is used to express requirements. The language is automatically analyzed for completeness and consistency using an algorithm specifically developed for the RSML language. In [125], a similar approach is used for analysis of requirements expressed in the SCR language. These two approaches rely on special purpose algorithms for the efficient and automated analysis of consistency and completeness. Consequently, the proposed algorithms cannot be reused for other languages. In contrast, the approach proposed in this work utilizes a general purpose solver, a SAT solver. The proposed translation from TASM specifications to Boolean formulas in CNF can be reused for other specification languages. Furthermore, the use of a mature SAT solver guarantees that the analysis procedure is optimized since mature implementations of SAT solvers are generally available [229].

In the ASM community, various derivatives of the ASM language have been developed, including the ASM-SL language used in the ASM Workbench [59] and the Abstract State Machine Language (AsmL) used at Microsoft [116]. A mapping between ASM-SL and finite state machines, for the purpose of model checking, was proposed in [249]. A mapping between the AsmL language and finite state machines was proposed in [109, 110]. The mapping proposed in this thesis resembles the mappings proposed in these two approaches except that it ignores the effect of rule applications and does not need to generate a global reachability graph. The proposed mapping is concerned only with relationships between rule guards inside a single machine and hence produces a smaller state space than might be generated through a complete reachability graph.
5.1.2 Completeness

Informally, \textit{completeness} is defined as the system specification having a response for every possible input combination. In the TASM world, for a given machine, this criteria means that a rule will be enabled for every possible combination of its monitored variables. The \textit{monitored} variables are the variables in the environment which affect the machine execution. Formally, the disjunction of the rule guards of a given machine must form a tautology. The letter \( S \) is used to denote an instance of the \textit{SAT} problem. The completeness problem can be expressed as a \textit{SAT} problem in the following way:

For a given machine, for \( n \) rules:

\[
S \equiv \neg ( G_1 \lor G_2 \lor \ldots \lor G_n )
\]

\[
TASM = \begin{cases} 
\text{complete} & \text{if } S \text{ not satisfiable} \\
\text{incomplete} & \text{if } S \text{ satisfiable} 
\end{cases}
\]

The completeness problem is casted as the negation of the disjunction so that counterexamples can be generated by the \textit{SAT} solver. If \( S \) is satisfiable, all the assignments that make \( S \) satisfiable can be automatically generated by the \textit{SAT} solver. If \( S \) is not satisfiable, the specification is complete.

Trivial cases happen when an individual rule guard represents a tautology. A specific example of a trivial case is the \textit{else} rule. The \textit{else} rule guarantees that the specification of a given machine is complete since the \textit{else} rule will be enabled if no other rule is enabled.

\textbf{Theorem 5.1.} \textit{Completeness is preserved through hierarchical composition using sub machines}

\textit{Proof.} Per the definition of completeness, for a sub machine \( SM \) with \( m \) rules whose guards are of the form \( SG_j \), if \( SM \) is complete, its rules form a tautology:
Consider a machine $\mathcal{M}$ which uses sub machine $\mathcal{SM}$ in its effect expression, in rule $R_p$. Per the definition of completeness, if machine $\mathcal{M}$ is complete, its rules form a tautology:

$$SG_1 \lor SG_2 \lor \ldots \lor SG_m \equiv T$$

(1)

Per Theorem 4.2, an equivalent machine $\mathcal{M}'$ can be obtained by eliminating sub machine $\mathcal{SM}$ from rule $R_p$. The proof must demonstrate that $\mathcal{M}'$ is complete. Per the definition of completeness, it must be shown that the disjunction of the guards of the rules of machine $\mathcal{M}'$ form a tautology:

$$G_1 \lor G_2 \lor \ldots \lor G_p \lor \ldots \lor G_n \equiv T$$

(2)

Equation 3 can be rewritten by grouping the guard $G_i$ and the guards $SG_j$ and using the distributive law of $\land$ over $\lor$ [28]:

$$G_1 \lor G_2 \lor \ldots \lor (G_p \land SG_1) \lor (G_p \land SG_2) \lor \ldots \lor (G_p \land SG_m) \lor \ldots \lor G_n$$

(3)

By gathering terms and using the associativity of $\lor$, equation 4 can be rewritten:
Equation 5 can be expanded through the distribution law of $\lor$ over $\land$ [28] and gathering terms:

$$[G_1 \lor G_2 \lor \ldots \lor G_n] \lor [G_p \land (SG_1 \lor SG_2 \lor \ldots \lor SG_m)]$$ (5)

Given Equation 1 and Equation 6, it naturally follows that Equation 6 is a tautology since it can be reduced to the conjunction of two tautologies. Consequently, machine $M'$ is complete and completeness is preserved through hierarchical composition using sub machines. The proof can be easily generalized to multiple sub machines within a given rule and across multiple rules.

Theorem 5.1 states that if a sub machine is complete and if a machine which uses the sub machine is also complete, then the equivalent machine without hierarchical composition (see Theorem 4.2) is also complete. This property is important because it implies that machines can be verified in isolation for completeness and those results still hold when combined hierarchically. These results are meaningful because it greatly reduces the complexity of the verification procedure since the derivation of the equivalent machine quickly leads to state explosion through exponential growth in the number of rules. Consequently, given Theorem 5.1, if all machines in a TASM specification are complete, then the specification is complete.
5.1.3 Consistency

Informally, for a state-based specification, consistency is defined as no state having more than one transition enabled at the same time [123]. The definition given in [125] is similar but is extended to include other properties of the specification such as syntactical correctness and type checking. The definition of consistency adopted in this approach is the same as in [123]. In terms of TASM specifications, this definition states that, for a given machine to be consistent, no two rules can be enabled at the same time. This definition will lead to a set of $SAT$ problems to define consistency:

For a given machine, for each pair of rules $R_i, R_j$ where $1 \leq i < j \leq n$:

$$S \equiv G_i \land G_j$$

$$TASM = \begin{cases} 
\text{consistent} & \text{if } S \text{ not satisfiable} \\
\text{inconsistent} & \text{if } S \text{ satisfiable}
\end{cases}$$

This definition yields a set of $\binom{n}{2}$ $SAT$ problems. The individual $SAT$ problems can also be composed into a single $SAT$ problem. As for completeness, the $SAT$ problem is defined in such a way that if the specification is not consistent, a counterexample is automatically generated. If $S$ is satisfiable, all the assignments that make $S$ satisfiable can be automatically generated by the $SAT$ solver.

$$S \equiv (G_1 \land G_2) \lor (G_1 \land G_3) \lor \ldots (G_1 \land G_n) \lor (G_2 \land G_3) \lor (G_2 \land G_4) \lor \ldots (G_2 \land G_n) \lor \ldots \lor (G_{n-1} \land G_n)$$

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A trivial case occurs if there is only one rule. Other trivial cases happen if there are only two rules, one of which is a guarded rule and the other rule which is the special else rule. Before the SAT instances are generated, the else rule, if it exists, is removed from the machine specification being analyzed. It is important to note that consistency is a desirable property of specifications but not a requirement. For example, if the behavior of the environment is modeled, non-determinism can be introduced in the specification. But the remainder of the specification can be verified to be consistent even though the complete specification might not be consistent by choice. Similarly to Theorem 5.1, consistency of a machine can be verified in isolation and generalized to the complete specification.

**Theorem 5.2.** Consistency is preserved through hierarchical composition using sub machines

*Proof.* In this proof, the notation from the proof of Theorem 5.1 is reused. Given a consistent sub machine $SM$ with $m$ rules and a consistent machine $M$ with $n$ rules, it is shown that two tautologies follow from the definition of consistency.

Since machine $M$ is consistent, for each pair of rules $R_i, R_j$ of machine $M$ where $1 \leq i < j \leq n$:

$$-(G_i \land G_j) \equiv \neg G_i \lor \neg G_j \equiv T$$ (1)

Since machine $SM$ is consistent, for each pair of rules $SR_k, SR_l$ of machine $SM$ where $1 \leq k < l \leq m$:

$$-(SG_k \land SG_l) \equiv \neg SG_k \lor \neg SG_l \equiv T$$ (2)

Per Theorem 4.2, an equivalent machine $M'$ can be obtained by eliminating sub machine $SM$. The proof must demonstrate that $M'$ is consistent. Per the definition of consistency, it must be shown that the conjunction guards of the rules of machine
\( M' \) are invalid (that their negation forms a tautology). Since it is already known that
the guards not affected by the sub machine call are already consistent with respect
to each other, it is sufficient to show that the affected rules are consistent. If the sub
machine call occurs in rule \( R_p \), the guards of the affected rules in \( M' \) will be of the
following form, per theorem 4.2, for \( 1 \leq k \leq m \):

\[
(G_p \land SG_k)
\]  

(3)

When determining the consistency of the rules of machine \( M' \), two cases need to
be considered. The first case involves the consistency of an affected rule with respect
to an unaffected rule. Symbolically, it involves showing that Equation 4 forms a
tautology, for \( 1 \leq k \leq m \), \( 1 \leq i \leq n \), and \( i \neq p \):

\[
\neg((G_p \land SG_k) \land G_i)
\]  

(4)

Equation 4 can be expanded using DeMorgan’s Laws [28] and the terms can be
rearranged using the associativity of \( \lor \):

\[
((\neg G_p \lor \neg G_i) \lor \neg SG_k))
\]  

(5)

Given Equation 1, it is obvious that Equation 5 is a tautology. The second case
involves the consistency of two modified rules with respect to one another. Sym-
bolically, it involves showing that Equation 6 forms a tautology, for \( 1 \leq k < l \leq m \):

\[
\neg((G_p \land SG_k) \land (G_p \land SG_i))
\]  

(6)
Equation 6 can be expanded using DeMorgan’s Laws [28] and the terms can be rearranged using the associativity of $\lor$:

$$(-G_p \lor (-SG_k \lor -SG_i))$$

(7)

Given Equation 2, it is obvious that Equation 7 is a tautology. Consequently, machine $M'$ is consistent and consistency is preserved through hierarchical composition using sub machines. The proof can also be easily generalized to multiple sub machines within a given rule and across multiple rules.

5.1.4 Mapping to SAT

To implement the automated verification of completeness and consistency of TASM models in the TASM toolset, rule constraints are translated to Boolean formulas and verified using the SAT4J SAT solver. In order to translate TASM specifications to SAT, each variable included in the rule guards must be reduced to finite domains and mapped to Boolean propositions. The complete translation approach is detailed in Appendix B and the algorithm is summarized below:

1. Create problem instance $S$ depending on the property to be checked (consistency or completeness), as explained in Section 5.1.2 and in Section 5.1.3
2. Replace function machine calls with extra rules, as explained in Section B.2.1
3. Replace symbolic right-hand sides with values from the chosen configuration, as explained in Section B.2.4
4. Reduce integer variables to user-defined type variables, as explained in Section B.2.3
5. Iterate through all monitored variables and create at least one clauses and at most one clauses, as explained in section B.2.2
6. Convert problem formulation $S$ to conjunctive normal form and create the full $SAT$ instance, as explained in Section B.2.2

The details of each step of the translation algorithm are explained in Appendix B. Some restrictions are imposed on TASM specifications that can be mapped to a $SAT$ instance. In the current implementation of the TASM toolset, specifications containing float variables cannot be mapped to $SAT$ unless a simple interval reduction is possible, as explained in Appendix B. The input format of popular $SAT$ solvers is standardized according to the “DIMACS” format and must be input in Conjunctive Normal Form (CNF) [158]. The resulting $SAT$ problem is automatically analyzed using the open source SAT4J $SAT$ solver [158]. The toolset also provides the capability to “export” the generated $SAT$ problem, so that the problem can be analyzed and solved outside of the TASM toolset.

5.1.5 Example

In this section, an example of the translation algorithm and the verification of completeness is provided. The example is a machine definition of the production cell case study presented in Section 2.8.1. The specification is for the behavior of the “loader” component, which is the component of the system responsible for putting blocks on the feed belt. The machine specification, expressed in the TASM language, is shown in Listing 5.1.

For the verification of completeness, the translation to $SAT$, for initial conditions where “number = 5”, yields 7 unique propositions:
Listing 5.1 Definition of the loader machine

R1: The feed belt is empty, put a block on it
{ 
  t := 2;
  power := 200;

  if loaded_blocks < number - 1 and feed_belt = empty then
    feed_belt := loaded;
    loaded_blocks := loaded_blocks + 1;
    feed_begin := True;

}\n
R2: This is the last block...
{ 
  t := 2;
  power := 200;

  if loaded_blocks = number - 1 and feed_belt = empty then
    feed_belt := loaded;
    loaded_blocks := loaded_blocks + 1;
    feed_begin := True;
    loader_done := True;

}\n
R3: The feed belt is loaded, do nothing
{ 
  t := next;

  if feed_belt = loaded and loaded_blocks < number then
    skip;
}

Once the mapping between TASM variable values and SAT Boolean propositions has been established, the rule guards, $G_i$, can be expressed in terms of the Boolean propositions. The completeness problem, $S$, is then constructed according to the definition of completeness:

$$G_1 \equiv b_1 \wedge b_4 \wedge b_7$$
$$G_2 \equiv b_2 \wedge b_4 \wedge b_7$$
$$G_3 \equiv b_5 \wedge (b_1 \lor b_2)$$
$$S \equiv \neg(G_1 \lor G_2 \lor G_3)$$

The complete translation to SAT, in CNF, yields 13 total propositions:
The SAT problem resulting from the translation is relatively small and running it through the SAT4J solver yields a solution in negligible time. For this machine, the rule set is not complete. The TASM toolset uses the SAT4J solver to generate the set of counterexamples in which no rule is enabled. An assignment to propositions that makes the problem satisfiable is \( b_2 = true, b_4 = true, b_6 = true \) and all other propositions are assigned false. In terms of the TASM specification, the counterexample which is generated is the set “\( \text{loaded.blocks} = 4, \text{feed.belt} = \text{empty}, \text{feed.block} = \text{available} \)”. To check the consistency of the rule set for the “loader” machine, the same set of propositions is generated, but the set of clauses grows to 159. However, many of the clauses are redundant, due to the long form used for the conversion to CNF. Future work in tool development will improve the translation to CNF by removing redundant clauses. Nevertheless, the set of SAT problems can be
verified to be unsatisfiable in negligible time. In other words, the rules of machine "loader" are consistent.

5.2 Functional Analysis: Model Checking

As mentioned in Section 2.1, the functional correctness of a system can be formulated as a set of liveness and safety properties [154]. Formal verification through model checking represents one of the big successes from the formal methods community because it provides an approach to verification which is fully automated and can generate a witness trace [71]. Safety and liveness can be verified using a model checking approach by formulating the properties as temporal logic formulas. As mentioned in Section 2.7, a model checking approach is composed of some automata variant as a specification formalism and a temporal logic for property specification [67]. In the proposed framework, the model checking of functional properties utilizes the UPPAAL tool suite [24] which is a toolset for the modeling and verification of timed automata.

In order to verify the safety and liveness properties of TASM specifications using UPPAAL, the TASM models need to be translated to the timed automata of UPPAAL [29]. UPPAAL is a suite of tools to analyze real-time systems and is composed of an editor, a verifier, and a simulator [24]. Because the UPPAAL tool suite contains a model checker, the UPPAAL verifier, the translation to UPPAAL can be leveraged to also verify timing properties of TASM specifications using a combination of temporal logic and observer automata [129]. Safety assertions and liveness properties can be formulated in the temporal logic of UPPAAL, a subset of Timed Computation Tree Logic (TCTL) [244], and analyzed using the UPPAAL verifier. The verification of timing properties is described in Section 5.3. The TCTL of UPPAAL contains facilities for specifying quantifiers over variables, which are applied to paths and to states along the paths. The path quantifiers include "A", which means "for all paths" and "E", which means "there exists a path". The state quantifiers include "\(\forall\)", which means "for all states" and "\(\exists\)", which means "there exists a state". The formula \(\phi\) is a predicate over variable values. The various combinations of the path and
state quantifiers are given below, including the special quantifier "-->". A detailed description of UPPAAL’s TCTL is provided in [24].

- A [ ] φ: For all paths, φ holds in all states.
- A <> φ: For all paths, there exists a state where φ holds.
- E [ ] φ: There exists a path where φ holds in all states.
- E <> φ: There exists a path where there exists a state where φ holds.
- ψ --> φ: In all paths, if ψ holds, φ will eventually hold at a later point in the path.

5.2.1 Mapping to UPPAAL

To implement the automated verification of safety, liveness, and timing properties of TASM specifications in the TASM toolset, TASM models are translated to UPPAAL’s timed automata. The translation of TASM to timed automata involves removing function machines, sub machines, and translating TASM variables to UPPAAL’s datatypes. The complete translation approach is detailed in Appendix C and the algorithm is summarized below:

1. For each main machine in the TASM model, remove hierarchical composition according to the rules of Theorem 4.1 and of Theorem 4.2

2. Translate the environment:
   (a) Discard resource definitions
   (b) Translate each user-defined type to a corresponding bounded integer type of UPPAAL, as explained in Table C.2.1
   (c) Translate each variable and corresponding datatype to the bounded integer type of UPPAAL, as explained in Table C.2.1

3. For each “flattened” main machine
(a) Create a timed automaton to represent the machine

(b) Create an initial urgent location called “pivot”

(c) For each rule $R_i$ of the machine, add a branch from the “pivot” state according to the approach explained in Section C.2.2

(d) If the machine contains an “else” rule, add an extra branch according to the approach depicted in Section C.2.2

(e) For rule that contains the “$t := \text{next}$” annotation, build an urgent edge using an extra automaton and an urgent channel

The details of each step of the translation algorithm are explained in Appendix C. Some restrictions are imposed on TASM specifications that can be mapped to timed automata. In the current implementation of the TASM toolset, specifications containing float variables cannot be mapped to timed automata. The toolset also provides the capability to “export” the generated UPPAAL problem, so that the problem can be analyzed and solved outside of the toolset.

### 5.2.2 Example

The example from Section 5.1.5 is reused in this section to illustrate the translation from TASM to UPPAAL and the verification of safety and liveness properties using UPPAAL’s TCTL. The TASM specification given in Listing 5.1 is translated to UPPAAL’s timed automata, and the result is given in Figure 5-1. The automaton in Figure 5-1 has three locations, corresponding to the three rules of Listing 5.1. The “Loader.R2.go” channel is an urgent channel used to enforce the transition after a state change has occurred, corresponding to the “$t := \text{next}$” annotation. The datatypes of TASM are translated to the bounded integer datatype of UPPAAL. In the case of the user-defined types of TASM, the enumeration members are converted to integers, as is the case for the $\text{feed}\_\text{begin}$ variable.

Once a TASM specification has been translated to timed automata, the UPPAAL tool suite can be used to verify safety and liveness properties of the specified system.
For example, for the timed automaton of Figure 5-1, a safety property stating that “the loader will never stop loading blocks until it has loaded all the blocks” can be formulated in TCTL. Furthermore, the liveness property “eventually, the loader loads the total number of blocks” can also be formulated in TCTL. Both properties are shown below:

- A [] loader.done == 1 imply loaded_blocks == number
- A <> loaded_blocks == number

![Timed Automaton Diagram](image)

Figure 5-1: Timed automaton for Listing 5.1

5.3 Execution Time Analysis

This section provides a general approach to verify the minimum time and the maximum time that it takes for a TASM model to complete a path from an arbitrary state to another arbitrary state in the model. The time that can elapsed in a TASM model is determined by the explicit time annotations contained in the specification. In the real-time system community, the terms Worst-Case Execution Time (WCET) and Best-Case Execution Time (BCET) [89] are used to denote properties of execution
times of software and hardware implementations. In the real-time community, the BCET and WCET refer to execution times resulting from implementation artifacts where time passage is typically not explicitly stated and must be obtained through analysis. In this section and in the remainder of this thesis, the terms WCET and BCET are used, but in the context of a model where time passage is expressed explicitly. WCET and BCET are formulated as reachability problems in terms of the system states defined in the model. The execution time analysis approach can be used to perform a variety of time-related analysis, including schedulability analysis and system level analysis such as end-to-end latency. For example, in terms of system states, the traditional definition of the WCET of a task can be expressed as the maximum time that it takes for a task to reach the state execution complete from a state where the task is ready for execution. A similar formulation can be made for the BCET of a task.

Similarly to the verification of safety and liveness presented in Section 5.2, the verification of timing properties is achieved by mapping a TASM model to the input formalism of the UPPAAL analysis engine. For the verification of execution time, the timed automaton [5] formalism is used as the input language to define system states and system behavior. More specifically, the version of timed automata used is the extended version of the Alur-Dill formalism supported by the UPPAAL tool suite [29]. In the proposed approach, the timing analysis of system models is achieved automatically using the standard functionality of UPPAAL and modeling patterns - observer automata, the bounded liveness pattern, and temporal logic formulas [157].

The presented approach provides an approach to obtain WCET and BCET between any two system states, using an algorithm called iterative bounded liveness. The approach formulates execution time analysis as a reachability problem, which has been shown to be decidable for timed automata [7]. The use of observer automata removes the need to modify system models with extraneous annotations for the sole purpose of timing analysis, as is the case in [25], and in the bounded liveness pattern in [157]. In Section 5.3.3, the presented approach is illustrated through the analysis of a example problem depicting a simple scheduling problem. More complex
examples are available in the case studies presented in Chapter 8.

5.3.1 Related Work

WCET analysis is an active research area in the real-time system community and sophisticated algorithms, models, and tools have been developed to analyze execution time of implementation languages for various hardware configurations. Thorough surveys of WCET techniques for programming languages and execution environments are available in [89] and in [150]. The output of these approaches can be used to annotate formal system models with timing properties, for the purpose of analyzing correctness with tools such as UPPAAL or Kronos [89]. The use of a formalism like timed automata can be used to analyze both timing correctness and functional correctness [157]. Furthermore, timed automata can be used for top-down analysis, to gain insight into system behavior before the system is implemented, when defects are typically cheaper to correct [37]. The approach to execution time analysis presented in this section can be considered a complement to the WCET analysis techniques of implementations, as performed in the real-time community. The iterative bounded liveness approach can be used in a top-down fashion before implementations exist, and can later be validated using bottom-up analysis provided by WCET approaches for software and hardware, once the system is implemented.

The use of high level system models for timing analysis has been performed in the context of statecharts [91] with compilation techniques. The approach presented in this work differs in that it relies on the explicit timing expressed in the model instead of translating the model to code to extract timing metrics. A similar approach was conducted in the context of Petri Nets [236] and in the context of priced timed automata [25]. The approach presented in this section differs in that it does not require modification of the system models for the purpose of timing analysis. Annotating the system model can inadvertently result in changes in the semantics of the model and clutters readability for the sole purpose of performing analysis. The use of observer automata is similar to the work on test case generation and time optimal test suites, summarized in [36], and in [128]. Using observer automata provides a flexible and
non-intrusive way to analyze system models. The iterative bounded liveness approach is beneficial in that it provides flexible and reusable means of measuring minimum and maximum execution times between any two states of timed automata models, without modifying the system model. The approach is flexible and can be used to verify timing properties of system models such as schedulability and end-to-end latency.

5.3.2 Iterative Bounded Liveness

The approach to analyzing execution time is formulated using timed automata. In the rest of this section, it is assumed that a TASM specification has been translated to the timed automata of UPPAAL using the translation approach described in Appendix C.

The timed automaton formalism, also called Alur-Dill automata [5], extends finite state automata with a set of real-valued clocks to denote the passage of time. In a timed automaton, all transitions are instantaneous, but time elapses between transitions. Transition guards can contain predicates over clocks to enforce time passage before a transition is taken. State invariants are used to enforce upper bounds on the time passage in a given state. The timed automata used in UPPAAL extend Alur-Dill automata with Integer variables, Boolean variables, committed and urgent locations, and communication channels [24]. In UPPAAL’s timed automata, a location is equivalent to a state in Alur-Dill automata. Urgent locations are used to denote that time should not elapse in a location.

A brief review of the syntax and semantics of the timed automata of UPPAAL, combining terminology and notation from [29], [157], and [36] is provided. Formally, a timed automaton is a tuple $\langle L, l_0, C, V, I, E \rangle$, where:

- $L$ is a set of locations
- $l_0 \in L$ is the initial location
- $C$ is a set of real-valued clocks
- $V$ is a set of variables
• \textbf{I}: \textit{B(C) \rightarrow L} is a mapping of simple clock constraints to locations, denoting location invariants

• \textbf{E} \subseteq \textit{L \times G \times A \times L} is a set of edges between locations where:
  
  \begin{itemize}
    \item \textit{G} is a predicate over variables \textit{V}, simple clock constraints \textit{B(C)}, and channel communications
    \item \textit{A} is a set of output actions, including clock resets, variable assignments, and channel communications
  \end{itemize}

The semantics of a timed automaton are defined as a transition system over system states. A \textit{state} \( s \in S \) is a tuple \( \langle l, \sigma, u \rangle \), where:

• \( l \in L \) is an automaton location

• \( \sigma: \mathbb{D} \rightarrow V \) is a mapping of values to variables

• \( u: \mathbb{R}_{\geq 0} \rightarrow C \) is a valuation function for each clock in \( C \)

The initial state is \( \langle l_0, \sigma_0, \{0\} \rightarrow C \rangle \), where all clocks are assigned the value 0. A \textit{transition} is a relation \( T \subseteq S \times S \) whose members satisfy the following conditions:

• \( \langle l, \sigma, u \rangle \longrightarrow \langle l', \sigma', (u \setminus r + t) \cup \{0\} \rightarrow r \rangle \) if \( \forall t' : 0 \leq t' \leq t \Rightarrow u + t \in I(l) \) and

• \( \exists e \in E = \langle l, g, a, l' \rangle \) such that:
  
  \begin{itemize}
    \item \( g \) is satisfied in \( \langle l, \sigma, u \rangle \)
    \item the variable assignments in \( a \) yield \( \sigma' \) from \( \sigma \)
    \item \( t \) is the amount of time elapsed in \( \langle l, \sigma, u \rangle \)
    \item \( r \) is the set of clock resets in \( a \)
  \end{itemize}

These definitions can be easily extended to networks of timed automata by using vectors. For a more detailed description of the syntax and semantics of \textit{UPPAAL} 's timed automata, the reader is referred to [29].
Maximum and Minimum Execution Time

In the analysis of system specifications, the analysis of execution time is of special interest to understand the semantic properties of specifications that contain concurrent entities. The notation $a \rightarrow b$ denotes the "small-step" transition from a state $a \in S$ to a state $b \in S$. The relation $T$ is used to denote the set of all "small-step" transitions $a \rightarrow b \in T \subseteq S \times S$. The notation $a \mapsto b$ denotes the "big step" transition from state $a$ to state $b$. The "big step" transitions can be defined in terms of "small-step" transitions:

$$a \mapsto b \equiv a \rightarrow s_1 \rightarrow \cdots \rightarrow s_n \rightarrow b$$

where: $a \rightarrow s_1, s_n \rightarrow b \in T \land \forall 0 < i < n : s_i \rightarrow s_{i+1} \in T$

In other words, $\mapsto$ is the transitive closure of $T$. The duration of a "small-step" transition, $t_{a\rightarrow b}$, is defined as the time $t \geq 0$ that can elapse during a transition $a \rightarrow b \in T$. The duration of a "big-step" transition $t_{a\rightarrow b}$ is defined in terms of durations of "small-step" transitions where $t_{a\rightarrow b} \equiv (\Sigma_{i=1}^{n-1} s_i \rightarrow s_{i+1}) + t_{a\rightarrow s_1} + t_{s_n \rightarrow b}$. $t_{\max_{a\rightarrow b}}$ and $t_{\min_{a\rightarrow b}}$ are defined as:

$$t_{\max_{a\rightarrow b}} \equiv \{t'_{a\rightarrow b} | \forall t_{a\rightarrow b} : t_{a\rightarrow b} \leq t'_{a\rightarrow b}\}$$

$$t_{\min_{a\rightarrow b}} \equiv \{t'_{a\rightarrow b} | \forall t_{a\rightarrow b} : t_{a\rightarrow b} \geq t'_{a\rightarrow b}\}$$

When analyzing execution time of timed automata models, the properties of interest are BCET and WCET. Execution time is defined as the time, $t_{p_0\rightarrow p_1}$, that it takes to go from a state $p_0$ to a state $p_1$. The Best-Case Execution Time (BCET) is the lower bound of $t_{p_0\rightarrow p_1}$, that is, $t_{\min_{p_0\rightarrow p_1}}$, and the Worst-Case Execution Time (WCET) is the upper bound of $t_{p_0\rightarrow p_1}$, that is, $t_{\max_{p_0\rightarrow p_1}}$.

These properties can be analyzed using the UPPAAL tool suite and temporal logic.
formulas. The general problem of determining execution time of programs is undecidable because termination is undecidable, although approximations yield adequate results [89]. For specifications expressed using timed automata and verified using temporal logic, the reachability problem is decidable [7]. To verify execution time of timed automata, a combination of observer automata and the bounded liveness pattern [24] is used. Bounded liveness is a temporal logic formula pattern, combined with an augmentation of the model, which can be used to verify that execution time is appropriately bounded. The pattern is of the form $\phi_{max} \equiv \forall \cdot [b \implies (z \leq t)]$ where $b$ is a fresh Boolean variable and $z$ is a fresh clock. Both $b$ and $z$ augment the timed automata model for the purpose of performing execution time analysis. The trick is for $b$ to be true whenever the property $p$ being checked holds. The clock $z$ is reset when the property $p$ begins to hold. Informally, the temporal logic formula states “the property $p$ holds for at most $t$ time units”. The same idea is used, but it is grounds into an observer automaton instead of modifying the system model. The analysis also seeks to “find” the value of $t$, instead of “verifying” whether a model satisfies a $t$ given a priori. To achieve this, the model is queried iteratively, to converge on the $t$ corresponding to BCET or WCET.

**Observer Automata**

An observer automaton is a timed automaton which is not part of the system model, but which can be used to monitor certain properties of the system model. For example, observer automata have been used successfully in [36] to monitor coverage criteria with respect to test case generation. To verify execution time between two arbitrary states of the system model, the properties of the states that are monitored must be stated. The specification of properties is limited to predicates over variables and omit locations and clock values of the system model. In the context of the observer automaton, the time $t_{p_0 \rightarrow p_1}$ means that there exists some trace $(\cdot, \sigma, \cdot) \rightarrow \ldots \rightarrow (\cdot, \sigma', \cdot)$ where $p_0 \subseteq \sigma$ and $p_1 \subseteq \sigma'$. This meaning does not affect the semantics of the model since it is part of the observer automaton and has no side-effect outside of the behavior of the observer automaton. The observer automaton is built using
the concept of bounded liveness and using the state path to be verified. A sample observer automaton is shown in Figure 5-2, where \( z \) is a fresh clock variable, \( p_0 \) (a predicate over variable values) is the initial state from which to measure time, and \( p_1 \) (a predicate over variable values) is the final state to which time is measured. The observer automaton contains a Boolean variable \( b \) which is true \( (b == 1) \) in all paths from \( p_0 \) to \( p_1 \). Furthermore, the clock \( z \) is added and reset for each transition out of \( p_0 \); the \texttt{OBSERVER.go} variable is an urgent channel, used to ensure that the only time that elapses in the observer automaton is time that elapses in the system model. Whenever a transition is enabled in the observer automaton, it is taken without delay. Location \( q^2 \) is marked urgent to ensure that no time elapses in that location.

![Figure 5-2: Observer automaton](image)

**Algorithm**

In order to verify the execution time, the bounded liveness pattern of \cite{157} is utilized iteratively. The temporal logic formula \( \phi_{\min} \equiv \text{"}A [*] (b == 1 \implies (z \geq t))\text{"} \) states that “the property \( p \) holds for at least \( t \) time units”. Conversely, the formula \( \phi_{\max} \equiv \text{"}A [*] (b == 1 \implies (z \leq t))\text{"} \) states that “the property \( p \) holds for at most \( t \) time units”. \( \phi_{\max} \) is used to obtain \( t_{\max_{p_0 \rightarrow p_1}} \) and \( \phi_{\min} \) is used to obtain \( t_{\min_{p_0 \rightarrow p_1}} \). \( t_{\max_{p_0 \rightarrow p_1}} \) is obtained by iteratively verifying \( \phi_{\max} \) with increasingly large values for \( t \) until \( \phi_{\max} \) is satisfied. Conversely, \( t_{\min_{p_0 \rightarrow p_1}} \) is obtained by iteratively verifying \( \phi_{\min} \) with smaller values for \( t \) until \( \phi_{\min} \) is satisfied. Because the \texttt{UPPAAL} model checker generates a counterexample when a temporal logic formula does not hold, the values of \( z \) given by the counterexample can be used as the value of \( t \) for the following iteration. The notation \( TA \) denotes the timed automata system model.
The notations $\phi_{\min}(x)$ and $\phi_{\max}(x)$ also denote $\phi_{\min}$ and $\phi_{\max}$ where $t$ is substituted for $x$. The algorithm used to obtain the WCET is shown in Listing 5.2. The algorithm to obtain the BCET can be obtained by replacing $\phi_{\max}$ by $\phi_{\min}$ and WCET by BCET in Listing 5.2.

**Listing 5.2 Iterative bounded liveness algorithm to calculate WCET**

- Verify $\phi_{init}$ on timed automata model $TA$
- If $\phi_{init}$ is satisfied, let $t_{est} = z$, using the value of clock $z$ stored in the UPPAAL simulator illustrating that $\phi_{init}$ is satisfied
- Loop until $\phi_{max}(t_{est})$ is satisfied
  - Verify $\phi_{max}(t_{est})$ on timed automata model $TA$
  - if $\phi_{max}(t_{est})$ is not satisfied, let $t_{est} = z$, using the value of clock $z$ stored in the UPPAAL simulator
- $WCET = t_{est}$

The initial value of $t$ used for the iteration can be obtained using the UPPAAL simulator and the simple reachability formula $\phi_{init} \equiv "E <> o.a.q2"$ where $o.a.q2$ is the state of the observer automaton that is reached when the path has been observed. If $\phi_{init}$ can be satisfied, there is at least one path from $p_0$ to $p_1$ from the initial state of the system model. Once $t_{min_{p_0-p_1}}$ and $t_{max_{p_0-p_1}}$ have been established, the UPPAAL simulator can be used to generate the sequence of steps that lead to $t_{min_{p_0-p_1}}$ and $t_{max_{p_0-p_1}}$ respectively. For $t_{min_{p_0-p_1}}$, this can be achieved by setting $t = t_{min_{p_0-p_1}} + 1$ in $\phi_{min}$ and reading the counterexample trace in the UPPAAL simulator. For $t_{max_{p_0-p_1}}$, this can be achieved by setting $t = t_{max_{p_0-p_1}} - 1$ in $\phi_{max}$ and reading the counterexample trace in the UPPAAL simulator. $t_{min_{p_0-p_1}}$ is bounded from below by $0$. If $t_{max_{p_0-p_1}}$ is unbounded, $\phi_{max}$ will never be satisfied. Depending on the problem definition, a maximum value of $t$ in $\phi_{max}$ should be agreed upon to determine that $t_{max_{p_0-p_1}}$ is unbounded. It is important to note that a cycle in the state transitions will not lead to unbounded $t_{max_{p_0-p_1}}$ because the clock $z$ is reset on all transitions out of $p_0$. Unbounded $t_{max_{p_0-p_1}}$ can occur purely as a side-effect of the properties of locations en route to $p_1$. For example, if a location on the path $p_0 \rightarrow p_1$ has no
location invariant, \( t_{\text{max}_{p_0\rightarrow p_1}} \) could be unbounded. However, given the restrictions put on the models, this situation will never happen and \( t_{\text{max}_{p_0\rightarrow p_1}} \) will converge, as explained in the following subsection.

Unbounded Delays and Convergence of Execution Time

In order for \textit{iterative bounded liveness} to converge, the timed automata system model must not contain unbounded delays that can occur while the observer automaton of Figure 5-2 is in state \( q_1 \). In timed automata, delays can be bounded either by setting a \textit{location invariant} to limit how much time can elapse in a given location, or by having an \textit{urgent edge} out of a given location. With these two conditions, delays are guaranteed to be bounded, given that urgent edges will become enabled within a bounded amount of time. While these restrictions might seem limiting, in the context of WCET analysis, all delays must be bounded, or a bound must be estimated as is the case of approximations for loop bounds in program analysis [89]. For systems that have unbounded delays, execution time analysis can occur for BCET, but WCET analysis would be pointless. The limitations on delays are similar to the restrictions in [235] where timed automata are restricted to be \textit{output urgent} for the sake of testability.

5.3.3 Example: The Scheduling Problem

This subsection provides an illustrative example to illustrate the analysis of execution time. The example deals with the scheduling of the task graph shown in Figure 5-3. The task graph contains four tasks, each annotated with BCET and WCET figures. The arrows describe the precedence constraints for execution of the tasks. In order for the TASM system model to have unbounded delays, it is assumed that tasks will start executing as soon as the processor is free and when their dependencies (if any) have completed execution. This assumption is congruent with scheduling theory and prevents unbounded delays before the beginning of a task's execution.

The TASM model describing the scheduling problem is shown in Listing 5.3, in
Listing 5.4, and in Listing 5.5. Listing 5.3 shows the environment definition. A task can be in 3 possible states – *wait*, *execute*, and *done*. The *wait* state is used to denote a task that has not executed yet, the state *execute* is used to denote a task that is executing, and the state *done* is used to denote a task that has completed execution. The processor can be in 2 possible states – *free* and *busy*. The meaning of the processor states is self-evident. Listing 5.4 shows the definition of the scheduler that enforces the precedence constraints. It is interesting to note that the scheduler contains non-determinism, meaning that the set of rules are not consistent per the definitions given in Section 5.1.3. However, the non-determinism is introduced purposefully because given the problem definition, task1 and task2 can execute in any order because they do not have precedence constraints. Listing 5.5 shows the behavior of task 1. When the task is executing, it will take between 5 and 10 time units to complete, per the definition given in Figure 5-3. Each task is modeled as a main machine and TASM models for task 2, task 3, and task 4 are similar to Listing 5.5. The complete TASM model contains 5 main machines – 1 for the scheduler and 1 for each task.

The UPPAAL model, obtained through the translation algorithm described in Appendix C is shown in Figure 5-4, Figure 5-5, and Figure 5-6. Figure 5-4 shows the timed automaton for the TASK1 main machine of Listing 5.5. In the TASK1 automaton, location *pivot* is used to denote the initial location, location *TASK1.R1* is used to denote that the task is executing, corresponding to the execution of rule *R1* in the TASM main machine specification. The clock *c* is used to enforce the lower and upper bounds on the execution times of the task, through an invariant at location *TASK1.R1* and through a clock guard on the edge from the *TASK1.R1* location and the *pivot* location. The variable *proc* is used to signal that the processor is free.
Listing 5.3 TASM environment for the scheduling problem

ENVIRONMENT:

USER-DEFINED TYPES:

\[
\text{task\_status} := \{\text{wait, exec, done}\}; \\
\text{proc\_status} := \{\text{free, busy}\};
\]

VARIABLES:

\[
\text{task\_status} \text{ task}_1 := \text{wait}; \\
\text{task\_status} \text{ task}_2 := \text{wait}; \\
\text{task\_status} \text{ task}_3 := \text{wait}; \\
\text{task\_status} \text{ task}_4 := \text{wait}; \\
\text{proc\_status} \text{ proc} := \text{free};
\]

\((\text{proc} == 1)\) or busy \((\text{proc} == 2)\). There are 4 binary variables in the model, \text{task}_1, \text{task}_2, \text{task}_3, \text{task}_4 to denote whether a given task has finished executing \((\text{task}_b == 3)\) or not \((\text{task}_n == 2)\). The TASK1 automaton has an urgent edge, enforced by the urgent channel \text{TASK1\_else}, which ensures that a task starts executing as soon as it is capable, to avoid an unbounded delay before execution begins.

The goal of the example is to study the BCET and WCET of completing all the tasks with their precedence constraints. In the formulation of the problem, this property is equivalent to verifying the maximum and minimum amount of time for a path that goes from the state where none of the tasks have started executing \((\text{task}_1 == 1 && \text{task}_2 == 1 && \text{task}_3 == 1 && \text{task}_4 == 1)\) to a state where all of the tasks have completed execution \((\text{task}_1 == 3 && \text{task}_2 == 3 && \text{task}_3 == 3 && \text{task}_4 == 3)\). Following the convention of Section 5.3.2, the observer automaton encodes these two conditions as edge guards, and uses the clock \(z\) and the binary variable \(b\) to measure the time that elapses in location \(q_1\) of the observer automaton of Figure 5-6.

Using the iterative bounded liveness approach, the BCET for all tasks to execute can be verified to be 55 time units and the WCET can be verified to be 85 units. It is trivial to verify that this result is correct because the BCET and WCET of the sequential execution of all the tasks is simply the summation of the individual BCETs.
Listing 5.4 SCHEDULER main machine describing the behavior of the scheduler for the scheduling problem

R1: Execute task 1
{  
    if task1 = wait and proc = free then  
      task1 := exec;  
      proc := busy;  
}

R2: Execute task 2
{  
    if task2 = wait and proc = free then  
      task2 := exec;  
      proc := busy;  
}

R3: Execute task 3
{  
    if task3 = wait and task1 = done and proc = free then  
      task3 := exec;  
      proc := busy;  
}

R4: Execute task 4
{  
    if task4 = wait and task2 = done and task3 = done and proc = free then  
      task4 := exec;  
      proc := busy;  
}

R5:  
{  
    t := next;  
    else then  
      skip;  
}

Figure 5-4: Timed automaton for the TASK1 main machine
Listing 5.5 TASK1 main machine describing the behavior of task 1 of the scheduling problem

R1:
{
    \( t := [5, 20] \);

    if task1 = exec then
        task1 := done;
        proc := free;
    }

R2:
{
    \( t := \text{next} \);

    else then
        \text{skip};
    }

Figure 5-5: Timed automaton for the SCHEDULER main machine
and WCETs of each task. However, the purpose of this example was not to yield insight into the scheduling problem, but to give an illustrative example of the approach. The scheduler could also be extended to reflect a multi-processor architecture and the scheduling algorithm could be analyzed using the same observer automaton. More complex examples of observer automata and execution time analysis are available through the case studies presented in Chapter 8.

5.4 Resource Consumption Analysis

This section presents an approach to analyze the minimum and maximum amount of resources consumed by a TASM model, per the resource annotations. These minimum and maximum amounts are determined through an algorithm analogous to the algorithm to determine completeness and consistency presented in Section 5.1. The algorithm is implemented in the TASM toolset using a combination of the translation to SAT described in Appendix B and the translation to timed automata described in Appendix C.

5.4.1 Related Work

The analysis of resource usage, such as memory and stack usage has been performed in the context of programming languages [89, 119]. In the model based community, modeling of resources is gaining popularity [180], especially in the Quality of Service (QoS) community [252]. The approach presented in this section is unique in that
it uses generally available solvers to calculate the best-case and worst-case resource consumption. Furthermore, the presented approach can calculate a safe upper bound and lower bound on resource consumption, without generating a global reachability graph, mitigating the state explosion problem. The proposed approach is flexible and can accommodate different levels of accuracy depending on the complexity of the problem at hand.

5.4.2 Approach

Because parallel resource usage is additive in the TASM language, the maximum amount of resources consumed will occur when the summation of the resource consumptions of parallel machines is at a maximum. To determine this maximum amount, the algorithm iterates through the rules of each machine and tries to find a set of rules for each machine that satisfies the following conditions:

For a TASM model with \( n \) main machines, for \( 1 < i < n \), where the subscript \( i \) denotes the \( i^{th} \) machine, and \( res_i \) denotes the amount of resources consumed by the \( i^{th} \) machine, and \( G_i \) denotes the guard of the \( i^{th} \) machine for the rule corresponding to the \( res_i \) resource consumption:

\[
totres = \sum_{i=0}^{n} res_i
\]

\( ( G_1 \land G_2 \land \ldots \land G_n ) \) is satisfiable

\[
totres_{\max} = \{ totres \mid \forall totres' : totres' \leq totres \}
\]
The state that satisfies Equation 5.2 is reachable.

The first condition simply restates the additive properties of the parallel consumption of resources. The second property states that the maximum amount of resources consumed must occur in a state where all rules consuming resources can be executed simultaneously. The third condition defines the maximum amount of resources consumed. The fourth condition states that the state that satisfies Equation 5.2 must be a reachable state.

**Listing 5.6 Algorithm to determine maximum resource usage**

- Remove hierarchical composition from all main machines $M_i$ according to the approach explained in Theorem 4.1 and in Theorem 4.2
- $\text{totres} = -1$
- Loop over all sets of rules:
  - Select a set of rules that includes one rule from each machine $M_i$
  - Calculate $\text{totres}'$ using Equation 5.1
  - if $\text{totres}' > \text{totres}$ then
    * if Equation 5.2 is satisfiable and Equation 5.4 holds then $\text{totres} = \text{totres}'$
- $\text{totres}_{\text{max}} = \text{totres}$

The first step of the algorithm calculates the "flattened" version of each main machine so that hierarchical composition is removed, to enable the direct comparison of rule guards. The algorithm loops over all sets of rules to try every combination of parallel rules to test the resource consumption of possible parallel behaviors. For each combination of rules, the resource consumption is calculated and the conjunction of the rule guards is checked for satisfiability. Satisfiability is a weaker notion than the logical properties introduced in Section 5.1 because there can be multiple states satisfying the disjunction of the rule guards. The first concern of the analysis is to determine whether Equation 5.2 is satisfiable. The following step of the algorithm
concerns itself with determining whether the state that satisfies Equation 5.2 is a reachable state of the system. If reachability is not verified, the calculated version of $\text{totres}_{\text{max}}$ will yield a safe overapproximation. In other words, the calculated value provides a valid upper bound, but that upper bound might not be attainable in reality. For many systems, this approximation might be sufficient, in which case the reachability analysis can be skipped. However, if an exact measure is required, the reachability analysis will ensure that the algorithm yields an optimal value of $\text{totres}_{\text{max}}$. Clearly, the algorithm described in Listing 5.6 can be repeated for every resource in the specification. Furthermore, an analogous algorithm can be derived to calculate the minimum amount of consumed resources.

**Implementation**

The implementation of the algorithm in the TASM toolset follows the strategy of Section 5.1 and of Section 5.3. The implementation strategy uses mapping to both $\text{SAT}$ and to UPPAAL's timed automata to perform the analysis. The algorithm of Listing 5.6 does not specify how the sets of rules are assembled. The method used to select the set of rules can yield performance optimizations depending on the properties of the model. For example, the rules of individual machines can be sorted and $\text{totres}_{\text{max}}$ can be calculated using a breadth-first search approach. Other heuristics can be used to perform the calculation. In the TASM toolset, the approach sorts the rules of each machine and uses an exhaustive search. Possible optimizations could be performed and will be considered in future work. However, for the case studies of Chapter 8, the performance of the brute-force search proved adequate.

Verifying Equation 5.2 in the TASM toolset is achieved by translating the conjunction of the rule guards to $\text{SAT}$, following the approach presented in Appendix B. If there is a state $s$ that satisfies Equation 5.2, the $\text{SAT}$ solver will return the state $s$ to the TASM toolset. The state $s$ is returned to the toolset as a set of variables and associated values. The reachability analysis is implemented using the timed automata model and UPPAAL. The timed automata model can be obtained using the approach presented in Appendix C. If a timed automata model has already been generated for
functional analysis or for execution time analysis, this model can be reused for the reachability analysis. The generation of the timed automata model needs to happen only once. To verify the reachability properties of state $s$, a simple reachability temporal logic formula can be used, with state $s$ translated to the language of UPPAAL:

$$E \leftrightarrow s$$

If state $s$ is reachable, the UPPAAL verifier will confirm that the formula holds.

### 5.4.3 Example

This section provides an example to illustrate the approach to verify minimum and maximum resource usage. The example reuses version 4 of the light switch example from Section 4.1.5, described in Listing 4.6, Listing 4.8, and Listing 4.7. Since this example does not contain hierarchical composition, it does not need to be flattened. Furthermore, since there are 3 rules in each main machine, there are 9 possible combinations of rule pairs that contain 1 rule from each machine. For each machine, the rules and corresponding memory consumptions are summarized below:

- **LIGHT_CONTROL**: $(R_1, \text{memory} = 300)$ $(R_2, \text{memory} = 100)$ $(R_3, \text{memory} = 0)$
- **FAN_CONTROL**: $(R_1, \text{memory} = 100)$ $(R_2, \text{memory} = 200)$ $(R_3, \text{memory} = 0)$

Iterating through the possible pairs of rules, it is easy to see that the maximum memory consumption occurs when rule $R_1$ of machine LIGHT_CONTROL is executed and when rule $R_2$ of machine FAN_CONTROL is executed simultaneously. However, it must be determined whether the rule guards of these two rules can be enabled at the same time, that is, if the following formula is satisfiable:

$$(\text{light} = \text{OFF} \text{ and light.switch} = \text{UP}) \text{ and } (\text{fan} = \text{ON} \text{ and fan.switch} = \text{DOWN})$$

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<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Rules</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>memory</td>
<td>500</td>
<td>$R_1$, $R_2$</td>
<td>$((\text{light, OFF}), (\text{light}_\text{switch, UP}), (\text{fan, ON}), (\text{fan}_\text{switch, DOWN}))$</td>
</tr>
<tr>
<td>bandwidth</td>
<td>60</td>
<td>$R_1$, $R_1$</td>
<td>$((\text{light, OFF}), (\text{light}_\text{switch, UP}), (\text{fan, OFF}), (\text{fan}_\text{switch, UP}))$</td>
</tr>
</tbody>
</table>

Table 5.1: Maximum resource usage

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Rules</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>memory</td>
<td>0</td>
<td>$R_3$, $R_3$</td>
<td>$((\text{light, ON}), (\text{light}_\text{switch, UP}), (\text{fan, ON}), (\text{fan}_\text{switch, UP}))$</td>
</tr>
<tr>
<td>bandwidth</td>
<td>0</td>
<td>$R_3$, $R_3$</td>
<td>$((\text{light, ON}), (\text{light}_\text{switch, UP}), (\text{fan, ON}), (\text{fan}_\text{switch, UP}))$</td>
</tr>
</tbody>
</table>

Table 5.2: Minimum resource usage

Translating this formula to SAT and running it through the SAT solver shows that the formula is satisfiable with the state $((\text{light, OFF}), (\text{light}\_\text{switch, UP}), (\text{fan, ON}), (\text{fan}\_\text{switch, DOWN}))$. Encoding this state in a temporal logic formula and verifying the formula with the UPPAAL tool suite demonstrates that the state is reachable.

The same algorithm can be used to determine the maximum bandwidth usage for the model. Furthermore, the dual version of the algorithm can be used to determine the minimum memory and power usage for the model. The results of the analysis for the maximum resource usage are shown in Table 5.1 and the results of the analysis for the minimum resource usage are shown in Table 5.2.

### 5.5 Segue into Chapter 6

This chapter described the types of analysis that can be performed on TASM specifications using the proposed framework. More specifically, this chapter detailed how the completeness and consistency, safety and liveness, execution time, and resource consumption properties of TASM models can be analyzed automatically using the framework. The following chapter, Chapter 6, describes how two or more TASM models at different levels of abstraction can be meaningfully related. More specif-
ically, Chapter 6 provides an approach to trace model features syntactically and integrates syntactic traceability with notions of semantic equivalence to establish a notion of semantic equivalence between the models. The presented approach enables bi-directional traceability of TASM models through levels of abstraction all the while ensuring semantic integrity under certain conditions.
Chapter 6

Bi-Directional Traceability

This chapter presents an approach to relate the syntax of two disparate TASM models. The proposed relationship, called bi-directional traceability, enables the tracking of model features throughout lifecycle phases and levels of abstraction, both for functional properties and for non-functional properties. Section 6.2.1 presents seven "standard" types of changes that can occur between two TASM models, as surveyed through modeling literature and experience with modeling. Each type of change is expressed as a syntactical mapping between the machines and rules of two TASM models. As presented in this chapter, traceability is a purely syntactical concept; however, in Section 6.2.2, for each proposed type of change, a set of correctness criteria is given to ensure that, if the criteria are met, the proposed change preserves the semantics of the original model. Section 6.3 provides an illustrative example to demonstrate the traceability approach combined with the use of the correctness criteria to ensure semantic equivalence throughout the change.

6.1 Related Work

The growing popularity of model-driven software engineering is yielding a new set of challenges for model management, model maintenance, and model evolution [168]. Since modeling typically happens at different levels of abstraction, often across lifecycle phases, the ability to relate disparate models to one another is becoming increas-
ingly important to ensure consistency between models. For example, in the context of the Unified Modeling Language (UML), efforts have been exerted to define and enforce consistency between different diagrams [138]. Furthermore, the features of a model typically depend on a set of design decisions or assumptions. The ability to trace and visualize the effects of these features, and hence of associated decisions and assumptions, is important in complex system engineering [217]. Furthermore, traceability provides means to visualize and analyze the effects of changes to the specification, throughout the lifecycle of the system being engineered. However, traceability is, by definition, a syntactical concept, in the style of versioning systems, and provides no notion of semantic equivalence between the related artifacts. In the formal methods community, where models have precise semantics, theories of refinement have been developed to demonstrate semantic equivalence between two different models [174]. In these refinement approaches, the emphasis is put on correctness and imposes strict restrictions on system designers to ensure semantic correctness. In this chapter, a novel approach to model management is presented. The proposed strategy merges the benefits of syntactical traceability, for change management, and refinement correctness, for semantic integrity. The approach presented in this chapter provides an agile approach to relate models at different levels of abstraction and to relate models representing different aspects of the system such as functional behavior and timing behavior. The proposed traceability approach supplies benefits because it provides syntactic bi-directional traceability, augmented by a set of correctness criteria that can guarantee semantic integrity.

6.1.1 Syntactic Change Management

In the software engineering community, models of traceability have been developed for architecture models [94, 226] and for requirements [217]. In these approaches, change management and heterogeneous model integration is the key motivation. Furthermore, traceability models that cross lifecycle phases have been developed in [168] using the concept of connectors. Syntactic change management, in the context of programming languages, is widely used in the software engineering communities [78, 139].
In the context of programming language, the term “Software Configuration Management (SCM)” or “Version Control” are used to describe the set of tools and processes used to visualize program changes and to create software versions. A vast suite of tools are available to implement version control including open source offerings that include the Concurrent Versions System (CVS) [241]. In the software engineering community at large, notions of refinement correctness are typically overlooked and the focus is put on change management and syntactical mapping. The primary focus of traceability in the software engineering community is to visualize and control the changes that are made to product implementations, without concerning itself with the correctness of the changes.

In contrast, this chapter presents an approach to traceability that incorporates both syntactical traceability, to track changes, and a set of correctness criteria to maintain semantic integrity. Furthermore, in the engineering of real-time systems, different types of models are used, such as high level models, component models, and task graphs. The approach presented in this chapter enables traceability of model features throughout these disparate models, all the while ensuring semantic integrity under certain conditions.

6.1.2 Refinement Theory

The idea of software development being conducted in a controlled and provably correct fashion, in incremental steps, goes back to the days of Niklaus Wirth [250], and Edsger Dijkstra [80]. Since these seminal ideas, refinement theory has found widespread adoption and development in the formal methods community. In the formal methods community, the majority of refinement schemes revolve around two principles – the principle of “substitutivity” and the principle of state equivalence. In the principle of “substitutivity”, the core idea revolves around the idea that a program could be replaced by another program and the change would be undetectable by the user [79]. In such a scheme, a refinement is deemed “correct” if the observable behavior of a program/model is undetectable after a refinement has occurred. The observations can take the form of input-output pairs, pre/post states and invariant preservation
as can be found in the B method [2]. In the principle of state equivalence, the states of the two models to be related are enumerated, and a mapping is defined between the sets of states [43]. Furthermore, the semantic equivalence between two models can be established through a notion of trace equivalence through a subset relation and bisimulation, as can be found in the process algebra community [95, 131] and in the Input/Ouput Automata (I/OA) formalism [147]. The bisimulation proof method serves as the basis for many refinement approaches in the formal methods community and can express both "substituvity" or state equivalence, depending on what information the traces contain [227].

There has been a significant amount of theory developed around refinement, such as the refinement calculus [17], Morris' basis [174], and Roever's Data refinement [77]. These schemes aim to provide rigorous means by which refinement correctness can establish semantic equivalence. However, they do not address the syntactic nature of change management introduced by a refinement. The Abstract State Machine refinement approach is more general and can support many popular refinement schemes [43]. The ASM approach uses commuting diagrams as a mapping between states of interest and an equivalence notion (≡) between data in locations of interest in corresponding states. The approach proposed in this work is a subset of the general ASM refinement approach, by selecting a suitable set of criteria to establish basic correctness locally, without considering the complete semantics of the models. The correctness criteria proposed in this work do not preclude a more general notion of equivalence between models, as advocated in [43]. Formal approaches to refinement can be used in conjunction of the strategy proposed in this chapter, if desired.

From a practitioner's perspective, the motivations for establishing semantic equivalence between two models aim to reduce verification effort. In an ideal world, if verification was performed on a given model, the verification results would still hold in the refined model and the verification efforts would not need to be repeated. The philosophy of the approach presented in this chapter is to provide a set of correctness criteria which, if met, guarantee that verification results hold in the refined model.
6.2 Concepts

The concept of traceability establishes a mapping between two models. In the context of model-driven engineering, traceability typically happens between two models at different levels of abstraction, where the lower level model is assumed to be a refinement of the higher level model [168]. In general, the refined version of a model contains more details than the original version, although this property does not necessarily hold. For example, an optimization is a refinement which could remove details from an original model. This definition is also congruent with refinement concepts such as simulation relations in the formal methods community [174]. In this chapter, the concept of traceability and the concept of refinement correctness are differentiated. Traceability is defined as an invertible function between two models, mapping syntactical elements. The mappings can fall under different categories, depending on the differences between the two models. Refinement correctness can be established though a set of correctness criteria for the different types of syntactical mappings.

In the context of the TASM specification language, traceability is defined as a function between the rules of two models [202]. In the TASM language, rules are contained inside of machines. However, in the definition of traceability, the machine structure is ignored without loss of generality since rules can be renamed using the name of the machine as a prefix. The machine to which a rule belongs becomes important when specifying correctness criteria, but is irrelevant for the syntactical mappings.

Formally, traceability between model $M_1$ and model $M_2$ is defined as a partial function $T$ over the set of rules $X_1$ of model $M_1$ and the set of rules $X_2$ of model $M_2$:

$$T : \mathcal{P}(X_1) \rightarrow \mathcal{P}(X_2)$$

The partial function is defined over the power set of $X_1$ and the power set of $X_2$, as a function between arbitrary sets, to reflect the possibility that traceability does
not have fixed arity and can be many-to-many. In the context of a partial function, the *domain of definition* is the set of elements in the domain for which the function is defined. In the context of a partial function, the *codomain of definition* is the set of elements in the image for which the function is defined. Two function operators are introduced, `ddef` and `codef`, which operate on T:

- `ddef(T) \triangleq` domain of definition of T
- `codef(T) \triangleq` codomain of definition of T

Although the function T is defined in a one-way fashion, bi-directional traceability can be achieved by taking the inverse of T. The ability to invert the function requires that the partial function be a bijection over `ddef(T)` and `codef(T)`. Furthermore, to define the properties of T, a definition of a *partition* is given, where the empty set can be an element of the partition. Formally, a set P of subsets of X is a *partition* if it has the following properties:

- The union of the elements of P = X
- The pairwise intersection of the elements of P = ∅

With the definitions of `ddef`, `codef`, and *partition*, the formal definition of bi-directional traceability between two models can be formulated. The definition is given in terms of the properties of the function T:

- T is a bijection over `ddef(T) \rightarrow codef(T)`
- `ddef(T)` must form a partition of X₁
- `codef(T)` must form a partition of X₂

The requirement that the function be a bijection over the domains of definition ensures that the function is invertible. This is a necessary condition for traceability to be bi-directional. The partition requirement on the domains of definition ensures that every rule in X₁ and X₂ is involved in one and only one mapping for each refinement level. This requirement is necessary when trying to ensure semantic equivalence between the two models using the correctness criteria.
6.2.1 Types of Refinements

In the previous section, traceability through levels of abstraction was established as a mapping between the rules of two TASM models. In this section, categories of mappings are defined so that the differences between the two models capture the rationale for the change. More specifically, this section defines seven categories of refinements, defined formally as elements of the function $T$, defined in the previous section, which share a common property and arity. Each category defines a conceptual type of refinement that can be traced bi-directionally.

The list of refinement types have been motivated by synthesis of refinement approaches as found in the literature [17, 174] and through experience with developing models using stepwise refinement. At a high level, in the context of TASM models, a refinement is defined as the addition, deletion, or modification of rules in a model $M_1$, resulting in a refined model $M_2$. The types of refinement described in this section attempt to express the motivations for performing a refinement. It is important to restate that traceability does not depend on a particular type of change since the types of changes are simply elements of the function $T$, that is, mappings between rules. But the categories are helpful syntactically, to convey the rationale behind the mapping, and semantically, when trying to establish semantic equivalence between the models. The categories are used in Section 6.2.2 where criteria are defined, for each category, to establish the correctness of the refinement. The refinement categories are expressed as ordered pairs of sets of rules. For example, the refinement described below denotes an arbitrary mapping between $n$ rules of one model and $m$ rules of another model:

$$\langle\{R_1, R_2, \ldots, R_n\}, \{S_1, S_2, \ldots, S_m\}\rangle$$

The subscripts of the rules denote the ordinal of the rule in the ordered set. For certain categories, the ordering of rules is irrelevant but for other categories, the ordering is important. When the ordering matters, it is used to denote a sequence of
execution starting with the first ordinal and terminating with the last ordinal.

Step Expansion

A step expansion refers to a type of refinement where a "step" in model $M_1$ is refined into multiple steps in model $M_2$. In the formal methods community, such a refinement is called a "non-atomic" refinement [79]. In the context of the TASM language, since a step is the execution of a rule, the expansion of a step implies a mapping between one rule and multiple other rules, a one-to-many relationship:

$$T_{\text{exp}} \triangleq (\{R\}, \{S_1, S_2, \ldots, S_m\})$$

In a step expansion refinement, the ordering of the rules $S_i$ is important, especially when the correctness criteria are defined.

Step Contraction

The step contraction refinement is the dual of the step expansion refinement. A step contraction refinement refers to a type of refinement where multiple steps in model $M_1$ are refined into a single step in model $M_2$. The refinement is a many-to-one mapping:

$$T_{\text{con}} \triangleq (\{R_1, R_2, \ldots, R_n\}, \{S_1\})$$

As for the step expansion refinement, the order of the rules $R_i$ is important.

Rule Expansion

A rule expansion refinement is a one-to-many mapping. In the context of a single rule, a rule expansion refinement is used to add or modify a time annotation, to add or modify resource annotations, to add more conditions to the rule guard, and to add
extra effect expressions. The rule expansion refinement can also be used to expand a rule into multiple rules, resulting in a one-to-many mapping. Syntactically, the rule restriction refinement is similar to the step expansion refinement. The differences occur in the correctness criteria used to establish the semantic equivalence between the mapped rules. Conceptually, the step expansion refinement is meant to describe a refined sequential execution, where the extra rules are executed in sequence. The rule expansion refinement is meant to describe the expansion of the state, through the addition of variables to the model or by expanding the list of members in a user-defined type. The added state components can lead to added conditions in the rule guards and added assignments in the rule effect expressions.

\[ T_{res} \triangleq (\{R_1\}, \{S_1, \ldots, S_m\}) \]

**Rule Contraction**

Similarly to the step contraction refinement, the rule contraction refinement is also a many-to-one mapping. The rule contraction refinement is the dual of the rule expansion refinement. The rule contraction refinement is used to remove or modify a time annotation, to remove or modify resource annotations, to remove conditions from the rule guard, and to remove effect expressions. The refinement is also used to remove state components from the model, through the removal of variables or the removal of members of user-defined types. Removing variables can lead to a reduced number of rules as the number of items in the rule guards and in the rule effect expressions are reduced.

\[ T_{exp} \triangleq (\{R_1, \ldots, R_n\}, \{S_1\}) \]

**Rule Addition**

Rule addition refers to a type of refinement where behavior is added to a model, caused by expansion of the state space. In terms of the TASM language, this refinement
corresponds to the addition of one or more rules to an existing set of rules, a zero-
to-many mapping. The difference between the rule addition refinement and the rule
expansion refinement concerns the correctness criteria. A rule addition refinement
which adds \( p \) rules to a set of \( m \) rules would yield the following mapping:

\[
T_{add} \triangleq \{ \}, \{ S_{m+1}, \ldots, S_{m+p} \}
\]

**Rule Deletion**

A rule deletion refinement is a refinement where a set of rules is removed from an
existing set, caused by a reduction in the state space. The rule deletion refinement is
the dual of the rule addition refinement, and it is defined as a many-to-zero mapping.
A rule deletion refinement which removes \( p \) rules from a set of \( m \) rules would yield
the following mapping:

\[
T_{del} \triangleq \{ \{ R_1, \ldots, R_{m-p} \}, \{ \} \}
\]

**Any**

While the three categories of refinements defined above, with their associated dual,
represent common refinement types as surveyed through the literature and identified
through modeling experience, it is possible that other types of refinements are nec-
essary. Furthermore, since traceability is not dependent on the types of refinements,
it is important not to restrict the usability of the traceability features by requiring
the strict use of refinement types. Because of these motivations, a “wild card” type
of refinement is defined, to define traceability without intent. This wild card, called
an “any” refinement, is simply a generic many-to-many mapping between the rules
of two models:
Complete Traceability Relationship

These seven types of refinements are also complemented by the identity refinement, $T_{id}$, which maps a rule from model $M_1$ to an identical rule in model $M_2$. Conceptually, the identity refinement is simply a special case of all seven types of refinements; consequently, it is not described as a separate refinement, but it is introduced as special notation that is useful when establishing semantic equivalence. Given these relationships, define the complete traceability relationship between a $M_1$ and a refined model $M_1$ as defined, through the partial function $T$:

$$T = T_{sexp} \cup T_{con} \cup T_{res} \cup T_{rres} \cup T_{exp} \cup T_{add} \cup T_{del} \cup T_{any} \cup T_{id}$$

Where each $T_n$ is a set whose elements are refinements of type $T_n$, corresponding to the types of refinements defined in previous subsections. Given the definition of $T$, the definition of the various categories of refinements, and the relationship between the categories and the function $T$, a syntactical basis for bi-directional traceability of software models is established. In Section 6.2.2, the syntactic notion of traceability is complemented with the semantic notion of equivalence through defining notions of refinement correctness. The semantic integrity is achieved by giving correctness criteria for each category of refinement. The idea behind the correctness criteria is such that, if a criterion holds for a given refinement, then an established property of the original model will hold in the refined model without needing to repeat the verification efforts.
6.2.2 Correctness Criteria

To define the correctness criteria for each category of refinement, the internal details of individual rules must first be syntactically related according to the traceability approach. Listing 6.1 and Listing 6.2 contain two symbolic rules, rule $R_i$ ($1 \leq i \leq n$) from model $\mathcal{M}_1$ and rule $S_j$ ($1 \leq j \leq m$) from model $\mathcal{M}_2$. Rule $R_i$ contains a time annotation, $tr$, and $p$ resource annotations, $rk$. Similarly, rule $S_j$ contains a time annotation, $ts$, and $p$ resource annotations, $sk$.

**Listing 6.1 Symbolic rule for model $\mathcal{M}_1$**

```plaintext
Ri: Rule of Model $\mathcal{M}_1$
{
  tr := [rai, rbi];
  r1 := [qi1, rii];
  ...
  rp := [qip, rip];

  if RGi then
    REi;
}
```

**Listing 6.2 Symbolic rule for model $\mathcal{M}_2$**

```plaintext
Sj: Rule of Model $\mathcal{M}_2$
{
  ts := [saj, sbj];
  s1 := [uj1, ujl];
  ...
  sp := [sjp, ujp];

  if SGj then
    SEj;
}
```

The correctness criteria for each refinement type apply to the three aspects of the TASM language - function, time, and resource consumption. The correctness criteria are expressed as relationships between the annotations, the guards, and the effect expressions of the rules contained in the sets of mappings. If certain annotations are not present in a model, there are no restrictions on the behavior of the refined model concerning those annotations. The goal of the correctness criteria is to establish semantic integrity between the two sets of rules, to ensure that semantics are preserved.
between the two models. For the step expansion, rule expansion, and rule addition refinement types, the idea surrounding the refinement correctness stipulates that if a given semantic property holds in the original model, it will also hold in the refined model if the correctness criteria are met. If the correctness criteria do not hold, no semantic equivalence can be guaranteed by the approach given in this section, although ad-hoc arguments can be used to prove correctness and verification efforts can be exerted to ensure correctness. The correctness criteria do not need to hold for the refinement to be correct, but if they do hold, the amount of verification that needs to be performed on the refined model is reduced because the refined model comes with the semantic guarantees of the original model. If no criteria hold, the refinement comes with no guarantees and verification must be performed on the refined model as if the model is an entirely new model.

The step expansion, rule expansion, and rule addition refinement types capture refinements as introduced through top-down design. The general philosophy surrounding the correctness criteria is that the higher level model dictates the behavior that the refined model must exhibit. This philosophy relies on the reality that higher level models might typically exist before lower level models. Consequently, higher level models are deemed to be "correct" since analysis can be performed on the high level models before the low level models are developed. The dual of these refinement types, namely the step contraction, the rule contraction, and the rule deletion refinement types, capture refinements as introduced through bottom-up design, with properties that hold in the lower level model being guaranteed to hold in the higher level model, if the correctness criteria hold. For each correctness criterion, the criterion is given, followed by a proof that if the criterion holds, the semantics of the original model are preserved in the refined model.

In this chapter, the term *semantics* is used as a general term to denote a property established in a model using the analysis approaches described in Chapter 5. The idea behind the correctness criteria is such that if the criteria are met for the refinement, properties established in the original model will also hold in the refined model. In the context of the TASM language, the established properties that could hold through the
Refinement include safety and liveness, expressed as reachable and unreachable states, BCET and WCET, and minimum and maximum amounts of resource consumption. The motivations behind the approach is to reduce the amount of verification that needs to be performed on the refined model. Since traceability is a useful syntactic concept to track and understand design assumptions, adding notions of semantic equivalence to the traceability approach can reduce the duplication of verification activities. The correctness criteria govern the three aspects of the TASM language – function, time, and resources. The correctness criteria are defined for these three aspects by defining conditions that need to hold in the mapping for properties of the original model to hold in the refined model. These conditions govern the three aforementioned aspects:

- Function, through relating the rule guards and rule effects
- Time, through relating the time annotations
- Resources, through relating the resource annotations

In the following subsections, the correctness criteria for each type of refinement is defined in terms of these three aspects. The phrase “semantics are preserved” is used for brevity when stating the theorems to establish the preservation of properties between two models. What is meant by “semantics are preserved” is primarily that safety and liveness analysis performed on the original model is maintained in the refined model. Furthermore, if the conditions relating the time and resource annotations are strict equalities instead of inequalities, and the criteria governing the rule guards and effect expressions hold, WCET and BCET analysis is also preserved. A similar argument can be made for the resource annotations, for the preservation of minimum and maximum resource consumption analysis performed on the original model.

**Step Expansion**

The correctness criteria for a step expansion refinement is such that the parent rule defines constraints on the set of expanded rules. The step expansion refinement is
used to divide the execution of a single rule into two or more consecutive steps. The
division is typically achieved by adding an extra variable to the state space, which
acts as a program counter to enforce the sequential execution of the refined rules.
The refinement of timing behavior requires that the total execution time of refined
rules be less than equal to the execution time of the parent. This relationship is
logical since the time behavior of the children rules represents a subset of the time
behavior of the parent. If verification has been performed on the higher level model,
it is logical to assume that established functional properties will still hold in the child
model given the subset relationship. Formally, for the rule $R_1$ shown in Listing 6.1,
which is expanded to $m$ rules $S_j$, one of which is shown in Listing 6.2, the correctness
criteria for the time annotations are shown below:

$$ra_1 \leq sa_1 + sa_2 + \ldots + sa_m$$
$$rb_1 \geq sb_1 + sb_2 + \ldots + sb_m$$

Since time annotations are non-deterministic execution times for the rule, verifica-
tion performed on the model will consider all possible times inside the annotation
interval. For the quantitative timing behavior to be preserved through the refinement,
such as worst-case execution time, the relationship between the time annotations must
be equality instead of inequality. This is necessary since execution time analysis, for
WCET and BCET, depends on quantitative values of rule executions and not only
on the possible interleavings of rule executions. The correctness criteria for resource
consumption follow a similar pattern. However, since resource consumption is additive
through parallel steps but not through sequential steps, the relationship involves
the maximum and minimum resource consumptions:
\[ q_{11} \geq \min(s_{11}, s_{21}, \ldots, s_{m1}) \]
\[ \vdots \]
\[ q_{n1} \geq \min(s_{n1}, s_{n2}, \ldots, s_{nm}) \]
\[ r_{11} \leq \max(u_{11}, u_{21}, \ldots, u_{m1}) \]
\[ \vdots \]
\[ r_{n1} \leq \max(u_{1n}, u_{2n}, \ldots, u_{mn}) \]

As for time annotations, for the results of the resource consumption analysis performed on model \( M_1 \) to hold in model \( M_2 \), the inequalities should be equalities. Furthermore, for resource consumption semantics to hold, the correctness criteria regarding the rule guards must also hold. For the guards, the correctness criteria between \( M_1 \) and \( M_2 \) is such that the expanded model must not change the semantics of the guard \( RG_1 \). Formally, this relationship implies that the disjunction of each guard \( SG_j \) must be logically equivalent to \( RG_1 \):

\[ RG_1 \equiv (SG_1 \lor \ldots \lor SG_m) \]

Essentially, this relationship states that the disjunction of guards of the expanded rules must form a tautology whenever the guard of rule \( R_1 \) is enabled. In other words, on of the expanded rules must execute whenever \( R_1 \) would execute. For the effect expressions, the correctness criterion requires that everything that happens in \( RE_1 \) must also happen as a result of executing the sequence of refined rules \( S_j \). Per TASM semantics, the effect of executing the rule is applied after the rule execution has completed. Consequently, this effect expression relationship can be expressed as the effect expression of rule \( R_1 \) being contained in the intersection of the effect expression of rule \( R_1 \) and the union of the effect expressions of the various \( S_j \):
Furthermore, the added effects in the rule effect expressions of the refined rules must not affect the execution of any other rule \( R_i \) in the model. This restriction also concerns the execution of the original rule \( R_1 \). The last condition necessary for the correctness of the refinement requires that the refined rules \( S_j \) are executed in an atomic sequence. This means that, for every \( 1 \leq i < m \), the effect of executing rule \( S_i \) causes the guard of rule \( S_{i+1} \) to be enabled. Furthermore, no other rule in the model can change the sequence of execution.

These four correctness criteria involving the time, resource consumption, guard, and effect expressions of the two sets of rules form the basis of the correctness criteria for the various types of refinement. If the listed criteria hold, safety, liveness, completeness and consistency results from model \( M_1 \) will hold in model \( M_2 \). Furthermore, for the execution time analysis to hold, strict equalities must hold for the time annotation criteria. Similarly, for the resource consumption analysis results to hold, strict equalities must hold for the resource annotation criteria. In the following sections, the correctness criteria of other refinement types are explained reusing the notation introduced in this section and the notation from Listing 6.1 and from Listing 6.2. For each type of refinement, the correctness criteria are stated, followed by a argument to prove that, if the criteria holds, the semantics are preserved through the refinement.

**Theorem 6.1.** If the correctness criterion for the step expansion refinement holds, the semantics of model \( M_1 \) are preserved in model \( M_2 \).

**Proof.** Suppose that rule \( R_1 \) of model \( M_1 \) is enabled in state \( ST_0 \) and that executing rule \( R_1 \) in state \( ST_0 \) yields state \( ST_1 \). Let \( ST'_k \) be the refined state containing \( ST_k \), with the added variable to enforce sequential execution. Since the disjunction of the refined rules \( S_j \) form a tautology when rule \( R_1 \) is enabled, one of the refined rules must be enabled in state \( ST'_0 \). The ordering of the execution of refined rules can...
be selected arbitrarily without loss of generality. In this case, the index of the rules is selected as the order of execution. Let rule $S_1$ be the enabled rule in state $S^\prime T_0$. Executing rule $S_1$ in state $S^\prime T_0$ yields an intermediate state $S T_01$. Since the execution of the refined rules is required to be sequential, the execution of the rules will yield $j - 1$ intermediate states. Since the effect of executing rule $R_1$ must be included in one of the effect expressions of the refined rules, state $S T_0$ will be contained inside one of the intermediate states and eventually into the final state resulting from executing the refined rules in sequence. From the requirement that no other effect expression can affect any other rule, including rule $R_1$, it naturally follows that the final state resulting from executing the sequence of refined rules $S_j$ will be $S^\prime T_0$. 

**Step Contraction**

The step contraction refinement is the dual of the step expansion refinement, with the direction of the refinement being reversed. Consequently, the correctness criteria detailed in the previous section are exactly the same for this refinement type, but in the reverse direction, including the reversal of the containment relationships. In the rule contraction refinement, the total time of the rules in the refinement for model $M_1$ specify the constraints on the rule in model $M_2$: 

\[
ra_1 + ra_2 + \ldots + ra_m \leq sa_1
\]

\[
rb_1 + rb_2 + \ldots + rb_m \geq sb_1
\]

A similar relationship can be defined for the correctness criteria for resource consumptions. This relationship is omitted for brevity. For the relationship between the guards and the effect, the criteria are similar to those detailed for the step expansion refinement:
\[(RG_{11} \lor RG_{12} \lor \ldots \lor RG_{1m}) \equiv SG_1\]
\[RE_1 \cap (RE_1 \cup RE_2 \cup \ldots \cup RE_n) \cap SE_1 = SE_1\]

**Theorem 6.2.** If the correctness criterion for the step contraction refinement holds, the semantics of model $M_2$ are preserved in model $M_1$.

**Proof.** The proof of this theorem is identical to the proof of Theorem 6.1, in the reverse order. \(\square\)

**Rule Expansion**

The rule expansion refinement adds information to a rule, in the form of a modified time annotation, modified resource annotations, an expansion of the guard, or an expansion of the effect expression. For time and resource annotations, the correctness criteria require that the annotations in rule $R_2$ be contained in the annotations of rule $R_1$. In other words:

\[
ral \leq saj, \forall j = 1 \ldots m \\
rb1 \geq sbj, \forall j = 1 \ldots m \\
q1k \leq sjk, \forall j = 1 \ldots m, k = 1 \ldots p \\
r1k \geq ujk, \forall j = 1 \ldots m, k = 1 \ldots p
\]

The presented relation between the annotations of both models will ensure that functional behavior is maintained for the model, as explained in Theorem 6.3. For execution time analysis and resource consumption analysis to be preserved, the annotations must be equalities instead of inequalities.

If the guard is expanded by adding extra conditions to the guard, the disjunction of the $S_j$ guards in the mapping must be logically equivalent to the guard of $R_1$. 

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What this means is that the $S_j$ guards must not be true with variable assignments that make $R_1$ false and one of the $S_j$ guards must be true whenever $R_1$ is true:

$$RG_1 \equiv (SG_1 \lor \ldots \lor SG_m)$$

If the effect expression is expanded, by adding extra assignments of values to variables, the effect expression of $R_1$ must be contained in the effect expression of $S_j$:

$$RE_1 \subseteq SE_j, \forall j = 1 \ldots m$$

Furthermore, for any other unchanged rule $R_i$ from the unrefined model, the added items in the refined effect expression must not change the value of the guard of rule $R_i$. The idea behind the rule expansion refinement is that the behavior of the refined rules are contained within the behavior of the unrefined rule. Consequently, if verification involving the unrefined rule was performed, those results should still hold in the refined rules.

**Theorem 6.3.** *If the correctness criterion for the rule expansion refinement holds, the semantics of model $M_1$ are preserved in model $M_2$.*

*Proof.* Since the disjunction of the guards of the refined rules are logically equivalent to the guard of the original rule, at least one of the $S_j$ guards of model $M_2$ will be enabled whenever rule $R_1$ of model $M_1$ is enabled. And since the effect expression of rule $R_1$ of model $M_1$ is contained in every refined rule of model $M_2$, the effect of executing rule $R_1$ is preserved. Furthermore, since the expanded effect expressions do not affect the evaluation of the guards of other rules, the refinement is, in effect, limited to the refined rule and hence preserves the semantics of model $M_1$. $\square$

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Rule Contraction

Rule contraction is analogous to rule expansion and concerns the modification of the time annotation, the modification of resource annotations, the modification of guard conditions, the modification of effect expressions, and the consolidation of rules. The rule contraction refinement would be used when removing variables from the state, resulting in a contraction of the state space and of the number of rules contained in the model. The correctness criteria are similar to the correctness criteria for the rule expansion refinement, but apply in the reverse order:

\[
\begin{align*}
ra_{i} & \leq sa_{i}, \forall i = 1, \ldots, n \\
rbi & \leq sb_{i}, \forall i = 1, \ldots, n \\
qik & \geq s_{ik}, \forall i = 1, \ldots, n, k = 1, \ldots, p \\
rik & \leq u_{ik}, \forall i = 1, \ldots, n, k = 1, \ldots, p \\
SG_{i} & \equiv (RG_{i} \lor \ldots \lor RG_{n}) \\
SE_{1} & \subseteq RE_{i}, \forall i = 1, \ldots, n
\end{align*}
\]

The idea behind the rule expansion refinement is that the behavior of the unrefined rules is contained inside the behavior of the refined rule. Consequently, if verification involving the refined rule is performed, these results will hold in the unrefined rules.

**Theorem 6.4.** If the correctness criterion for the rule contraction refinement holds, the semantics of model $M_{2}$ are preserved in model $M_{1}$.

*Proof.* This proof is identical to the proof of Theorem 6.3. $\square$

Rule Addition

The rule addition refinement refers to a refinement where a set of rules is added to a model. This refinement can be used to add steps in sequential execution or to add
parallel rules to handle new conditions resulting from an extended state space. For
sets of rules, completeness and consistency have been defined in Section 5.1. The
correctness criteria concern the preservation of completeness and consistency through
rule addition. The functions \textit{comp} and \textit{cons} are defined between a set of rules and the
set \{True, False\}. The function returns the value True if a set of rules is complete
(consistent) and vice-versa [123]. Using the notation from Section 6.2, \(X_1\) is the set
of rules of model \(M_1\) and \(X_2\) is the set of rules of model \(M_2\). Using these definitions,
the correctness criteria for rule addition can be defined:

\[
\text{cons}(X_1) \rightarrow \text{cons}(X_2) \\
\text{comp}(X_1) \rightarrow \text{comp}(X_2)
\]

What this criteria mean is that adding a rule to an existing rule set must not
introduce non-determinism. Non-determinism introduced through the addition of a
rule would preserve the semantics only if the effect expressions of the two inconsistent
rules would be identical. However, it is not clear why adding a rule that is essentially
a copy of another rule would be a useful refinement. If the rule is added to add parallel
behavior to handle an extended state space, its effect expression must contain only
updates to variables in the extended space. If the rules are added to augment the
number of steps in a sequence of execution, updates to the variable representing the
order of execution are acceptable, as long as the order of effect expressions is preserved
from the original set of rules and do not affect rules outside the machine where the
rule is added.

\textbf{Theorem 6.5.} \textit{If the correctness criterion for the rule addition refinement holds, the
semantics of model \(M_1\) are preserved in model \(M_2\).}

\textit{Proof.} The behavior of rules added to reflect the addition of sequential steps is ana-
lized first. Suppose that \(m\) rules \(S_j\) are added as intermediate steps between original
rule \(R_1\) and \(R_k\). The proof follows the principles of the proof of theorem 6.1. Suppose

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rule $R_1$ is enabled in state $ST_0$ and yields state $ST_1$, in which state rule $R_k$ is enabled and yields state $ST_k$ after execution. The addition of the rules must follow an atomic sequence where rule must be modified such that executing $R_1$ must yield a new state $ST_1$ where $S_1$ is enabled. The added rules must yield an atomic sequence of rule executions that will yield state $ST_1$ such that executing rule $R_k$ will complete the chain. Since the added rules are required to not have side-effects on other rules, the behavior is preserved.

For rules that are added to handle an extended state space in parallel, the guarantees of completeness and consistency ensure that the rules do not conflict with existing rules in the machine. Furthermore, the requirement that the rules be side-effect free is a restricted case which guarantees that the semantics aren't changed since the rules do not interfere with existing rules.

Rule Deletion

Similarly, the correctness criteria for rule deletion must not affect the completeness the rule set or the consistency of the rule set where it is added. For example, if a set is complete, removing a rule must not make it incomplete in order to preserve the semantics.

\[
\begin{align*}
\text{cons}(X_1) & \rightarrow \text{cons}(X_2) \\
\text{comp}(X_1) & \rightarrow \text{comp}(X_2)
\end{align*}
\]

**Theorem 6.6.** If the correctness criterion for the rule deletion refinement holds, the semantics of model $M_2$ are preserved in model $M_1$.

**Proof.** This proof is identical to the proof of Theorem 6.5.
Any

The any refinement type does not contain correctness criteria and does not carry guarantees of semantic equivalence. This refinement is used purely for syntactic traceability with no semantic guarantees.

Identity

The correctness criteria for the identity refinement simply ensures that the mapping does not modify the rule:

\[ tr = ts \]
\[ s_i = r_i, \forall i = 1 \ldots m, m = n \]
\[ RG_1 = SG_1 \]
\[ SE_1 = RE_1 \]

It is straightforward from this identity mapping to verify that the mapping does not modify the semantics of the model.

6.3 Example

In this section, an example is provided to illustrate the concepts explained throughout this chapter. In Chapter 8, the Electronic Throttle Controller (ETC) case study provides a more complex example of bi-directional traceability between disparate models, with the correctness criteria ensuring semantic guarantees between models. The refinements and the traceability properties of the ETC case study are presented in Section 8.4. In this section, the light switch example, originally presented in Section 4.1.5, is refined, first by expanding the state space and secondly through the addition of tasks and a scheduler. The light switch example contains two components, a light bulb and a switch. The controller software is responsible for turning on the
light based on the switch position. A high level model might contain simple logic to describe the behavior of the software, as shown in Listing 6.3. The model of Listing 6.3 describes the requirement “if the switch is UP, the light shall be ON” and the requirement “if the switch is DOWN, the light shall be OFF”.

### Listing 6.3 Model 1 of light switch

R1: Turn on  
{  
  if switch = UP then  
  light := ON;  
}

R2: Turn off  
{  
  if switch = DOWN then  
  light := OFF;  
}

A refinement of the requirements might extend the functionality of the light by introducing additional conditions on the behavior of the software, leading to a refined model. For example, Listing 6.4 describes behavior that meets the same requirement as in Listing 6.3 but incorporates the extra requirement “when turning the light ON during day time, the light intensity shall be LOW while it shall be HIGH during nighttime”. This extra functionality is added to the model of Listing 6.3 by expanding the state space. Two new user-defined types are added – one to describe the time of day (values “DAY” and “NIGHT”) and one to describe the intensity of the light (values “LOW” and “HIGH”). Two extra variables are added to the state to denote the time of day and the light intensity.

Establishing syntactical traceability between model 1 and model 2 is fairly straightforward. The refinement type for the mapping between the two rules is of the “Rule Expansion” type, where rule $R_1$ is mapped to rules $S_{11}$ and $S_{12}$. In the refinement, items are added to the rule guards and to the effect expressions. Formally, the syntactical mapping is:
Listing 6.4 Model 2 of light switch

S11: Turn on, low {
    if switch = UP and timeofday = DAY then
        light := ON;
        intensity := LOW;
    }

S12: Turn on, high {
    if switch = UP and timeofday = NIGHT then
        light := ON;
        intensity := HIGH;
    }

S2: Turn off
{
    if switch = DOWN then
        light := OFF;
    }
\[ T = T_{\text{exp}} \cup T_{\text{id}} = ((\{R_1\}, \{S_{11}, S_{12}\})) \cup ((\{R_2\}, \{S_2\})) \]

\[ = ((\{R_1\}, \{S_{11}, S_{12}\}), (\{R_2\}, \{S_2\})) \]

Since the guards of the rules are changed in model 2, the correctness criteria for the rule expansion refinement must establish guard equivalence. The equivalence can be visualized in Table 6.1 for rule \( R_1 \). The truth table clearly shows that the disjunction of rule \( S_{11} \) and rule \( S_{12} \) is equivalent to the guard of rule \( R_1 \).

<table>
<thead>
<tr>
<th>switch</th>
<th>timeofday</th>
<th>timeofday</th>
<th>( R_1 )</th>
<th>( S_{11} )</th>
<th>( S_{12} )</th>
<th>( S_{11} \lor S_{12} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>UP</td>
<td>DAY</td>
<td>NIGHT</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>T</td>
<td>F</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>F</td>
<td>T</td>
</tr>
<tr>
<td>F</td>
<td>T</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>F</td>
<td>F</td>
<td>T</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>

Table 6.1: Truth table to verify the correctness criteria for the rule expansion refinement between rule \( R_1 \) and rules \( S_{11} \) and \( S_{12} \)

Since the model contains only one machine, no time annotations, and no resource annotations, it is clear that the correctness criteria hold for the rule expansion refinement. Furthermore, the changes in the effect expressions of the refined rules do not affect any other rules, preserving the semantics of model 1. What this means is that a statement made about the possible traces of the model 1 will hold in the refined model. For example, the property that a “state where the switch is UP will eventually always be followed by a state where the light is ON” will hold in both models.

In order to add interesting features to the model, a scheduler driven by a 1 ms clock is added to the model. The scheduler fires a task that has a period of 30 ms. The task has an execution time lasting between 1 and 10 ms. The scheduler is added as an extra main machine, in order to drive the system and switch the task’s status between “wait” and “exec”. The task is another main machine which simply waits to be activated. The scheduler is shown in Listing 6.5 and the task is shown in Listing 6.6.
Listing 6.5 Model of the scheduler with 1 ms clock, firing a task with a period of 30 ms

T1: Fire
{ 
  t := 1;

  if tick = 30 then 
    tick := 1;
    task := exec;
}

T2: Tick
{ 
  t := 1;

  else then 
    tick := tick + 1;
}

Listing 6.6 Model of the task, model 3

P1: Execute
{ 
  t := [1, 10];

  if task = exec then 
    task := wait;
}

P2: Wait
{ 
  t := next;

  else then 
    skip;
}
In Listing 6.4, the task is simply a placeholder which does not provide any functionality other than consume time. The model of the task can be combined with model 2 of Listing 6.4 to wrap the functionality of model 2 inside of the tasking model. The resulting model is shown in Listing 6.7.

**Listing 6.7 Combined model with task implementation, model 4**

D1: Turn on, low
{
  if task = exec and switch = UP and timeofday = DAY then
    light := ON;
    intensity := LOW;
    switch := wait;
}

D2: Turn on, high
{
  if task = exec and switch = UP and timeofday = NIGHT then
    light := ON;
    intensity := HIGH;
    task := wait;
}

D3: Turn off
{
  if task = exec and switch = DOWN then
    light := OFF;
}

D4:
{
  t := next;
  else then
    skip;
}

Because model 4 is a refinement of model 3 and a refinement of model 2, the traceability relationship yields two branches. The branch between model 3 and model 4 yields the following syntactic traceability relationship:
\[ T = T_{\text{exp}} \cup T_{\text{id}} = (\{P_1\}, \{D_1, D_2\}) \cup (\{P_2\}, \{D_4\}) \]
\[ = (\{P_1\}, \{D_1, D_2\}, \{P_2\}, \{D_4\}) \]

The correctness criteria for the rule expansion refinement between rule \( P_1 \) and rules \( D_1, D_2, \) and \( D_3 \) is shown in Table 6.2. Since the variables involved in the refinement are binary variables, there is no need to include columns for the value "NIGHT" and for the value "wait", since these values are captured in the columns for the value "DAY" and for the value "exec". It is clear from the table that the correctness criteria hold for the guards of the refined rule. The time and resource annotations also conform to the correctness criteria. The mapping between rule \( P_2 \) and rule \( D_4 \) is trivially correct because the two rules are exactly the same since it is an identity refinement.

<table>
<thead>
<tr>
<th>switch = UP</th>
<th>timeofday = DAY</th>
<th>task = exec</th>
<th>( P_1 )</th>
<th>( D_1 )</th>
<th>( D_2 )</th>
<th>( D_3 )</th>
<th>( D_1 \lor D_2 \lor D_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>T</td>
</tr>
<tr>
<td>F</td>
<td>F</td>
<td>T</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
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<td>T</td>
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<td>F</td>
<td>T</td>
<td>T</td>
<td>F</td>
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<tr>
<td>F</td>
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<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>F</td>
<td>T</td>
<td>T</td>
</tr>
</tbody>
</table>

Table 6.2: Truth table to verify correctness the criteria for the rule expansion refinement between rule \( P_1 \) and rules \( D_1, D_2, \) and \( D_3 \)

Furthermore, since the added effect expressions from model 3 to model 4 concern only the newly introduced variables, the locality condition of the correctness criteria also holds. It is interesting to note that the refinement from model 3 to model 4 could have been achieved through hierarchical composition, by wrapping the functionality of model 2 inside a submachine. In this case, the correctness criteria with regards to
the guards would require the sub machine to be complete, leading to the appropriate correctness criterion for the guards, according to Theorem 5.1. The machine depicted in Listing 6.7 corresponds to the “flattened” machine that would be obtained by removing the hierarchical composition, as explained in the proof of Theorem 4.2. Since the correctness criteria hold for the refinement from model 3 to model 4, the properties of model 3 are preserved in model 4. For example, the worst-case execution time of each task is preserved, as are the schedulability attributes. A similar approach is used in Section 8.4 for the ETC case study, where the functionality of the controller is implemented using a set of tasks.

Model 4 can also be viewed as a refinement of model 2. The traceability branch between model 2 and model 4 yields the following syntactic traceability relationship:

\[
T = T_{\text{exp}} \cup T_{\text{add}} = ((\{S_{11}\}, \{D_1\}), (\{S_{12}\}, \{D_2\}), (\{S_2\}, \{D_3\})) \cup ((\{\}, \{D_4\}), (\{\}, \{T_1, T_2\}))
\]

\[
= ((\{S_{11}\}, \{D_1\}), (\{S_{12}\}, \{D_2\}), (\{S_2\}, \{D_3\}),
(\{\}, \{D_4\}), (\{\}, \{T_1, T_2\}))
\]

The correctness criteria for the mapping between rule \(S_2\) and rule \(D_3\) resembles the criteria for the mapping displayed in Table 6.2. To be more thorough and for the correctness criteria to hold, extra rules should be added to model 4 to reflect the cases where the task is in the “wait” state. However, this mapping is guaranteed by the “Else” rule. The mapping preserves the semantics of model 2 since the modifications are local to the expanded state space. A similar argument can be made for the rule expansion refinements of rule \(S_{11}\) and rule \(S_{12}\). The correctness criteria get a bit more complex to visualize for the rule addition refinements since the addition of the “Else” rule is done to modify the termination semantics of the machine and to handle the case where the task is in the “wait” state. Such a dual purpose refinement makes the model simpler, but exacerbates the proof of the preservation of semantics. In order to make the preservation easier to demonstrate, model 2 could have already contained
the "Else" rule and model 4 could have contained 3 extra rules to handle the case where the task is in the "wait" state. Furthermore, the addition of the scheduler, which acts on the refined rules, complicates the problem. Nevertheless, using simple arguments, it is possible to see that the addition of the scheduler does not affect the order of execution of the functional model, and the property "if the switch is UP, the light will always eventually be ON", from model 1 still holds. Properties from model 2 with regards to the light intensity also hold.

This simple example provides an illustration of the concepts outlined in this chapter. The example provides an interesting application of the proposed approach, to combine a tasking model and a functional model, all the while preserving some behavioral semantics during the refinement process. In the first branch of traceability, scheduling attributes were preserved while in the second branch, functional attributes were preserved. Section 8.4.2 uses a similar technique to achieve traceability and refinement correctness on a more complex example using the Electronic Throttle Controller (ETC) case study.

6.4 Segue into Chapter 7

This chapter presented an approach to relate different TASM models syntactically, through a mapping between the rules of the two models. The proposed strategy also presented a set of archetypical refinement types, as surveyed through literature and experience with modeling. Each refinement type is accompanied by a set of correctness criteria which, if satisfied, preserve certain semantic aspects between the two models. The approach was demonstrated using an extended version of the light switch example from Section 4.1.5. The following chapter, Chapter 7, presents an approach to generate test cases automatically based on TASM specifications. The presented method enables the automated generation of unit test cases, integration test cases, and regression test cases.
Chapter 7

Test Case Generation

This chapter presents an approach to automatically generate test cases based on a model expressed in the TASM language. The generation of test cases is achieved for unit testing, integration testing, and regression testing. The test cases are generated to achieve coverage of the TASM model according to the rule coverage criteria, as defined in the ASM community. Unit test cases are generated in the context of an individual machine without hierarchical composition. Integration test cases are generated by combining unit test cases hierarchically. The traceability relationship, described in Chapter 6, is leveraged to provide an approach to the generation of regression test cases. The generation of unit, integration, and regression test cases is provided in separate sections and illustrative examples are given at the end of each section.

7.1 Related Work

Testing remains the main activity in industry and in software engineering circles to build confidence into the system being engineered [220, 242]. Even though testing can never establish the absence of defects [81], the popularity of testing has grown the practice and theory considerably, leading to well-established definitions and concepts in the software engineering community [26, 169, 176].

The growing popularity of testing has led to various approaches to automatically
generate test cases [74, 86] and to the development of various tools [27]. More recently, the advent of model-based software engineering has given birth to model-based testing, an approach to test case generation where a model or specification is used as the basis to generate test cases [32, 130, 222]. Model-based testing builds upon previous results from the requirements engineering community where requirement specifications are used to generate test cases [75, 112, 245]. In model-based testing, two key approaches are used to automatically generate test cases, constraint-based test case generation [214] and test case generation using model checkers [8]. Test case generation using model checkers relies on some form of automata model to generate test sequences that are used to cover certain aspects of the model such as states and transitions [102]. Notably, the UPPAAL tool suite has been used to generate test cases for real-time systems in [128]. In [128], synchronization channels are used to model the inputs and outputs of the system and the automata model is assumed to be "input enabled and output urgent" to ensure that the generated test suite is time optimal [36]. The approach described in [128] is not applicable to TASM specifications because the language does not contain synchronization channels. Furthermore, the generation of test sequences, as performed using model checkers, relies on assumptions about the system under test, which may not be applicable in practice, as explained in Section 7.5.1. The approach presented in this chapter does not preclude the generation of test sequences, but provides a more generic approach to test case generation which can be tailored to a specific purpose.

The test case generation strategy presented in this chapter relies on constraint programming and symbolic combination of test cases, a strategy related to the approach presented in [15] and in [16]. However, the definition of templates is unique to the TASM-based approach although it resembles the theory of equivalence classes explained in [176]. The approach presented in this chapter uses the specification as an oracle, that is, as the authority on the correct input/output behavior of the system under test [219]. In other words, the specification describes the expected output of the system for each class of inputs. Much of the theory on test case generation concerns unit testing; the strategy described in this chapter extends unit testing capabilities by
combining unit test cases to achieve integration testing. Furthermore, the approach presented in this chapter uses traceability attributes to generate regression test cases in the occurrence of specification modifications or extensions. The regression test case generation uses structured model changes as the basis for test case generation, similar to mutation-based approaches were a well-defined set of defects are used to generate test cases [247]. This section reviewed the popular approaches to test case generation at a high level and situated the proposed approach in light of past efforts. In the following subsections, different coverage criteria are reviewed and test case generation efforts within the Abstract State Machine (ASM) community are reviewed.

7.1.1 Coverage Criteria

The purpose of performing testing activities is to achieve a desired level of confidence into the functionality of the system being tested. However, in order to achieve a satisfactory level of testing, some criteria need to be put in place to decide what to test and when to stop the testing activities. For this reason, traditional ad-hoc approaches to testing have been replaced with structured approaches to testing whose aim is to achieve a predetermined level of coverage of the system under test [176]. The possible levels of coverage are captured into coverage criteria, which express properties of the system under test, such as program branch coverage and program variable definition and usage coverage. The list of possible coverage criteria is quite large and a good survey is provided in [256]. In the field of safety-critical systems, the DO-178B standard requires that an implemented system of a certain criticality level be tested to achieve the Modified Condition/Decision Coverage (MC/DC) criterion [64, 216]. Standard DO-178B also requires that requirements be tested, expressing that the testing of the implemented system also cover all requirements. In the field of model-based testing and specification-based testing, the coverage criteria used for generating test cases refer to coverage items of the model such as states and transitions [153, 184].

In the context of Abstract State Machines (ASM), coverage criteria have been defined in [103]. The coverage criterion used in the approach presented in this chapter is the rule coverage criterion presented in [103]. The rule coverage criterion is
analogous to the transition coverage criterion described in [184] and in [256] which concern variants of automata.

7.1.2 Abstract State Machines

In the ASM community, test cases have been generated automatically based on specifications, using model checking techniques [104]. The approach generates test sequences to achieve different coverage criteria, including rule coverage. The approach presented in this chapter differs from the approach presented in [104] in that it uses constraint logic programming to generate test cases. Furthermore, the approach presented in this chapter also generates test cases and not test sequences. Another approach in the ASM community generates test cases based on the AsmL language, an ASM derivative developed at Microsoft [116]. The test case generation approach derives a finite state machine approximation of an AsmL specification for the purpose of generating test cases using established algorithms [110]. The test case strategy is accompanied by a tool for automated generation [109]. The AsmL approach to test case generation provides an underapproximation of the true finite state machine, as explained in [110] through the execution of the specification. The approach presented in this chapter differs from the AsmL approach in that it does not rely on generating a finite state machine. However, the concept of hyperstate described in [110] is closely related to the concept of test case template described in this chapter. A benefit of the approach described in this chapter is the ability to generate test cases incrementally and locally, and combining the test cases to achieve coverage of the specification. Furthermore, the generation of regression test cases has not been addressed in the ASM community.

7.2 Test Case Generation Concepts

This section provides definitions of concepts that are used in the three subsequent sections when describing the test case generation algorithms. The provided definitions are defined by the presented research. However, many of the concepts have already
been defined in test case generation theory [176]. Where applicable definitions borrowed from the testing community are cited. The concept of a template is unique to the test case generation approach presented in this chapter although the notion of template has been used extensively in other software engineering branches.

7.2.1 Definitions

The test case generation strategy uses concepts from set theory to generate test cases symbolically. Throughout the description of the algorithms, the terms template and instance are used to explain the approach. At a high level, a template is a generic concept which describes a family or a set of items which share a common property. This definition is analogous to the definition of a set in discrete mathematics [232]. Analogously, an instance is a single member of a template, analogous to an element of a set in discrete mathematics. The terms template and instance are used over set and member because the terms are well-established terms in the software engineering community. Furthermore, for a template/instance pair, the term template is used to describe the properties of the members of the template while the term instance will be generally omitted for brevity. For example, in the rest of this section terms like variable template and test case template are used to denote a set of items sharing a given property while the terms variable and test case are used to denote instances of the templates.

A variable template is a variable name accompanied by a set of possible values for the variable. A variable template is analogous to a datatype but the term template is used to maintain consistent naming across concepts. For example, a variable template for an integer variable named *a* with a lower bound of -11 and an upper bound of 50 would be defined as "a{-11 < a < 50}". A variable instance or variable for short, is the variable with an associated value taken from the template, which, in this case, is the interval [-11, 50]. For example, the variable "a = 0" is an instance of the variable template "a{-11 < a < 50}". Analogously, a state template is a set of variable templates. A state instance, or state for short, is a member of a state template where each member of the state are variables which are, in turn, instances
of the variable templates defined in the state template. The definition of a test case instance is given before the definition of a test case template to avoid crowding the definitions with the word template.

A test case instance or test case for short, TC, is a pair of state instances \((S, S')\) where \(S\) is the pre state and \(S'\) is the post state. A test case describes expected behavior of a model as follows: "if a step of the model is executed in state \(S\), the resulting state will be state \(S'\)." It is important to note that the state \(S\) does not need to be a complete state, that is, a state containing values for all the variables of the model. The state \(S\) should contain enough variable values to exercise an aspect of interest of the model, for example, a specific rule. Similarly, the state \(S'\) also does not need to be a complete state, but needs to contain the expected changes in the state caused by the test case. Item of the state not included in the pre state or in the post state are assumed to have no effect on the purpose and outcome of the test case.

A test case template, TCT, is a family or set of test cases which exercise the same aspect of the model. A test case template is composed of a pre state template, \(ST\), and of a post state template, \(ST'\). For example, a test case template might dictate that the pre state \("a > 3, b < 10"\) exercises a desired aspect of the model with expected post-state \("a = a + b"\). The provided test case template describes a set of test cases containing numerous, potentially infinite, possibilities for test cases that satisfy the template. A test case is an instance of a test case template, whose pre state and post state are contained in the pre state template and in the post state template of the test case template. For example, the test case \(\langle \text{“a = 5, b = 6”, “a = 11”} \rangle\) is an instance of the test case template \(\langle \text{“a > 3, b < 10”, “a = a + b”} \rangle\).

If some form of model coverage is the goal of the test case generation, the test case and the test case template concepts can be augmented to include the intended coverage item for the test case or test case template. A coverage test case (alternatively, coverage test case template) is a pair that relates a test case TC (alternatively, test case template TCT) with a coverage item CI: \(\langle TC, CI \rangle\) (alternatively, \(\langle TCT, CI \rangle\)).

A test suite instance or test suite for short, TS, is a set of coverage test cases.
which achieves a specific purpose. A *coverage test suite* is a set of coverage test cases which seeks to achieve a specific level of coverage. A coverage test suite is said to be *adequate* if its set of test cases collectively achieve a desired coverage criterion of the model. A coverage test suite is said to be *minimal* if its set of test cases is adequate and no two test cases exercise the same coverage item. The definitions of adequate and minimal are congruent with established test case generation theory [176].

In these definitions, the assumption is such that the model can be started in any state and that the state is fully observable. The post state is observed after executing a single step of the model. While this assumption might not be immediately adequate in practice, it provides greater flexibility when generating the test cases. As explained in Section 7.5, the test case generation strategy is generic and can be adapted to the specific properties of the system being tested.

In the presented framework and in this chapter, the coverage criterion used for test case generation is the “rule coverage criterion”, which requires that all rules of the specification be exercised [103]. Given this definition, an adequate test suite for a given TASM specification would be a set of test cases which collectively exercise all rules in all machines of a TASM specification. Given the rule coverage criterion, in the context of TASM, a coverage test case \( CTC_i \) would be of the form \( \langle \langle S, S' \rangle, \{ R_i \} \rangle \), where \( \{ R_i \} \) denotes a set of rules covered by the test case. For a TASM specification \( M \) with \( n \) rules \( \{ S_1, \ldots, S_i, \ldots, S_n \} \), for an adequate coverage test suite for specification \( M \), the union of the coverage items in each coverage test case contained in the test suite must be equal to the set of rules in the TASM specification \( M \).

### 7.2.2 Operations on Templates

In Section 7.4, test case templates generated for unit testing are combined to derive integration test case templates. In doing so, operations are performed on test case templates. Because the templates are defined hierarchically, test case templates contain state templates, which, in turn, contain variable templates. To perform the combination of templates, operations from set theory are used, including intersec-
tion ($\cap$) and union ($\cup$). The combination operations are distributed inward and are applied in a manner congruent with traditional set theory. For example, taking the intersection of two test case templates would involve taking the intersection of the two pre states. Taking the intersection of the two pre states involves taking the intersection of the two sets of variable templates. When taking the intersection of the variable templates, the result of the intersection contains only the variables common to both sets. Furthermore, the definition of each variable template would be intersected. For template definitions defined as enumerations, the intersection is applied using traditional set theory. For template definitions defined as inequalities, the intersection is applied according to the principles of interval arithmetic.

In its basic form, interval arithmetic is the definition of operations where the operands are intervals. In the test case strategy, interval arithmetic is useful in two facets – when combining test case templates and when computing the post state template based on a pre state template. Since variable templates for integer and for real variables can be expressed as equalities using $>$, $<$, $\leq$, and $\geq$, calculating the post state template involves performing operations on templates. For templates that contain sets of values for a variable, normal set operations apply and arithmetic operations are defined as the cartesian product of operations. If a variable is “free” in a test case template, that is, it appears only as a right-value, bounds on the values of the variable can be provided by the user or can be obtained from the variable definition in the TASM specification. The following subsection describes the principles of interval arithmetic used in the test case generation strategy.

Interval Arithmetic

The operations performed on integer-valued and real-valued variables expressed as intervals follow the basic conventions of interval arithmetic, as described in [148] and in [145]. These operations are summarized below, following the convention that “[” and “[” are used to express inclusion for a bound of the interval, while “(” and “)” are used to express exclusion for the associated bound of the interval.
Table 7.1: Pre and post state for sample test case template for Listing 7.1

<table>
<thead>
<tr>
<th>Pre State</th>
<th>Post State</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>number{10},</code></td>
<td><code>loaded_blocks([LB + 1, 10], [21, UB + 1])</code>,</td>
</tr>
<tr>
<td><code>loaded_blocks([LB, 9), [20, UB])</code>,</td>
<td><code>feed.begin(True),</code></td>
</tr>
<tr>
<td><code>feed.belt{empty}</code></td>
<td><code>feed.belt{loaded}</code></td>
</tr>
</tbody>
</table>

Pre State

- `number{10}`
- `loaded_blocks([LB, 9), [20, UB])`
- `feed.belt{empty}`

Post State

- `loaded_blocks([LB + 1, 10], [21, UB + 1])`
- `feed.begin(True),`
- `feed.belt{loaded}`

The last operation denotes that an operation between an inclusive bound and an exclusive bound results in an exclusive bound. It is important to note that set operations and interval arithmetic can be combined. For example, for the rule given in Listing 7.1, the relevant test case template and test case instance involves set operations and interval arithmetic. In the rest of this chapter, the notation “varnameval1, \ldots, valn” is used to denote that variable “varname” can take on any value “vali”, where “var_i” can be an interval. The example from Listing 7.1 yields the test case template described in Table 7.1. In the table, the interval bounds LB and UB denote the upper bound and lower bound values of the variable, as specified in the TASM environment definition. Since the variable `number` is free in the test case, its value was arbitrarily selected to be 10, although an interval for the variable could also have been derived from the variable definition in the TASM specification.

The test case template given in Table 7.1 can be easily converted to a coverage test case template by adding the `R1` rule to the pre state and post state pair. Furthermore, since a template describes a family of test cases, it can be instantiated to yield a coverage test case. An instance of the coverage test case template is shown in
Listing 7.1 Rule for sample test case template

R1: The first rule
{
    if (loaded_blocks < number - 1 or loaded_blocks >= 20) and feed_belt = empty then
        feed_belt := loaded;
        loaded_blocks := loaded_blocks + 1;
        feed_begin := True;
}

<table>
<thead>
<tr>
<th>Pre State</th>
<th>Post State</th>
<th>Coverage Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>number{10},</td>
<td>loaded_blocks = 11,</td>
<td>R1</td>
</tr>
<tr>
<td>loaded_blocks = 8,</td>
<td>feed_begin = True,</td>
<td></td>
</tr>
<tr>
<td>feed.belt = empty</td>
<td>feed.belt = loaded</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.2: Coverage test case corresponding to the template of Table 7.1

Table 7.2. It is fairly straightforward to see that the test case shown in Table 7.2 is, indeed, an instance of the test case template shown in Table 7.1.

7.2.3 Machines and Test Suites

The strategy presented in this chapter uses a combination of unit test case generation and integration test case generation to generate test suites to cover all the rules of all machines in a TASM specification. In the test case generation strategy, a generated test suite is associated with a given machine in the TASM specification. In the following sections, the terminology “the test suite of machine M” is used to describe the test suite that covers the rules of machine M. Regardless of whether the test suite is generated for unit testing or for integration testing, the generated test suite is derived to cover a specific machine and remains associated with that machine. The association can be visualized as a pair between a machine and a test suite (M, TS). Of course this relationship also holds for other variations of test suites such as test suite templates and coverage test suites.
7.3 Unit Test Case Generation

*Unit testing* refers to the testing of a piece of software in isolation. In programming language terms, unit testing could concern the testing of a function, the testing of a class, or the testing of an algorithm [176]. The term *unit* is used to denote that a small piece of the total program (in this case a small piece of the specification) is targeted and that other pieces of the program are abstracted away in the test case generation and execution. In terms of a TASM specification, the basic units of structural organization are rules and machines. While the rules are used as the coverage items, the machines are used as the basic units for test case generation. In the unit test case generation strategy, it is assumed that the machine for which test cases are being generated is "flat", meaning that it does not contain hierarchical composition. Per Theorem 4.1 and Theorem 4.2, any machine with hierarchical composition could be "flattened". However, the test case generation strategy does not necessarily require that a machine with hierarchical composition be flattened before generating test cases. While this approach would work using the unit test case generation algorithm presented in this section, Section 7.4 considers hierarchical composition as part of the integration test case generation strategy; treating hierarchical composition as part of the integration testing strategy leads to better complexity results than flattening the machine and using the unit test case generation algorithm. Any TASM model that contains hierarchical composition will also contain at least one machine which does not contain hierarchical composition. The complete test case generation algorithm described in Section 7.5 explains how the unit test case generation algorithm is used on machines that do not use hierarchical composition and how the integration test case generation algorithm combines the unit test cases for machines that use hierarchical composition.

Since the algorithm performs the calculation of the pre state template and of the post state template for each rule, the generated test suite template will be adequate if, for each rule, the guard of the rule is satisfiable. Furthermore, if the machine is consistent, the test suite will be minimal. The unit test case algorithm can be
Listing 7.2 Unit test case generation algorithm for a machine M

- For each rule $R_i$ of machine M:
  
  - Create pre state template $PreS_i$:
    * Bind each free variable in the guard $G_i$
    * For each other variable $v_{ij}$ in the guard $G_i$
      - Find sets of values that make $G_i$ True
  
  - Create post state template $PostS_i$:
    * Calculate the post state template by executing $R_i$ on the pre state template
  
  - Create test case template $TCT_i$:
    * $TCT_i = \langle (PreS_i, PostS_i), R_i \rangle$
    * Add the test case template $TCT_i$ to the template test suite $TCTS$

- Associate the test suite $TCTS$ with machine M: $\langle M, TCTS \rangle$
implemented by reusing the mapping to SAT described in Appendix B, for TASM specifications whose rule guards meet the characteristics described in the appendix. The SAT4J SAT solver provides the set of all solutions that satisfy the propositional formula given as the SAT instance. Given the "discretization" of the state involving integer and real variables, as explained in Appendix B, the iteration of solutions can easily be aggregated to yield the pre state template and the post state template can be calculated using the operations described in Section 7.2.

7.3.1 Complexity Analysis

Because the algorithm described in Listing 7.2 operates on a machine that does not contain hierarchical composition, the generated number of test case templates generated will be equal to the number of rules for machine M. The number of generated test case templates will always be fixed for the algorithm in Listing 7.2. However, the properties of the guard of each rule greatly affects the complexity of generating the test case. For an implementation using a SAT solver, the complexity analysis for the translation is available in Section B.3.1. However, contrary to the usage of the SAT solver for the verification of completeness and consistency where demonstrating the existence of a solution is the goal, the test case generation algorithm needs to iterate through all solutions and aggregate the results into the pre state template. The performance of the aggregation will be linear in the number of solutions since each variable can be expanded as needed depending on the properties of the solution. For generating the post state template, simple arithmetic is necessary, leading to linear performance in the number of variables. The complexity of test case generation resides in the translation of the rule guards to SAT and executing the resulting problem through the solver. The complexity of the test case generation itself is fairly straightforward.
7.3.2 Example

A short example is provided to illustrate the algorithm described in Listing 7.2. The example provides 3 rules of a sample machine from the Timeliner case study, with some modifications to illustrate the concepts of interval arithmetic and test case templates. The Timeliner case study is analyzed in details in Section 8.5. In the context of the example, the meaning of the machine is irrelevant as it is used solely to generate test cases. In Listing 7.3, the variable NOMINAL_TEMP_MID is a constant equal to 25 and the lower bound of the temperature variable is -10 and its upper bound is 40, inclusively.

Listing 7.3 Rules of the SEQUENCE_TEMP_MONITOR_WORK sub machine (partial)

R7: b3 -> b4 {
    t := 2390;
    if temp_seq_b = b3 and temperature <= 19 then
        temp_seq_b := b4;
        heating := on;
        delta := NOMINAL_TEMP_MID - temperature;
    }
R8: b4 -> b4 {
    t := 1630;
    if temp_seq_b = b4 and temperature < 22 then
        temp_seq_b := b4;
        temp_seq_s := done;
    }
R9: b4 -> b0 {
    t := 3195;
    if temp_seq_b = b4 and temperature >= 22 then
        temp_seq_b := b0;
        heating := off;
        temp_seq_s := done;
    }

The generation of unit test cases for the machine of Listing 7.3, yields 3 coverage test case templates, one to cover each rule of the machine. The 3 test case templates are listed in Table 7.3. The calculation of the post state template for rule R7 utilizes the interval arithmetic rules from Section 7.2 for subtraction. While this example is
somewhat simple, it is taken almost verbatim from the case study. This example will also be reused in Section 7.4 and in Section 7.6 to illustrate the integration test case generation strategy and the regression test case strategy.

### 7.4 Integration Test Case Generation

Integration testing concerns testing the combination of two or more units, eventually resulting in the complete system being exercised. In the context of TASM specifications, the combination of units occur during hierarchical composition, where one unit uses another unit in an effect expression either as a sub machine or as a function machine.

#### 7.4.1 Hierarchical Composition

In the TASM language, hierarchical composition is achieved via function machines and sub machines. According to Theorem 4.1 and Theorem 4.2, hierarchical composition can be removed, yielding an equivalent “flattened” machine without hierarchical composition. Consequently, the algorithm for generating unit test cases could be applied to the equivalent “flattened” machine, removing the need for a special algorithm to generate integration test cases. However, there are two main reasons justifying the need for an algorithm for integration testing. First, unit testing typically happens before integration testing, meaning that the set of unit test cases for different machines will have already been generated when integration testing begins.

<table>
<thead>
<tr>
<th>Pre State</th>
<th>Post State</th>
<th>Coverage Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>$temp_{seq.b}{}{b3}$, $temperature = {-10, 19}$</td>
<td>$temp_{seq.b}{}{b4}$, $heating(on)$, $temperature{6, 35}$</td>
<td>$R_7$</td>
</tr>
<tr>
<td>$temp_{seq.b}{}{b4}$, $temperature = {-10, 22}$</td>
<td>$temp_{seq.b}{}{b4}$, $temp_{seq.s}{}{done}$</td>
<td>$R_8$</td>
</tr>
<tr>
<td>$temp_{seq.b}{}{b4}$, $temperature = {22, 40}$</td>
<td>$temp_{seq.b}{}{b0}$, $heating(off)$, $temp_{seq.s}{}{done}$</td>
<td>$R_9$</td>
</tr>
</tbody>
</table>

Table 7.3: Template test suite for the machine of Listing 7.3
Consequently, reusing the unit test cases would save a certain amount of work since the test case generation strategy does not need to start fresh. Secondly, obtaining the equivalent "flattened" machine through the approach explained in Theorem 4.1 and in Theorem 4.2 can lead to exponential growth in the number of rules of the "flattened" machine, if multiple units of hierarchical composition are used within a rule. The integration test case generation described in this section eliminates the need to flatten the machine, hereby avoiding possible exponential growth in the numbers of rules.

To make the generation of integration test cases slightly simpler, the approach assumes that there are no function machines used in the rule guards. This assumption is valid since the rule guards could easily be rewritten without the use of function machines, as explained in the proof of Theorem 4.1. Furthermore, another simplification involving function machines is used to ease the generation of integration test cases. A function machine can be converted to an equivalent sub machine by converting the arguments to the function machine into fresh environment variables, which become monitored variables of the sub machine. Furthermore, the variable to which the return value of the function machine is assigned can be added as a controlled variable of the sub machine. In the function machine, the output variable is replaced by the controlled variable. Given these two simplifications, the test case generation algorithm can be expressed as the combination of unit test cases of sub machines, as explained in Listing 7.4. Suppose that a given machine M uses a sub machine SM in the effect expression of one of its rules, rule \( R_i \). Also suppose that a coverage test suite template has been generated for submachine SM using the algorithm described in Section 7.3. Machine M and sub machine SM could share monitored variables. If they do, the algorithm must take into account the possibility that the rules of the two machines could be enabled under different conditions for the same variables. It is assumed that the machines do not share controlled variables because this would result in update set inconsistency per ASM theory [42]. In the description of the algorithm, it is assumed that the coverage test suite template for machine SM contains \( m \) test case templates, of the form \( TCT_{SM,j} = \langle (Pre_{SM,j}, Post_{SM,j}), S_j \rangle \), where the
subscript $SM, j$ is used to denote the machine to which the test case belongs, in this case machine $SM$ and the rule covered by the test case, in this case the $j^{th}$ rule effect expression.

In the algorithm of Listing 7.4, if the two machines do not share monitored variables, the resulting test suite is simply the union of the test case templates for machine SM with the test case template for rule $R_i$ or machine M. If the two machines share monitored variables, the variable templates for the shared variables are intersected using the set intersection and the interval arithmetic described in Section 7.2.2. In theory, the intersection of the pre states could be empty, but this situation would occur only if the guards of the sub machine contradict the guards of the machine which uses the sub machine. If this situation is encountered, it would result in the rules of the sub machine never being enabled. Such a situation would not occur purposefully, otherwise there is no point in using the sub machine in the model.

The algorithm provided in Listing 7.4 is given for hierarchical composition for a single sub machine. It can easily be generalized for $p$ sub machines $SM_k$ used in the effect expression. For $k$ machines that do not share variables, rules can be selected arbitrarily, one for each machine and can be aggregated into the test case template using the union operator. If the sub machines do not contain the same number of rules, some rule coverage will be repeated for some machines, but the combination of rules covered by each test case template will be unique. The total number of test case templates generated for $k$ sub machines will be equal to the number of rules of the sub machine that has the largest number of rules. If the machines share monitored variables, the generated test case templates are assembled using the intersection operator for the pre state, following the approach of Listing 7.4, but for $k$ machines. In this instance as well, the total number of generated test case templates is equal to the number of rules of the sub machine that has the largest number of rules.
Listing 7.4 Integration test case generation algorithm for a machine $M$ and a sub machine $SM$. Machine $M$ uses sub machine $SM$ in the effect expression of rule $R_i$.

* Generate the pre state $PreS_i$ for rule $R_i$ of machine $M$ using the approach given in Listing 7.2

- If machine $M$ and sub machine $SM$ do not share variables:
  * Generate the post state $PostS_i$ for rule $R_i$ of machine $M$, for the effect expressions not containing hierarchical composition, using the approach given in Listing 7.2
  * For each test case template $TCT_{SM,j}$ for sub machine $SM$:
    * Create $m$ test case templates for machine $M$:
      
      $TCT_i = \langle \{PreS_i \cup PreS_{SM,j}, PostS_i \cup PostS_{SM,j}\}, \langle R_i, S_j \rangle \rangle$

- If $M$ and sub machine $SM$ share monitored variables:
  * let $PreSS_{SM,j} \subseteq PreS_{SM,j}$ be the set of variable templates of machine $SM$ for monitored variables which are shared with machine $M$
  * let $PreSN_{SM,j} = PreS_{SM,j} \setminus PreSS_{SM,j}$
  * let $PreSS_i \subseteq PreS_i$ be the set of variable templates of machine $M$ for monitored variables which are shared with machine $SM$
  * let $PreSN_i = PreS_i \setminus PreSS_i$
  * calculate the new pre state $PreS'_i = (PreSS_i \cap PreSS_{SM,j}) \cup (PreSN_i \cup PreSN_{SM,j})$
  * Generate the post state $PostS_i$ for rule $R_i$ of machine $M$, for the effect expressions not containing hierarchical composition, using the pre state $PreS'_i$ and the approach given in Listing 7.2
  * For each test case template $TCT_{SM,j}$ for sub machine: $SM$:
    * Create $m$ test case templates for machine $M$:
      
      $TCT_i = \langle \{PreS'_i, PostS_i \cup PostS_{SM,j}\}, \langle R_i, S_j \rangle \rangle$

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7.4.2 Complexity Analysis

Generating the integration test case templates using the algorithm described in Listing 7.4 avoids the exponential growth that would result from generating a "flattened" version of the machine. Generating a flattened machine which uses multiple sub machines in its effect expression adds a number of rules to the host machine equal to the product of the number of rules of the sub machines. A coverage test suite template for the flattened machine would contain one test case per rule and hence an exponential number of test cases. For the algorithm given in Listing 7.4, the number of test cases necessary to cover the host machine and the sub machines is equal to the number of rules of the machine with the largest number of rules. The complexity for generating the pre state template of machine M is identical to the complexity of generating the pre state template for unit test cases, as explained in Section 7.4.2. Combining the test suite from machine M with the test suite from machine SM is linear in the number of rules for both machines. Calculating the post state template and the combination of the pre state template depends on the properties of the variables used in the rules.

7.4.3 Example

The example from Section 7.3.2 is extended to illustrate the generation of integration test cases. Two machines are added to the machine described in Listing 7.3. The first machine added, shown in Listing 7.5, does not contain hierarchical composition, and is analogous to the machine given in Listing 7.3. The humidity variable has a lower bound equal to 0 and an upper bound equal to 100. The test suite template for the machine of Listing 7.5 is given in Table 7.4 and has been obtained using the algorithm described in Listing 7.2.

The second machine which is added to the example uses both the machine from Listing 7.3 and the machine from Listing 7.5 in one of its rule effect expression. The machine is also adapted from the Timeliner case study with extensions to illustrate the generation of integration test cases. The machine of interest is shown in Listing 7.6. The coverage test case template for rule $P_4$ is easily generated using the algorithm
Listing 7.5 Rules of the SEQUENCE_HUMIDITY_MONITOR_WORK sub machine (partial)

S9: c4 -> c0 {
    t := 1950;
    if humid_seq_b = c4 and humidity > 39 then
        humid_seq_b := c0;
        humid_seq_s := done;
    }

S10: c5 -> c5 {
    t := 1630;
    if humid_seq_b = c5 and humidity < 50 then
        humid_seq_b := c5;
        humid_seq_s := done;
    }

S11: c5 -> c0 {
    t := 3195;
    if humid_seq_b = c5 and humidity >= 50 then
        humid_seq_b := c0;
        humidifier := off;
        humid_seq_s := done;
    }

Table 7.4: Template test suite for the machine of Listing 7.5
from Listing 7.2. The generated test suite is shown in Table 7.5 and contains 4 coverage test case templates. The test suite covers all the rules of the machines. The generated test suite shows the benefits of the integration testing strategy compared to generating a “flattened” machine and using the unit test case generation strategy. Generating an equivalent “flattened” machine would yield 10 rules, requiring 10 test cases to cover all the rules of the “flattened” machine. By using the integration test case generation algorithm described in Listing 7.4, 4 test cases are sufficient to cover all the rules of both machines.

Listing 7.6 Rules of the EXECUTE_PLANTSIM_SEQUENCES sub machine

<table>
<thead>
<tr>
<th>P3: Execute sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>{</td>
</tr>
<tr>
<td>if exec_seq = not_done then</td>
</tr>
<tr>
<td>SEQUENCE_HUMIDITY_MONITOR_WORK();</td>
</tr>
<tr>
<td>SEQUENCE_TEMP_MONITOR_WORK();</td>
</tr>
<tr>
<td>exec_seq := done;</td>
</tr>
<tr>
<td>}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>P4: Bundle finished</th>
</tr>
</thead>
<tbody>
<tr>
<td>{</td>
</tr>
<tr>
<td>if exec_seq = done then</td>
</tr>
<tr>
<td>plantsim_s := done;</td>
</tr>
<tr>
<td>exec_seq := not_done;</td>
</tr>
<tr>
<td>}</td>
</tr>
</tbody>
</table>

In order to add another level of hierarchical composition, which will prove useful in Section 7.6.4, an extra machine is introduced, which uses the machine shown in Listing 7.6 in rule $V_1$. The definition of the machine is shown in Listing 7.7. The test suite for the machine can easily be generated using the integration testing algorithm shown in Listing 7.4, combined with the test suite template shown in Table 7.5. The resulting test suite template is shown in Table 7.6.

### 7.5 Complete Test Case Generation Algorithm

The complete test case generation algorithm combines the unit test case generation approach from Section 7.3 and the integration test case generation strategy described in Section 7.4. The algorithm described in this section can be used on a machine at
Table 7.5: Template test suite for the machine of Listing 7.6

<table>
<thead>
<tr>
<th>Pre State</th>
<th>Post State</th>
<th>Coverage Item</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>exec.seq(not_done), humid_seq.b(c4), humidity = {(39, 100)}, temp_seq.b(b3), temperature = {[-10, 19]}</code></td>
<td><code>exec.seq(done), humid_seq.b(c0), humid_seq.s(done) temp_seq.b(b4), heating(on), temperature([6, 35])</code></td>
<td>$P_3, S_9, R_7$</td>
</tr>
<tr>
<td><code>exec.seq(not_done), humid_seq.b(c5), humidity = {[0, 50]}, temp_seq.b(b4), temperature = {[-10, 22]}</code></td>
<td><code>exec.seq(done), humid_seq.b(c5), humid_seq.s(done) temp_seq.b(b4), temp_seq.s(done)</code></td>
<td>$P_3, S_{10}, R_8$</td>
</tr>
<tr>
<td><code>exec.seq(not_done), humid_seq.b(c5), humidity = {[50, 100]}, temp_seq.b(b4), temperature = {[22, 40]}</code></td>
<td><code>exec.seq(done), humid_seq.b(c0), humidifier(off), humid_seq.s(done) temp_seq.b(b0), heating(off), temp_seq.s(done)</code></td>
<td>$P_3, S_{11}, R_9$</td>
</tr>
<tr>
<td><code>exec.seq(done), plantsim_s(done)</code></td>
<td><code>exec.seq(not_done), plantsim_s(done)</code></td>
<td>$P_4$</td>
</tr>
</tbody>
</table>

Listing 7.7 Rules of the PLANTSIM_BUNDLE sub machine

V1: Bundle Active
{
    if plantsim_bundle_status = active then
        EXECUTE_PLANTSIM_SEQUENCES();
}

V2: Bundle Inactive
{
    if plantsim_bundle_status = inactive then
        plantsim_s := done;
}
<table>
<thead>
<tr>
<th>Pre State</th>
<th>Post State</th>
<th>Coverage Item</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>exec_seq{not done}</code>, <code>humid_seq.b(c4)</code>, <code>humidity = {(39, 100)}</code>, <code>temp_seq.b(b3)</code>, <code>temperature = {[-10, 19]}</code>, <code>plantsim.bundle.status{active}</code></td>
<td><code>exec_seq{done}</code>, <code>humid_seq.b(c4)</code>, <code>humidity = {(39, 100)}</code>, <code>temp_seq.b(b3)</code>, <code>temperature = {[-10, 19]}</code>, <code>plantsim.bundle.status{active}</code></td>
<td><code>V_1, P_3, S_9, R_7</code></td>
</tr>
<tr>
<td><code>exec_seq{not done}</code>, <code>humid_seq.b(c5)</code>, <code>humidity = {[0, 50]}</code>, <code>temp_seq.b(b4)</code>, <code>temperature = {[-10, 22]}</code>, <code>plantsim.bundle.status{active}</code></td>
<td><code>exec_seq{done}</code>, <code>humid_seq.b(c5)</code>, <code>humidity = {[0, 50]}</code>, <code>temp_seq.b(b4)</code>, <code>temperature = {[-10, 22]}</code>, <code>plantsim.bundle.status{active}</code></td>
<td><code>V_1, P_3, S_{10}, R_9</code></td>
</tr>
<tr>
<td><code>exec_seq{not done}</code>, <code>humid_seq.b(c5)</code>, <code>humidity = {[50, 100]}</code>, <code>temp_seq.b(b4)</code>, <code>temperature = {[22, 40]}</code>, <code>plantsim.bundle.status{active}</code></td>
<td><code>exec_seq{done}</code>, <code>humidity = {[50, 100]}</code>, <code>temp_seq.b(b4)</code>, <code>temperature = {[22, 40]}</code>, <code>plantsim.bundle.status{active}</code></td>
<td><code>V_1, P_3, S_{11}, R_9</code></td>
</tr>
<tr>
<td><code>exec_seq{done}</code>, <code>plantsim.bundle.status{active}</code></td>
<td><code>exec_seq{not done}</code>, <code>plantsim.bundle.status{inactive}</code></td>
<td><code>V_1, P_4</code></td>
</tr>
</tbody>
</table>

Table 7.6: Template test suite for the machine of Listing 7.7
any level. The core idea behind the test case generation strategy is that a test suite can be associated with an individual machine to test the machine. The test cases are generated in a “bottom-up” fashion, by reusing the test suites already generated for machines which are combined through hierarchical composition. The complete test case generation algorithm is given in Listing 7.8.

**Listing 7.8 Complete test case generation algorithm for a given TASM specification**

- For a given TASM specification:
  
  - For each machine $M_i$ which does not contain hierarchical composition:
    * Generate a coverage test suite template $TCTS_i$ using the algorithm described in Listing 7.2
    * Associate the test suite with the machine: $\langle M_i, TCTS_i \rangle$
    * Add the pair to the test suite for the specification
  
  - For all remaining machines $N_j$ which do not have a test suite associated with them:
    * Gather all machines $P_k$ used for hierarchical composition in $N_j$
    * Loop recursively until all machines $P_k$ have an associated test suite in the model:
      * Generate a template coverage test suite, $TCST_k$, for machine $P_k$
        using the algorithm described in Listing 7.4
      * Associate the test suite with the machine: $\langle P_k, TCTS_k \rangle$
      * Add the pair to the test suite for the specification
    * Generate a coverage test suite template, $TCST_j$ for machine $N_j$ using the algorithm described in Listing 7.4
    * Associate the test suite with the machine: $\langle N_j, TCTS_j \rangle$
    * Add the pair to the test suite for the specification
    * Loop until all machines are included in the test suite for the specification

7.5.1 Test Sequences

The test case generation strategy described in this chapter concerns the generation of test cases to exercise a single rule, and hence a single step of the specification. The assumption, as stated in Section 7.2, is that the specification can be executed in any state and that the state resulting from a step execution is fully observable. However,
in practice, this is not necessarily the case since intermediate steps could be present between the consumption of inputs and the generation of outputs. For this reason, related approaches to test case generation often produce test sequences, which are sequences of inputs and outputs used to exercise the specification and the underlying system under test. The approach presented in this chapter could certainly be used to generate test sequences but provides a more flexible strategy to the execution of test cases. Since the test case templates are used to exercise a single rule, sequences could be generated by concatenating test case templates whose post states and pre states are congruent. Furthermore, a generic approach to test case generation could be devised by describing the properties of initial states and by describing the properties of observable states. Which such a theory, test sequences could be assembled using the concatenation of test case templates, with the pre state of the first test case template in the sequence meeting the property of the initial state and the final test case template in the sequence containing a post state which meets the observability criteria.

The test case generation strategy can be viewed as generating a set of ordered dominoes, where the top face is the pre state template and the bottom face is the post state templates. The dominoes can be assembled linearly to achieve a desired purpose, in the form of a test sequence. As long as all the test case templates from a given test suite are involved in a test sequence, the rule coverage criteria would still be preserved. These ideas are explored in the Timeliner case study in Section 8.5 and as part of future work in Chapter 9.

7.6 Regression Test Case Generation

Regression testing concerns the testing of an existing system which has already been tested to a certain extent, after changes have been made to either the system itself or to the specification. Conceptually, regression testing occurs after both unit and integration testing have been accomplished, to validate the correctness of a change made to the system or to the specification, during a late of the lifecycle [176]. Such a change
could be the fixing of a defect, a change in requirements, or the introduction of new functionality. During regression testing, it is generally assumed that it is not feasible to complete repeat the unit testing and the integration testing efforts, due to time and budgetary constraints. If the unit and integration testing efforts can be repeated without too much toil, there is no need for a specific approach to the generation of regression test cases. The goal of regression testing is to identify a subset of both unit and integration testing that should be performed to adequately validate the change in the system or in the specification. In terms of a TASM specification and the concepts introduced so far, the regression test case generation strategy focuses on two aspects – which test cases need to be generated and/or modified to accommodate the change and which test cases need to be executed and/or repeated to validate the change. The goal of the strategy is to provide a minimal set of tasks that need to be performed to gain confidence into the correctness of the change, as opposed to repeating the entire testing activities for every single change that occurs. However, it is generally understood that the validation of the correctness of the changes could equally be achieved through repeating the unit and integration testing activities described in the previous sections, albeit at a higher cost.

The generation of regression test cases is achieved by combining the approaches for unit test case generation and for integration test case generation with the traceability approach explained in Chapter 6. The idea behind the test case generation strategy is to provide a mapping between the original specification and the modified specification, using the archetypical refinement types from Section 6.2.1. For each type of refinement, the correctness criteria explained in Section 6.2.2 are used to guide the generation of test cases. It is important to distinguish specification changes between defect correction and functionality addition. This distinction is important because defect correction purposefully alters the semantics and the goal of the change is not to preserve semantics. Consequently, the refinement would most likely be of the “any” variety. However, if the defect correction is limited to a single rule, the regression test case strategy can handle this case appropriately. For changes that span multiple facets of the model and where no refinement types can be applied, the
generation of test cases would most likely need to be started anew using the algorithm of Section 7.5. In the following subsection, each type of refinement from Section 6.2.1 is listed and its effect on generation of regression test cases is analyzed.

7.6.1 Refinement Types

The regression test case generation strategy revolves around two basic concepts – adding/removing test cases to/from a test suite and modifying existing test cases. The specific approach depends on the type of refinement. Furthermore, the regression test case generation approach propagates changes upstream and downstream through hierarchical composition. When exploring the different types of refinement, 3 cases are considered. The first case considered is the situation where the change happens in a machine that is not involved in any sort of hierarchical composition. The second case to consider is the case where the modified machine is used for hierarchical composition, in the effect expression of another machine. Finally, the third case concerns the use of hierarchical composition in the rule of the machine where the change occurs. While these three cases are not mutually exclusive, they can be studied in isolation and the results can be generalized to a situation involving more than 1 of these situations. While the traceability approach presented in Chapter 6 aimed to provide an incremental approach to specification building, the regression test case strategy can be used as an incremental approach to test case generation. In the following subsections, it is assumed that unit test suites and integration test suites exist before the change is performed and the regression test cases are generated.

Step Expansion and Rule Expansion

As a reminder, the step expansion refinement is used to divide a step into multiple steps. Furthermore, the rule expansion refinement is used to modify an existing rule by adding items to the rule guard or to the effect expression. While both types of refinements capture different purposes, the regression test case generation strategy is the same for both of these types of refinements. As explained in Section 6.2.1,
both types of refinements are one-to-many mappings where the rule of the original
machine $M_1$, $R_i$, is divided into $m$ rules of a modified machine $M'_1$, $S_j$ ($1 \leq j \leq m$). For the case where $M_1$ is not involved in hierarchical composition, the coverage
test case template that covers rule $R_i$ is removed from the test suite, and $m$ new
coverage test case templates are generated using the approach described in Section 7.3,
corresponding to the added rules in the modified machine. The rules $S_j$ of machine
$M'_1$ are used as the coverage items. The new test case templates can be added to the
test suite without any changes.

For the case where a modified rule $S_j$ uses hierarchical composition in its effect
expression, each test case template which covers rule $R_i$ is removed from the test
suite. Integration test case templates can be generated and added to the test suite
using the approach described in Section 7.4 for each respective rule $S_j$.

For the case where the machine is used in the effect expression of another machine,
$M_2$, the test suite of machine $M_2$ needs to be regenerated for the test case templates
where rule $R_i$ is in the coverage items. For each test case template containing rule
$R_i$, $m$ new coverage test case templates are generated, to cover the rule where the
hierarchical composition occurs in machine $M_2$ and the new rules $S_j$ used for the
step or rule expansion. The changes in the test suite of machine $M_2$ are then prop-
agated bottom-up, wherever a test case template covers a rule involved in the chain
of changes. The algorithm which incorporates the three concepts is summarized in
Listing 7.9.

**Rule Addition**

The test case generation strategy for the rule addition refinement is similar but slightly
different than it is for the step and rule expansion refinements. Because the rule
addition refinement introduces a new rule $S_i$ which is unrelated to any rule in machine
$M_1$, the rule cannot already be involved in existing test case templates. Consequently,
the rule addition refinement will introduce new test case templates, but does not need
to remove or modify existing test case templates. If a rule is added to a machine,
a test case template is generated for the added rule according to Listing 7.2 if the
Listing 7.9 Regression test case generation for a step or rule expansion refinement

- Generate test suite for machine $M'_1$ by duplicating the test suite for machine $M_1$

- For rule $R_i$ of machine $M_1$:
  - If rule $R_i$ does not contain hierarchical composition:
    * Remove the test case template which covers rule $R_i$
    * Generate new test case templates for each refined rule $S_j$ using the approach described in Listing 7.2
  - If rule $R_i$ contains hierarchical composition:
    * For rules $S_j$ which contain hierarchical composition, generate test case templates using the approach described in Listing 7.4
    * For rules $S_j$ which do not contain hierarchical composition, generate test case templates using the approach described in Listing 7.2
    * Add all generated test case templates to the test suite for machine $M'_1$
  - If machine $M_1$ is used for hierarchical composition in another machine $M_2$:
    * Remove test case templates in machine $M_1$ where rule $R_i$ is in the coverage item
    * For each rule $D_k$ of machine $M_2$ which uses machine $M_1$ in its effect expression:
      - add $m$ new test case templates to the test suite of machine $M_2$, using the approach described in Listing 7.4
added rule does not use hierarchical composition, and according to Listing 7.4 if the rule contains hierarchical composition. If machine $M_1$ is used by another machine through hierarchical composition, coverage of rule $S_j$ needs to be propagated upwards by adding a new test case template to each test suite associated with a machine which uses machine $M_1$ as a sub machine in one of its rule effect expressions. As is the case for the step and rule expansion refinements, when the modified machine is used for hierarchical composition the changes to the test cases need to be propagated upwards throughout the chain of hierarchical composition.

Step Contraction, Rule Contraction and Rule Deletion

For a step contraction refinement, a rule contraction refinement, and a rule deletion refinement, the regression test case generation strategy is different because rules are removed and hence test case templates must be removed. If the rules being removed do not contain hierarchical composition, the corresponding test case templates can be removed directly in the test suite of machine $M_1$ and in all other test suites where a removed rule is part of the coverage criteria. However, if a removed rule contains hierarchical composition, the situation is more complex. For the rule deletion refinement, the corresponding test case templates can be removed directly because the hierarchical composition will no longer be part of machine $M'_1$. The deletion of test case templates can be propagated upwards. A problem occurs if there are multiple levels of hierarchical composition involving machine $M_1$, where the rule is removed. If multiple levels are present, removing the rule and the associated test case template upwards could cause the coverage test suite of a given machine to be incomplete. If this case occurs, the template test suite for the faulty machine can be generated anew, using the algorithm described in Listing 7.4. Furthermore, the test suites of all affected machines should also be regenerated fresh, using the same algorithm.
The Any Refinement

Since the "any" refinement is a type of refinement used for refinements that do not fit the listed types, the mapping is defined as a many-to-many mapping. Because there is no clear structure for the "any" refinement, regression testing strategies cannot be devised. If the arity of the refinement is analogous to the arity of the refinements mentioned previously, the strategies previously expressed could be used. However, if the arity of the refinement does not match the cases mentioned previously, the test case generation must start anew, using the algorithm described in Listing 7.8, invalidating all machine test suites affected by the "any" refinement.

7.6.2 Test Case Execution

The primary purpose of the regression testing strategy is to modify existing test suites to accommodate the changes introduced in the specification. In what has been discussed so far, the goal of the approach is to minimize the amount of test case generation that needs to be performed, if unit and integration test suites already exist. However, another important facet of regression testing is identifying which test cases need to be executed to fully exercise the changes introduced in the specification. Given the structure of the test case generation strategy expressed in Section 7.3 and in Section 7.4, the test suite associated with each machine contains coverage criteria for each test case template by listing covered rules. Determining which test cases need to be executed to exercise the change is fairly straightforward because the influenced rules can be easily identified through the coverage criteria. Consequently, by using the traceability approach from Chapter 6, and the regression test case generation strategy described in the previous section, the test cases that need to be executed can be easily identified.

7.6.3 Complexity Analysis

The worst-case scenario for the generation of regression test cases occurs when all the test suites of all the machines need to be regenerated, leading to the complexity of
the complete test case generation algorithm described in Listing 7.8. The complexity of that algorithm builds on the complexity of the unit test case generation algorithm and on the complexity of the integration test case generation.

For test case generation where only a subset of the test suite needs to be regenerated, the complexity of the test case generation will depend on the number of affected rules and of affected test case templates. In turn the number of affected test case templates will depend on the hierarchical composition properties of the TASM specification. In the worst case for hierarchical composition, the affected number of test cases will vary linearly with the number of machines in the specification and the number of modified/added rules in the changes made to the specification.

7.6.4 Example

The example from Section 7.4.3 is modified to demonstrate the test case generation strategy for regression testing. The machine shown in Listing 7.6 is refined through a step expansion refinement into two rules. The resulting machine is shown in Listing 7.10. In Listing 7.10, rule $P_3$ from Listing 7.6 is refined into two rules, rule $D_3$ and rule $D_4$. The traceability relationship for the refinement can be expressed as:

$$T = T_{sexp} \cup T_{id} = (\{P_3\}, \{D_3, D_4\}) \cup (\{P_4\}, \{P_4\})$$

$$= (\{P_3\}, \{D_3, D_4\}, \{P_4\}, \{P_4\})$$

For all other rules of all other machines in the example, the traceability is achieved through identity refinements.

Given the approach described in Section 7.6.1 for the step expansion refinement, only the test cases involving the $P_3$ rule as a coverage item need to be regenerated and executed. The test suite of machine $SEQUENCE.HUMIDITY.MONITOR.WORK$, shown in Table 7.3, and the test suite of the machine $SEQUENCE.TEMP.MONITOR.WORK$, shown in Table 7.4 do not need to be modified. For the $EXECUTE.PLANTSIM.SEQUENCES$, only the last row of the test suite shown in Table 7.5,
Listing 7.10 Rules of the refined EXECUTE.PLANTSIM SEQUENCES sub machine

D3: Execute sequences
{
    if exec_seq = not_done and seq = humid then
        SEQUENCE_HUMIDITY_MONITOR_WORK();
        seq := temp;
}

D4: Execute sequences
{
    if exec_seq = not_done and seq = temp then
        SEQUENCE_TEMP_MONITOR_WORK();
        exec_seq := done;
        seq := humid;
}

P4: Bundle finished
{
    if exec_seq = done then
        plantsim_s := done;
        exec_seq := not_done;
}
Table 7.7: Test suite template for the machine of Listing 7.10

<table>
<thead>
<tr>
<th>Pre State</th>
<th>Post State</th>
<th>Coverage Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>exec.seq(not done), seq(humid), humid_seq.b(c4), humidity = {(39,100)}</td>
<td>humid_seq.b(c6), humid_seq.s(done), seq(temp)</td>
<td>$D_3, S_9$</td>
</tr>
<tr>
<td>exec.seq(not done), seq(humid), humid_seq.b(c5), humidity = {(0,50)}</td>
<td>humid_seq.b(c5), humid_seq.s(done), seq(temp)</td>
<td>$D_3, S_{10}$</td>
</tr>
<tr>
<td>exec.seq(not done), seq(humid), humid_seq.b(c5), humidity = {(50,100)}</td>
<td>humid_seq.b(c6), humid_seq.s(done), seq(temp), humidifier{off}</td>
<td>$D_3, S_{11}$</td>
</tr>
<tr>
<td>exec.seq(not done), seq(temp), temp_seq.b(b3), temperature = {[-10,19]}</td>
<td>exec.seq(done), temp_seq.b(b4), heating(on), temperature{[6,35]}, seq(humid)</td>
<td>$D_4, R_7$</td>
</tr>
<tr>
<td>exec.seq(not done), seq(temp), temp_seq.b(b4), temperature = {[-10,22]}</td>
<td>exec.seq(done), temp_seq.b(b4), seq(humid)</td>
<td>$D_4, R_8$</td>
</tr>
<tr>
<td>exec.seq(not done), seq(temp), temp_seq.b(b4), temperature = {[22,40]}</td>
<td>exec.seq(done), temp_seq.b(b0), heating(on), seq(humid)</td>
<td>$D_4, R_9$</td>
</tr>
<tr>
<td>exec.seq(done)</td>
<td>exec.seq(not done), plant_sim.s(done), P_4</td>
<td></td>
</tr>
</tbody>
</table>

the test case template which covers rule $P_4$, does not need to be regenerated. The test case templates to cover the refined rules, rule $D_3$ and rule $D_4$, are regenerated using the algorithm given in Listing 7.4. The resulting test suite is given in Table 7.7. It is important to note that the EXECUTE_PLANTSIM_SEQUENCES machine is used as a sub machine in a rule effect expression of machine PLANTSIM_BUNDLE, in rule $V_1$, as shown in Listing 7.7. Consequently, the changes in the test suite for the EXECUTE_PLANTSIM_SEQUENCES need to be propagated in the test suite of the PLANTSIM_BUNDLE machine. The resulting test suite for the PLANTSIM_BUNDLE machine is shown in Table 7.8.
<table>
<thead>
<tr>
<th>Pre State</th>
<th>Post State</th>
<th>Coverage Item</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>exec_seq{not done}</code>, <code>seq{humid}</code>, <code>humid_seq.b{c4}</code>, <code>humidity = {(39, 100)}</code>, <code>plantsim.bundle_status{active}</code></td>
<td><code>humid_seq.b{c0}</code>, <code>humid_seq.s{done}</code>, <code>seq{temp}</code></td>
<td>$V_1, D_3, S_9$</td>
</tr>
<tr>
<td><code>exec_seq{not done}</code>, <code>seq{humid}</code>, <code>humid_seq.b{c5}</code>, <code>humidity = {[0, 50]}</code>, <code>plantsim.bundle_status{active}</code></td>
<td><code>humid_seq.b{c5}</code>, <code>humid_seq.s{done}</code>, <code>seq{temp}</code></td>
<td>$V_1, D_3, S_{10}$</td>
</tr>
<tr>
<td><code>exec_seq{not done}</code>, <code>seq{humid}</code>, <code>humid_seq.b{c5}</code>, <code>humidity = {[50, 100]}</code>, <code>plantsim.bundle_status{active}</code></td>
<td><code>humid_seq.b{c0}</code>, <code>humid_seq.s{done}</code>, <code>seq{temp}</code>, <code>humidifier{off}</code></td>
<td>$V_1, D_3, S_{11}$</td>
</tr>
<tr>
<td><code>exec_seq{not done}</code>, <code>seq{temp}</code>, <code>temp_seq.b{b3}</code>, <code>temperature = {[-10, 19]}</code>, <code>plantsim.bundle_status{active}</code></td>
<td><code>exec_seq{done}</code>, <code>temp_seq.b{b4}</code>, <code>heating{on}</code>, <code>temperature{[6, 35]}</code>, <code>seq{humid}</code></td>
<td>$V_1, D_4, R_7$</td>
</tr>
<tr>
<td><code>exec_seq{not done}</code>, <code>seq{temp}</code>, <code>temp_seq.b{b4}</code>, <code>temperature = {[-10, 22]}</code>, <code>plantsim.bundle_status{active}</code></td>
<td><code>exec_seq{done}</code>, <code>temp_seq.b{b4}</code>, <code>seq{humid}</code></td>
<td>$V_1, D_4, R_8$</td>
</tr>
<tr>
<td><code>exec_seq{not done}</code>, <code>seq{temp}</code>, <code>temp_seq.b{b4}</code>, <code>temperature = {[22, 40]}</code>, <code>plantsim.bundle_status{active}</code></td>
<td><code>exec_seq{done}</code>, <code>temp_seq.b{b0}</code>, <code>heating{off}</code>, <code>seq{humid}</code></td>
<td>$V_1, D_4, R_9$</td>
</tr>
<tr>
<td><code>exec_seq{done}</code>, <code>plantsim.bundle_status{active}</code></td>
<td><code>exec_seq{not done}</code>, <code>plantsim.s{done}</code></td>
<td>$V_1, P_4$</td>
</tr>
<tr>
<td><code>plantsim.bundle_status{inactive}</code></td>
<td><code>plantsim.s{done}</code></td>
<td>$V_2$</td>
</tr>
</tbody>
</table>

Table 7.8: Test suite template for the machine of Listing 7.7
Table 7.9: List of test cases that need to be executed to cover the refinement

<table>
<thead>
<tr>
<th>Machine</th>
<th>Test Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXECUTE.PLANTSIM.SEQUENCES</td>
<td>$D_3, S_9$</td>
</tr>
<tr>
<td></td>
<td>$D_4, R_7$</td>
</tr>
<tr>
<td>PLANTSIM.BUNDLE</td>
<td>$V_1, D_3, S_{10}$</td>
</tr>
<tr>
<td></td>
<td>$V_1, D_4, R_9$</td>
</tr>
</tbody>
</table>

Test Case Execution

Based on the generation of regression test cases, only a subset of the test case templates need to be executed to validate the correctness of the change. The set of test cases which need to be executed are shown in Table 7.9, for each machine affected by the change. Because there was no change to the $S_i$ rules and to the $R_i$ rules, only rule $D_3$ and rule $D_4$ need to be exercised in machine EXECUTE.PLANTSIM.SEQUENCES. A test case template to cover each rule was selected arbitrarily from Table 7.7. A similar approach is used for machine PLANTSIM.BUNDLE, where only 2 test case templates need to be executed to validate the effect of the change.

7.7 Segue into Chapter 8

This chapter presented an approach to automatically generate test cases based on a specification expressed in the TASM language. More specifically, facilities were presented to automatically generate unit test cases, integration test cases, and regression test cases. The test case generation capabilities represent the final feature of the proposed framework. In the next chapter, Chapter 8, experimentation using the presented framework is performed using three case studies.
Chapter 8

Case Studies

This chapter presents the results of the three case studies that are used to evaluate the capabilities of the presented framework. The applications used for the case studies are explained in details in Section 2.8. In this chapter, each case study is presented in a separate section and each section presents the TASM specification of the case study, the functional analysis results, the execution time analysis results, the resource consumption analysis results, and the test case generation results. In addition, the Electronic Throttle Controller (ETC) case study, analyzed in Section 8.2, in Section 8.3, and in Section 8.4, utilizes the bi-directional traceability strategy by relating three separate models of the ETC – a high level model, and tasking model, and a low level model. The ETC case study is also used to demonstrate the test case generation approach for regression testing. The other case studies are used to demonstrate the unit and integration test case generation capabilities of the framework.

For each case study, the TASM model is described in each respective section, but only a subset of the model listings are provided. The complete TASM models for each case study are provided in the appendices. The model for the production cell case study is provided in Appendix D, the model for the ETC case study is provided in Appendix E, and the model for the Timeliner case study is provided in Appendix F. Furthermore, for each case study, the UPPAAL model obtained through the translations is described, but the resulting complete UPPAAL model is not included, for brevity. Each case study is followed by a brief discussion of the results and a commentary.
on the practical usefulness of the framework features. The overall evaluation of the framework, in light of the results of the case studies, is presented in Chapter 9. Chapter 9 also recapitulates the contributions of the thesis in light of the research objectives presented in Chapter 1.

8.1 Production Cell

The production cell case study is an automated manufacturing system which is based on an industrial plant in Karlsruhe in Germany [163]. The case study is described in details in Section 2.8.1. As a reminder, the logical view of the production cell is provided in Figure 8-1 and contains 5 hardware components to achieve the system's goals – a loader, a feed belt, a robot, a press, and a deposit belt. The embedded controller must command each component to stamp blocks, which are introduced in the system by the loader. The controller reads the state of the system through a set of sensors, listed in Table 2.4 and commands the various hardware components through a set of actuators, listed in Table 2.2.

![Figure 8-1: Top view of the production cell](image)

8.1.1 Model

The TASM model of the production cell is described in great detail for this case study, because it is the first case study presented. The models pertaining to the other
Table 8.1: List of main machines used in the production cell model

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller</td>
<td>Main</td>
<td>Commands the actuators</td>
</tr>
<tr>
<td>Loader</td>
<td>Main</td>
<td>Loads blocks onto the feed belt</td>
</tr>
<tr>
<td>Feed</td>
<td>Main</td>
<td>Carries blocks from the loader to the robot</td>
</tr>
<tr>
<td>Robot</td>
<td>Main</td>
<td>Simulates the rotation of the robot</td>
</tr>
<tr>
<td>ArmA</td>
<td>Main</td>
<td>Simulates arm a</td>
</tr>
<tr>
<td>ArmB</td>
<td>Main</td>
<td>Simulates arm b</td>
</tr>
<tr>
<td>Press</td>
<td>Main</td>
<td>Stamps blocks</td>
</tr>
<tr>
<td>Deposit</td>
<td>Main</td>
<td>Carries blocks out of the system</td>
</tr>
</tbody>
</table>

case studies are described in less details. In the production cell TASM model, each component of the production cell is modeled as a main machine, except for the robot. As a reminder, in the TASM language, a main machine is a unit of concurrency. The robot component is modeled as three separate main machines to capture the parallel behavior of the motion base, arm a, and arm b, all of which can be commanded independently. Sub machines and function machines are used, mostly to structure the actions of the controller. The complete list of main machines is shown in Table 8.1. In the following sub sections, as each main machine is explained, the sub machines and function machines that are used in the model are given. The complete list of all machines used in the production cell case study model, is available in Table D.1 in Appendix D.

The Environment

As a reminder, in a TASM model, the environment contains the list of user-defined types, the list of global variables, and the list of resources used in the model. The list of user-defined types used in the production cell model is given in Listing 8.1. The status type is used to keep track of whether various parts of the system (e.g., the belts, the arms, and the press) are loaded or empty. The armposition type is used to represent the position of the arms with respect to the robot angle, in discrete steps. For example, if arm a is at the feed or at the press, the controller takes certain actions. If arm a is neither at the feed nor at the press, the arm is in transit. This "discretization" is used because if an arm is not at the press, at the deposit belt, or
at the feed belt, it makes no difference to the controller whether the robot angle is 31, 32, or 33 degrees. The discrete positions of the arms were obtained through the specification of the desired behavior of the controller in the problem definition [163].

The models for the arms use a slightly different approach than the rotation of the robot base. Instead of relating a continuous length to a set of discrete values, two discrete values of interest are used via the armextension type - retracted and extended. The Actuator type is used to indicate whether a motor or a magnet is on or off. The Polarity type is used to set the polarity of the various motors. The Stamp data type is used to set the block status in the press. Finally, the Error type is used to catch certain types of errors when performing safety analysis of the controller.

The use of the Error type and the topic of functional analysis and verification are treated in Section 8.1.2.

Listing 8.1 User-defined types of the production cell model

<table>
<thead>
<tr>
<th>Type</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>status</td>
<td>{empty, loaded}</td>
</tr>
<tr>
<td>armposition</td>
<td>{atfeed, atpress, atdeposit, intransit}</td>
</tr>
<tr>
<td>armextension</td>
<td>{retracted, extended}</td>
</tr>
<tr>
<td>Actuator</td>
<td>{on, off}</td>
</tr>
<tr>
<td>Polarity</td>
<td>{positive, negative}</td>
</tr>
<tr>
<td>Stamp</td>
<td>{notfinished, finished}</td>
</tr>
<tr>
<td>Error</td>
<td>{none, invaliddrop, invalidpickup}</td>
</tr>
</tbody>
</table>

The user-defined types of the model are used to restrict the set of values that the variables of the system can take. A subset of the variables that are used in the model, with their associated initial conditions, are shown in Listing 8.2. The complete list of variables is given in Listing D.2 and in Listing D.3 in Appendix D. The variables are grouped into sensors, which correspond to the sensors of Table 2.4, actuators, which correspond to the actuators of Table 2.2 and Table 2.3, constants, and redundant information. The redundant information is used to keep track of the system’s state, inside the software, as the controller performs actions. For example, the feed belt is loaded once the loader puts a block on it and stays loaded until the robot picks up the block. The loaded_blocks and the processed_blocks variables are used to keep track of how many blocks have been inserted in the system and how many blocks have exited the system. The wait variable and the robot_wait variable are used to...
synchronize the controller and the robot rotation. Essentially, they are used to enforce fairness [30], to make sure that the system's state can progress and that the robot can process a command from the controller. More specifically, since the controller actions are instantaneous, the wait variable is used to enable the environment to make progress between controller actions. Without this constraint, the controller could perform an infinite number of actions before other components get a chance to perform a single action, leading to so-called Zeno runs [30].

The convention of the robot_angle variable is that it is 0 when arm a is at the feed and arm b is at the press, as in Figure 8-1. As the robot rotates counter clockwise, the angle increases by 30 degrees. When the value of the robot_angle variable is 90, arm a is at the press and arm b is at the deposit. For the controller strategy used in this model, the value of the robot_angle variable will remain between 0 degrees and 90 degrees inclusively. The model also contains one resource, power, which gets consumed when the hardware components are operating.

Throughout the model, as a convention, capital letters are used to describe constants and sub machine calls. The ROTATION_ANGLE constant is used as the discrete angle by which the robot is rotated when the motor_robot actuator is on. The value "30" was selected as the delta of rotation because it fits the problem description of the durative actions listed in Table 2.5.

In the following subsections, the main components, modeled as main machines, are described one by one. The description of the ArmB main machine and of the Deposit main machine are omitted because they are similar to the ArmA main machine and to the Feed main machine, respectively. The complete TASM model for the production cell case study is available in Appendix D.

**Loader**

The loader is the component that drives the system by putting blocks on the feed belt. The rules of the Loader main machine are shown in Listing 8.3. In the listing, the variable number is an integer variable that is internal to the Loader machine. This variable is used in the constructor to determine how many blocks the loader will
Listing 8.2 Variables of the production cell model (partial)

//sensors
Integer[0, 90] robot_angle := 0;
Stamp press_block := notfinished;
Boolean feed_begin := False;
armextension armaext := retracted;
armextension armbext := retracted;
Boolean feed_end := False;
Boolean deposit_begin := False;
Boolean deposit_end := False;

//redundant info, derivable from sensors
armposition armapos := atfeed;
armposition armbpos := atpress;
status arma := empty;
status armb := empty;
status feed_belt := empty;
status deposit_belt := empty;
status press := empty;

//other variables
Boolean wait := False;
Boolean robot_wait := False;
Integer[0, 50] loaded_blocks := 0;
Integer[0, 50] processed_blocks := 0;
Boolean loader_done := False;
Error error := none;
armposition robot_destination := atfeed;

//actuators
Actuator motor_press := off;
Actuator motor_arma := off;
Actuator motor_armb := off;
Actuator magnet_arma := off;
Actuator magnet_armb := off;
Actuator motor_robot := off;
Actuator motor_feed := off;
Actuator motor_deposit := off;

Polarity motor_press_p := positive;
Polarity motor_arma_p := positive;
Polarity motor_armb_p := positive;
Polarity motor_robot_p := positive;
Polarity motor_feed_p := positive;
Polarity motor_deposit_p := negative;
The first rule, rule $R_1$, loads blocks on the feed belt as soon as the feed belt is empty. Per the properties of the actions listed in Table 2.5, loading a block on the belt takes 2 time units and consumes 200 units of power. Once the action is complete, the feed belt is loaded and the $feed\_begin$ sensor is set to true, to notify the controller that there is a block on the feed belt.

**Listing 8.3 Rules of the Loader main machine**

**R1:** The feed belt is empty, put a block on it

```plaintext
{ 
  t := 2;
  power := 200;
  if loaded_blocks < number - 1 and feed_belt = empty then 
    feed_belt := loaded;
    loaded_blocks := loaded_blocks + 1;
    feed_begin := True;
}
```

**R2:** This is the last block...

```plaintext
{ 
  t := 2;
  power := 200;
  if loaded_blocks = number - 1 and feed_belt = empty then 
    feed_belt := loaded;
    loaded_blocks := loaded_blocks + 1;
    feed_begin := True;
    loader_done := True;
}
```

**R3:** The feed belt is loaded, do nothing

```plaintext
{ 
  t := next;
  if feed_belt = loaded and loaded_blocks < number then 
    skip;
}
```

Rule $R_2$ is used to put the last block on the feed belt and to notify the controller that the loader will no longer put blocks on the feed belt, through the $loader\_done$ variable. The last rule, rule $R_3$, is used to wait and elapse time until the next state change. The "t := next" construct is used to keep the machine alive until a change to monitored variables occurs. Once all blocks have been loaded in the system, no rule will be enabled for the Loader machine and the machine will stop, per the semantics.
of the TASM language described in Section 4.3.

Feed Belt

The Feed main machine is a simple machine that contains only two rules. The rules of the machine are shown in Listing 8.4. Rule $R_1$ is the only rule that changes the state. The rule is enabled when there is a block on the belt, that block is at the beginning of the belt, the motor is on, and the polarity of the motor is positive. When this condition is met, the rule will take 5 time units to complete and will consume 500 units of power, per the description in Table 2.5. The effect of executing this rule will be such that the block will move from the beginning of the feed belt to the end, and the appropriate state change is reflected in the sensors $feed\_begin$ and $feed\_end$ by setting the appropriate variables.

**Listing 8.4 Rules of the Feed main machine**

R1: Block goes to end of belt

\[
\begin{align*}
\{ & t := 5; \\
& \text{power} := 500; \\
& \text{if} \ feed\_belt = \text{loaded} \text{ and } \text{feed\_begin} = \text{True} \text{ and} \\
& \quad \text{motor\_feed} = \text{on} \text{ and } \text{motor\_feed\_p} = \text{positive} \text{ then} \\
& \quad \text{feed\_begin} := \text{False}; \\
& \quad \text{feed\_end} := \text{True}; \\
\}
\]

R2: Else

\[
\begin{align*}
\{ & t := \text{next}; \\
& \text{else then} \\
& \quad \text{skip}; \\
\}
\]

Rule $R_2$ will be enabled and fired whenever rule $R_1$ is not enabled. Rule $R_2$ has no effect on the environment and is used solely to keep the machine running. Once again, the “$t := \text{next}$” construct is used to indicate that the machine will not perform any steps until a change to its monitored variables occurs.
Press

The Press main machine is similar to the Feed main machine. It simply reacts to the motor being on and causes the state change to take place once the stamping of the block is completed. The rules of the machine are shown in Listing 8.5.

Listing 8.5 Rules of the Press main machine

R1: Press is loaded, motor is on
{  t := 11;
   power := 1500;

   if motor_press = on and press = loaded and press_block = notfinished then
      press_block := finished;
}

R2: Else
{  t := next;

   else then
      skip;
}

The Deposit main machine is also similar to the Feed main machine shown in Listing 8.4. It is interesting to note that the three components described so far update the state only through the sensors and react to state changes only through the information available through actuator values. The Loader main machine is a bit different than the other machines explained so far because it is used to drive the system and is an active component, in contrast to the feed, press, and deposit which are purely reactive components.

Robot

The Robot main machine is used to describe the rotation of the base of the robot. The machine, whose rules are shown in Listing 8.6, uses the robot.wait variable to give a chance for the controller to stop the motor before rotation resumes. This behavior could also have been enforced by the use of a communication channel. The Robot main machine differs from other machines described so far because it uses
a sub machine called ROBOT\_MOTION. As a refresher, a sub machine is a unit of hierarchical composition. The behavior of the main machine is defined in terms of the sub machine by merging the update set yielded by the sub machine with update sets yielded by other sub machines, if applicable and with other updates to variables included in the rule effect expression. For rule R1, the updates to variables yielded by the ROBOT\_MOTION sub machine will be merged with the update to the robot\_wait variable. Since rule R1 does not have a time or resource annotation, the duration and resource consumption of the rule execution are defined by the sub machine annotations, if they are present. In the case of the ROBOT\_MOTION sub machine, the machine contains time and resource annotations, which will be used to determine the time and resource behavior of the Robot main machine.

**Listing 8.6** Rules of the Robot main machine

```haskell
R1: do
   { if robot\_wait = False then
     ROBOT\_MOTION();
     robot\_wait := True;
   }

R2: wait
   { t := next;

   if robot\_wait = True then
     robot\_wait := False;
   }
```

The use of a sub machine can be viewed as a nested if statement. Sub machines are nothing more than syntactic sugar to help structure specifications, as explained in Theorem 4.2. The rules of sub machine ROBOT\_MOTION are shown in Listing 8.7.

In Listing 8.7, rules R1 and R2 are used to rotate the robot clockwise and counter clockwise depending on the polarity of the motor. Rule R1 of the sub machine uses two function machines, rotate\_Clockwise and arm\_Position. In the TASM language, function machines are macros that are analogous to functions in programming languages. Function machines have no side-effect in that they do not change environment variables. The rotate\_Clockwise function is used to return the resulting angle of doing
Listing 8.7 Rules of the ROBOT MOTION sub machine

R1: rotate clockwise
{
  t       := 2;
  power   := 1000;

  if motor_robot = on and motor_robot_p = negative then
    robot_angle := rotateClockwise();
    armapos := armPosition(ARM_A_FEED_ANGLE, ARM_A_DEPOSIT_ANGLE,
                          ARM_APRESS_ANGLE, rotateClockwise());
    armbpos := armPosition(ARM_B_FEED_ANGLE, ARM_B_DEPOSIT_ANGLE,
                           ARM_BPRESS_ANGLE, rotateClockwise());

  }

R2: rotate counterclockwise
{
  t       := 2;
  power   := 1000;

  if motor_robot = on and motor_robot_p = positive then
    robot_angle := rotateCounterClockwise();
    armapos := armPosition(ARM_A_FEED_ANGLE, ARM_A_DEPOSIT_ANGLE,
                          ARM_APRESS_ANGLE, rotateCounterClockwise());
    armbpos := armPosition(ARM_B_FEED_ANGLE, ARM_B_DEPOSIT_ANGLE,
                           ARM_BPRESS_ANGLE, rotateCounterClockwise());

  }

R3: Else
{ 
  else then
    skip;
}
one rotation step. The function machine also ensures that the angle doesn’t go below 0 or over 360. Essentially, it returns \((\text{robot\_angle} + \text{ROTATION\_ANGLE}) \mod 360\). The \textit{armPosition} function machine is used to set the position of each arm based on the resulting robot angle. Since the \text{robot\_angle} will not be updated until after the rule has been completed, the \textit{armPosition} function machine needs to anticipate what the robot angle will be, which explains the call to the \textit{rotateClockwise} function machine as a parameter. The rules of the function machine \textit{armPosition} are shown in Listing 8.8. The durations and power consumptions used for the robot rotation, in rules \text{R1} and \text{R2}, are in accordance with the problem definition given in Table 2.5. For the \textit{armPosition} function machine, the new robot angle is passed in through the \textit{value} parameter. The other parameters include \textit{feed\_angle}, \textit{deposit\_angle}, and \textit{press\_angle}. These values are used to determine whether the rotation will result in a given arm being at the feed, at the press, at the deposit, or in transit.

**Listing 8.8 Rules of the \textit{armPosition} function machine**

\text{R1: CCW rotation will put arm at feed}
\{
    if value = \text{feed\_angle} then
        out := \text{atfeed};
    
}\n
\text{R2: CCW rotation will put arm at deposit}
\{
    if value = \text{deposit\_angle} then
        out := \text{atdeposit};
    
}\n
\text{R3: CCW rotation will put arm at press}
\{
    if value = \text{press\_angle} then
        out := \text{atpress};
    
}\n
\text{R4: Else, CCW rotation will put arm in transit}
\{
    else then
        out := \text{intransit};
    
\}
Arm A

The ArmA main machine is used to simulate the behavior of arm a. The action that arm a can perform include extending, retracting, picking up a block, dropping a block. The main machine uses two sub machines, DROP_ARM_A and PICK_UP_ARM_A.

**Listing 8.9 Rules of the ArmA main machine**

R1: Extend arm
{
  \( t := 3; \)
  power := 1200;

  if motor arma = on and motor arma_p = positive and
  armaext = retracted then
    armaext := extended;
}

R2: Retract arm
{
  \( t := 2; \)
  power := 1100;

  if motor arma = on and motor arma_p = negative and
  armaext = extended then
    armaext := retracted;
}

R3: Pick up block
{
  if magnet arma = on and arma = empty and
  armapos = atfeed and feed_end = True then
    PICK_UP_ARM_A();
}

R4: Drop block
{
  if magnet arma = off and arma = loaded then
    DROP_ARM_A();
}

R5: Else
{
  \( t := \text{next}; \)

  else then
    skip;
}

The rules of the DROP_ARM_A sub machine are shown in Listing 8.10. The sub
machine is interesting because it uses the error variable to communicate an erroneous state. More specifically, the sub machine will set the error variable to invaliddrop if the controller commands the arm to drop a block and the arm is not extended, if the controller commands the arm to load the press and the press is already loaded, or if the controller commands the arm to drop a block while the arm is in transit. The controller should not command the magnet to drop a block under these conditions. Using the variable is not necessary to detect that an erroneous state is reachable, but it illustrates the clever use of rules. The safety requirements to ensure that blocks are not dropped under undesirable conditions could be phrased using the value of the variable, such as “the value of the error variable is never equal to invaliddrop”.

Listing 8.10 Rules of the DROP_ARM_A sub machine

R1: Drop at press
{
    t := 2;
    power := 800;

    if armapos = atpress and arma = loaded and
        armaext = extended and press = empty then
        arma := empty;
        press := loaded;
        press_block := notfinished;
}

R2: Invalid drop
{
    if armapos != atpress or arma = empty or
        press = loaded or armaext != extended then
        error := invaliddrop;
}

As a reminder, rule R4 of Listing 8.9 does not contain time or resource consumption annotations. Consequently, the duration and resource consumption of the rule execution will come from the DROP_ARM_A sub machine, since that machine contains time and resource annotations.

Controller

The Controller main machine is the most complex machine of the model. In a fashion similar to the Robot main machine, the Controller machine uses a variable called
wait to enable the environment to make progress before performing an action. For the controller, this waiting is necessary because all the actions of the controller are instantaneous and the environment must be given a chance to make progress. Otherwise, the controller could perform an infinite number of steps before an environment change happens. In real-time system terms, the Controller main machine can be viewed as a sporadic task which gets released whenever a sensor value changes. The rules of the Controller main machine, shown in Listing 8.11, make heavy use of sub machines. The semantics of sub machines and hierarchical composition are such that all sub machines operate in parallel and the resulting update sets of each machine are composed with one another. The commanding of all of the actuators are performed independently, in parallel.

**Listing 8.11 Rules of the Controller main machine**

R1: Issue Commands

```java
if wait = False then
    OPERATE_FEED();
    OPERATE_DEPOSIT();
    OPERATE_ROBOT();
    OPERATE_ARM_A();
    OPERATE_ARM_B();
    OPERATE_PRESS();
    wait := True;
```

R2: Wait for a step

```java
else then
    wait := False;
```

The rules of the OPERATE_DEPOSIT sub machine are shown in Listing 8.12. The listing shows how the controller uses only sensor values to interpret the state of the system, and uses only the actuators to command the various components of the system. Listings for other sub machines of the "OPERATE_ABC" nature are similar and are given in Appendix D.
Listing 8.12 Rules of the *OPERATE* *DEPOSIT* sub machine

R1: turn on motor
{ 
  if motor_deposit = off and deposit_begin = True then 
    motor_deposit_p := negative; 
    motor_deposit := on; 
}

R2: turn off motor
{ 
  if motor_deposit = on and deposit_end = True then 
    motor_deposit := off; 
}

R3: nothing to do
{ 
  else then 
    skip; 
}

Complete Model

The complete production cell TASM model contains 8 main machines, one for each component shown in Figure 8-1, and one for the controller. The model also contains 3 function machines, and 16 sub machines. The complete production cell model is documented in Appendix D where the list of all machines is given in Table D.1.

8.1.2 Functional Analysis

The purpose of the production cell case study, as outlined in [163], is to evaluate and compare different formal methods. Part of the problem definition is to understand how different approaches model and prove properties of the production cell case study. Some of the properties that should be proved include restrictions on the commands that the controller sends out to the hardware components. For example, the controller shall not command the robot to drop blocks in places other than the press and the deposit belt. Furthermore, the robot should never be rotated when the arms are extended. In order to verify these properties in the TASM model, model checking presents a natural fit since the model is finite and the safety properties can be easily formulated as temporal logic properties over the variable values of the model.
Safety and Liveness Properties

For this case study, three safety properties are verified using a model checking approach. The safety properties are verified using two different strategies. The first strategy uses a simple safety invariant property over the variable values of the model, to express that "a certain state shall never be reached". Two safety properties are verified using this strategy. The first safety property states that "the robot shall not rotate while an arm is extended". The second property states that "arm a shall only be extended at the press and at the feed belt". The temporal logic formulas corresponding to the two properties are shown below:

- \[ A \neg (\text{motor_robot} = \text{on}) \rightarrow (\text{arma} = \text{retracted} \land \text{armb} = \text{retracted}) \]

- \[ A \neg (\text{arma} = \text{extended}) \rightarrow (\text{armapos} = \text{atpress} \lor \text{armapos} = \text{atfeed}) \]

The first temporal logic formula states that it is always true in the model that whenever the robot motor is on, the arms are retracted. The second temporal logic formula states that it is always true in the model that whenever arm a is extended, arm a is at the press or arm a is at the feed. The second strategy to verify safety properties involves embedded error values inside of the model, in a manner analogous to assertions in programming languages [132]. In the TASM model, the user-defined type \text{Error} in Listing 8.1 is used to create errors that can be embedded in the model. For example, in Listing 8.10, the \text{error} variable is set to \text{invaliddrop} if the controller tries to drop a block from arm a at a place other than the press. Similar rules were added to the \text{DROP ARM B}, \text{PICK UP ARM A}, and \text{PICK UP ARM B} sub machines. The first safety property wraps a set of safety assertions, including "the robot shall not drop blocks in places other than the press and the deposit belt", "the robot shall not drop a block in the press if the press is already loaded", and "the robot shall not drop a block if the arm is not extended". The second safety property also wraps a set of safety assertions similar to the first safety property, but concerns
the picking up of blocks. The included properties in the assertion include "the robot shall not pick up blocks in places other than the press and the feed belt". These two properties can be easily stated using the error variable and expressing the assertion as a simple safety invariant on the values of the variable:

- $A \ Diamond G \text{error} \neq \text{invaliddrop}$

- $A \ Diamond G \text{error} \neq \text{invalidpickup}$

The temporal logic formulas state that the error variable is never set to invaliddrop and is never set to invalidpickup. The assertions could be formulated in other ways, and other assertions could also be added to verify all of the properties specified in [163]. However, for the sake of the case study, these four properties are sufficient to demonstrate the functional verification capabilities of the framework using modeling and model checking.

Because the TASM model of the production cell is finite, it can lend itself quite naturally to the model checking capabilities of the presented framework, using the Uppaal tool suite. Furthermore, the safety properties that have been expressed as temporal logic formulas can be easily translated to the query language of the Uppaal model checker.

**Uppaal Model**

In order to model check the TASM model for safety assertions, the production cell TASM model leverages the Uppaal model checker, using the translation approach documented in Appendix C. The Uppaal model is generated only once and is also used to analyze execution time of the production cell system in Section 8.1.3. Because the timed automata used in Uppaal do not have hierarchical composition facilities, the TASM main machines need to be "flattened" per the approach described in the proof of Theorem 4.1 and in the proof of Theorem 4.2. The removal of hierarchical
composition can lead to exponential growth in the number of states in the “flattened”
machine when multiple units of hierarchical composition are used in the same rule.
For all machines in the production cell TASM model, except for the Controller main
machine, the flattening of the machines is tractable because the machines make lim-
ited use of hierarchical composition. However, the Controller main machine makes
heavy use of hierarchical composition within its main rule, and a basic flattening of
the main machine yields over one million rules \( (3 \times 3 \times 3 \times 2 \times 8 \times 3 \times 6 \times 7 \times 3 \times
6 \times 6 + 1 = 1,765,969) \). Clearly, this approach is not feasible to generate the UPPAAL
model. This explosive growth occurs because rule \( R_1 \) of machine Controller uses 6 sub
machines, which, in turn, make use of other sub machines. One way to mitigate the
exponential growth is to operate each component in sequence, instead of in parallel.
The sequential operation can be achieved by using an extra variable, which orders the
operations in sequence. In order to maintain the semantics of the original model, the
values of the sensors and actuators are “cached”, through “dummy variables”, at the
beginning of the operation phase and the outputs are “buffered”, also through tem-
porary variables, until the end of the operation phase. The Controller main machine
is modified to use the cached variables in its decisions and to output to the buffered
variables. The modified Controller main machine is shown in Listing 8.13. The mod-
ified main machine contains 9 rules and the “flattened” version of the machine in
Listing 8.13 contains 48 rules – 1 rule to flatten rule \( R_1 \), 3 rules to flatten rule \( R_2 \),
3 rules to flatten rule \( R_3 \), 10 rules to flatten rule \( R_4 \), 13 rules to flatten rule \( R_5 \), 13
rules to flatten rule \( R_6 \), 3 rules to flatten rule \( R_7 \), 1 rule to flatten rule \( R_8 \), and 1 rule
for rule \( R_9 \). Clearly, this definition of the machine is more manageable. The original
model is maintained in order not to affect the modeling because of the translation
details. If it can be demonstrated that the Controller model of Listing 8.13 is equiv-
alent to the model of Listing 8.11, then the modified model can be used to generate
the UPPAAL timed automata for the controller behavior without loss of semantics.

In order to show equivalence between the machine of Listing 8.13 and the machine
of Listing 8.11, two basic principles are invoked. The first one relies on the fact that
all controller actions are instantaneous and, hence, occur in the same quantitative
Listing 8.13 Rules of the modified Controller main machine

R1: Cache {
    if wait = False and seq = cache then
        CACHEDATA();
        seq := operate_feed;
    }

R2: Feed {
    if wait = False and seq = operate_feed then
        OPERATE_FEED();
        seq := operate_deposit;
    }

R3: Deposit {
    if wait = False and seq = operate_deposit then
        OPERATE_DEPOSIT();
        seq := operate_robot;
    }

R4: Robot {
    if wait = False and seq = operate_robot then
        OPERATE_ROBOT();
        seq := operate_arma;
    }

R5: Robot {
    if wait = False and seq = operate_arma then
        OPERATE_ARM_A();
        seq := operate_armb;
    }

R6: Robot {
    if wait = False and seq = operate_armb then
        OPERATE_ARM_B();
        seq := operate_press;
    }

R7: Press {
    if wait = False and seq = operate_press then
        OPERATE_PRESS();
        seq := output;
    }

R8: Press {
    if wait = False and seq = output then
        OUTPUT();
        seq := cache;
        wait := True;
    }

R9: Wait for a step {
    t := next;
    else then
        wait := False;
    }

time period. Furthermore, the operations do not depend on one another and can be performed in parallel or in any sequence since they do not share variables. Also, by using the "dummy variables" to cache the state and buffer the output, the decisions at each step are not affected by the actions of other main machines or by the output
<table>
<thead>
<tr>
<th>Machine</th>
<th>Rules</th>
<th>Flattened Rules</th>
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<tr>
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<td>48</td>
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</table>

Table 8.2: Number of rules for flattened main machines

of each operation. This semantics is equivalent to the semantics of performing each operation in parallel in a single step. The second principle relies on the fact that all changes that modify sensor values involved in the decisions of the controller are achieved through durative actions of other components. The two principles guarantee semantic equivalence because each output of the controller will appear in the sensors after a time delay, hence after a controller step has been performed. The number of rules for each flattened main machine of the production cell TASM model is shown in Table 8.2.

The complete UPPAAL model contains 14 timed automata, including 8 automata for each main machine of the TASM model and 6 automata to enforce the “Else rules” of 6 of the main machines. The timed automata for the Feed main machine is shown in Figure 8-2. The safety properties given as temporal logic formulas can be easily translated to UPPAAL’s TCTL query language. The UPPAAL queries corresponding to the safety properties described in the previous section are shown below:

- $A[] (motor\_robot == 1) \implies (armaext == 1 \&\& armbext == 1)$

- $A[] (armaext == 2) \implies (armapos == 1 \&\& armapos == 2)$

- $A[] (error != 2)$
These properties were verified successfully by running the queries through the UPPAAL verifier. The model can also be queried to verify certain liveness properties. For example, the property "eventually, all blocks loaded into the system get carried out of the system" can be expressed in the query language of UPPAAL. This property can be formulated as the liveness property "E<> processed_blocks == loaded_blocks". Other liveness and safety properties can be formulated in a similar fashion, as needed. The UPPAAL model derived in this section is reused in Section 8.1.3 when execution time is analyzed.

Completeness and Consistency

The analysis of completeness and consistency was performed using the approach described in Section 5.1. The results of verifying completeness are shown in Table 8.3. The table shows, for each machine, the number of propositions, the number of clauses, and whether or not the machine is complete. For machines that are trivially complete, the number of propositions and clauses is listed as "N/A". A similar table, Table 8.4, presents the results of verifying the consistency of each machine.

In Table 8.3, the only machine which is not complete is the Loader main machine. The machine is not complete because it stops after loading the predefined number of blocks. The counterexample generated by the SAT solver is the state where
<table>
<thead>
<tr>
<th>Name</th>
<th>Propositions</th>
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</tr>
<tr>
<td>ROTATE.ROBOT</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 8.3: Completeness analysis results for the production cell model

"loadedblocks >= number, feed.belt = empty". The machine was designed to stop after the number of loaded blocks exceeds the predefined threshold, so the incompleteness is to be expected. In Table 8.4, main machines Deposit, ArmA, and ArmB are inconsistent. These components model the environment of the controller and hence the lack of consistency uncovers assumptions about the behavior of the environment. For the Deposit main machine, the counterexample generated by the SAT solver is the state where "deposit.belt = loaded, deposit.begin = True, motor.deposit = on, motor.deposit.p = negative, deposit.end = True". In this counterexample, rule R1 and rule R2 are both enabled. The assumption about the environment is that deposit.begin variable and the deposit.end variable cannot be true at the same time. This assumption is congruent with the problem definition...
Table 8.4: Consistency analysis results for the production cell model

<table>
<thead>
<tr>
<th>Name</th>
<th>Propositions</th>
<th>Clauses</th>
<th>Consistent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loader</td>
<td>5</td>
<td>71</td>
<td>Yes</td>
</tr>
<tr>
<td>Feed</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Deposit</td>
<td>10</td>
<td>15</td>
<td>No</td>
</tr>
<tr>
<td>Press</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Robot</td>
<td>2</td>
<td>4</td>
<td>Yes</td>
</tr>
<tr>
<td>ArmA</td>
<td>10</td>
<td>40</td>
<td>No</td>
</tr>
<tr>
<td>ArmB</td>
<td>10</td>
<td>40</td>
<td>No</td>
</tr>
<tr>
<td>Controller</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>armPosition</td>
<td>7</td>
<td>129</td>
<td>Yes</td>
</tr>
<tr>
<td>rotateClockwise</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>rotateCounterClockwise</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>OPERATE_FEED</td>
<td>6</td>
<td>10</td>
<td>Yes</td>
</tr>
<tr>
<td>OPERATE_DEPOSIT</td>
<td>6</td>
<td>10</td>
<td>Yes</td>
</tr>
<tr>
<td>OPERATE_ROBOT</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>OPERATE_ARM_A</td>
<td>6</td>
<td>18</td>
<td>Yes</td>
</tr>
<tr>
<td>OPERATE_ARM_B</td>
<td>6</td>
<td>8</td>
<td>Yes</td>
</tr>
<tr>
<td>OPERATE_PRESS</td>
<td>6</td>
<td>12</td>
<td>Yes</td>
</tr>
<tr>
<td>PICK_UP_ARM_A</td>
<td>10</td>
<td>23</td>
<td>Yes</td>
</tr>
<tr>
<td>PICK_UP_ARM_B</td>
<td>10</td>
<td>23</td>
<td>Yes</td>
</tr>
<tr>
<td>DROP_ARM_A</td>
<td>10</td>
<td>23</td>
<td>Yes</td>
</tr>
<tr>
<td>DROP_ARM_B</td>
<td>10</td>
<td>23</td>
<td>Yes</td>
</tr>
<tr>
<td>ARM_A_FEED</td>
<td>12</td>
<td>80</td>
<td>Yes</td>
</tr>
<tr>
<td>ARM_A_PRESS</td>
<td>12</td>
<td>80</td>
<td>Yes</td>
</tr>
<tr>
<td>ARM_B_DEPOSIT</td>
<td>12</td>
<td>80</td>
<td>Yes</td>
</tr>
<tr>
<td>ARM_B_PRESS</td>
<td>12</td>
<td>80</td>
<td>Yes</td>
</tr>
<tr>
<td>ROBOT_MOTION</td>
<td>4</td>
<td>8</td>
<td>Yes</td>
</tr>
<tr>
<td>ROTATE_ROBOT</td>
<td>16</td>
<td>255</td>
<td>Yes</td>
</tr>
</tbody>
</table>

which states that the robot will not put a block on the belt if it is already loaded and which can be verified as a safety property. And since the block can be at one end of the belt only and not at both ends simultaneously, only one of the two sensors can be true at any given time. This assumption can be validated against the UPPAAL model by running the query “A[] ! (deposit_end == 1 & deposit_begin == 1)” to verify that the aforementioned state is not reachable in the model. Similar reasoning can be carried out for the other two inconsistent machines, ArmA and ArmB. For these machines, the environmental assumption is that the magnet will never be on if an arm is retracted and empty.
8.1.3 Execution Time Analysis

Since the controller model does not contain time annotations, the execution time analysis is not concerned with the performance of the software, but with the performance of the manufacturing system with regards to the controller strategy. For the model, one time property to verify is the amount of time required to process $n$ blocks. This property can be stated over the state variables as the time required to complete a path from a state where “loaded_blocks = 0, processed_blocks = 0” to a state where “loaded_blocks = n, processed_blocks = n”. To demonstrate the approach, $n$ is selected to be 10 blocks. Using the approach described in Section 5.3, an appropriate observer automaton is added to the UPPAAL model. The observer automaton, shown in Figure 8-3, observes the relevant path and measures the time required to complete the path.

![Observer automaton](image)

Figure 8-3: Observer automaton to verify the time needed to process 10 blocks

Using the UPPAAL verifier, the time required to process 10 blocks is verified to be 386 time units. Because the timing of the various components is deterministic, 386 time units corresponds to both the best-case execution time and the worst-case execution time, given the controller strategy.

8.1.4 Resource Usage Analysis

The production cell case study contains one resource, power. Power is consumed when the hardware components are operating, for example when the motor of the feed belt is turned on. Analogously to the time annotations, the controller model does not consume any resource and it is justified to assume that the power consumed
by the controller is negligible compared to the power consumed by the hardware components. Consequently, the *Controller* machine can be excluded from the iterative algorithm used to converge on the maximum and minimum resource consumption values. According to the algorithm described in Section 5.4, the derivation of minimum and maximum resource consumption uses flattened versions of each main machine. The flattened version of the *Controller* main machine contains the most rules. Removing the controller main machine greatly reduces the complexity of the algorithm. Without the *Controller* main machine, the algorithm described in Section 5.4 iterates through 10584 combinations of rules \((3 \times 2 \times 6 \times 7 \times 7 \times 2 \times 3)\) to find the optimal solution. The maximal solution consumes 6600 units of power, which is obtained by executing rule \(R_1\) of all main machines, in parallel, which consumes the most power, per Table 2.5. As mentioned in Section 5.4, the algorithm used to determine maximum resource consumption can lead to an overapproximation of the consumed resources. The Uppaal model can be used to determine whether the state which satisfies the maximum resource consumption is reachable. This can be achieved using a simple reachability query over the value of variables in the form of “\(E<>\) (variable values)”.

Executing the reachability query for the state which yields the maximal power consumption, as given by the SAT solver, reveals that it is not a reachable state. A simple analysis of the suggested state shows that the state is not reachable because the loader cannot be loading a block while the feed belt is on. By iterating through other solutions yielded by the resource consumption verification algorithm, the maximal resource consumption where the satisfying state is reachable yields a resource consumption of 6200 units of power. This state corresponds to both arms being retracted, while the press is stamping a block, the deposit belt is carrying a block, and the feed belt is carrying a block. Summary results are presented in Table 8.5. In the table, the first column shows the value of consumed power. The second column shows, for each main machine, the rule being executed to yield the listed resource consumption. The composite rule names describe which rules are being executed in machines used for hierarchical composition. The third column shows the state which
satisfies the parallel execution of the rules. The fourth column indicates whether the state is reachable or not, as verified using the UPPAAL model.

<table>
<thead>
<tr>
<th>Value</th>
<th>Rules</th>
<th>State</th>
<th>Reachable</th>
</tr>
</thead>
<tbody>
<tr>
<td>6600</td>
<td>Loader: $R_1$  Feed: $R_1$  Deposit: $R_1$  Press: $R_1$  ArmA: $R_1$  ArmB: $R_1$  Robot: $R_1R_3$</td>
<td>loaded_blocks &lt; 9, feed_belt = empty, feed_belt = loaded, feed_begin = True, motor_feed = on, motor_feed_p = positive, deposit_belt = loaded, deposit_begin = True, motor_feed = on, motor_feed_p = positive, motor_press = on, press = loaded, press_block = notfinished, motor_arma = on, motor_arma_p = positive, armaext = retracted, motor_armb = on, motor_armb_p = positive, armbext = retracted, robot_wait = False, motor_robot = on</td>
<td>No</td>
</tr>
<tr>
<td>6200</td>
<td>Loader: $R_3$  Feed: $R_1$  Deposit: $R_1$  Press: $R_1$  ArmA: $R_2$  ArmB: $R_2$  Robot: $R_1R_3$</td>
<td>loaded_blocks &lt; 10, feed_belt = loaded, feed_belt = loaded, feed_begin = True, motor_feed = on, motor_feed_p = positive, deposit_belt = loaded, deposit_begin = True, motor_feed = on, motor_feed_p = positive, motor_press = on, press = loaded, press_block = notfinished, motor_arma = on, motor_arma_p = negative, armaext = extended, motor_armb = on, motor_armb_p = negative, armbext = extended, robot_wait = False, motor_robot = on</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 8.5: Resource consumption analysis results for the production cell

For the minimum resource consumption, a trivial case happens after all blocks have been loaded and the robot is at the feed belt, waiting for a block to arrive. In this case, the power consumption is 0 units. The minimum non-zero resource consumption occurs at the beginning of the production process when there are no blocks in the system and the loader is putting the first block on the feed belt. In this case, the power consumption is 200 units.

8.1.5 Test Case Generation

In the production cell case study, the Controller main machine is the only main machine describing the behavior of software. The other main machines describe the behavior of hardware components considered part of the environment. Consequently, test cases are generated only for the machines linked to the Controller main machine,
using the algorithm described in Listing 7.8. The results of the test case generation are shown in Table 8.6. In Table 8.6, the first column provides the machine name, the second column lists the number of test case templates in the test suite template for the machine, and the third column lists the number of test cases from the test suite required for unit testing of the machine. Per the approach described in Chapter 7, the test cases are generated using the rule coverage criterion, explained in Section 7.1.1. Because the test case generation strategy does not require the machines to be “flattened”, the generation of test cases is achieved using the Controller machine shown in Listing 8.11, not the modified version provided in Listing 8.13. In Table 8.6, the test case results are for unit testing are equal to the number of rules for each machine. Furthermore, the number of test cases in the test suite are the test cases used to achieve both unit testing for the given machine an integration testing for sub machines used in hierarchical composition. The Controller main machine contains the most number of test cases, 14, which are used to cover the rules Controller main machine and the rules of all the sub machines. The number 14 is obtained through the maximum number of rules for the sub machines, in this case 13, plus 1 more test case used to exercise rule $R_2$ of the Controller main machine.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Test Suite</th>
<th>Unit Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>OPERATE.FEED</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>OPERATE.DEPPOSIT</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>OPERATE.ROBOT</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>OPERATE.ARM_A</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>OPERATE.ARM_B</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>OPERATE.PRESS</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>ARM_A.FEED</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>ARM_A.PRESS</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>ARM_B.DEPOSIT</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>ARM_B.PRESS</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>ROTATE.ROBOT</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 8.6: Test case generation results for the production cell model

A sample test case template from the Controller main machine test suite is shown in Table 8.7.
Table 8.7: Sample test case template from the test suite for the Controller main machine

8.1.6 Discussion

The production cell provides a case study of moderate complexity with interesting properties to verify. The TASM model of the production cell contains a model of the controller software, the crux of the model, and simplified models of the hardware components. Having a complete system model enables analysis of system properties, such as resource consumption and the amount of time required to process a fixed number of blocks, e.g., 10 blocks. Furthermore, reachability analysis yielded insight to analyze the reachable states in the controller and in the environment, given the controller strategy. This analysis was performed using safety invariants and using errors embedded in the model. The completeness and consistency analysis uncovered interesting environmental assumptions that could be validated using the UPPAAL model, such as the impossibility that the feed_begin and feed_end sensors be true simultaneously. The completeness and consistency analysis proved to be a valuable aid in building and debugging the TASM model. While the completeness and consistency results aren’t incredibly insightful once the model is completed, the capabilities were useful during development.

The translation from TASM to UPPAAL uncovered an important limitation in the translation algorithm with respect to the hierarchical composition mechanisms of the TASM language. Because UPPAAL does not have hierarchical composition facilities,
the construction of a “flattened” machine is a necessary step of the translation. The number of rules of the “flattened” machine grows exponentially with the number of sub machines used in parallel for hierarchical composition, for a given rule. Nevertheless, with minor modeling modifications, an equivalent TASM model was derived, which yielded a scalable translation. The primary purpose of the production cell case study is to demonstrate the modeling and analysis capabilities of the proposed framework. As such, the case study proved useful since it provides a model of moderate size and demonstrates the analysis of functional properties, execution time, and resource consumption.

The test case generation for the production cell case study was fairly straightforward since the Controller main machine and its associated sub machines do not use real or integer variables. Furthermore, when hierarchical composition is utilized, the composed machines do not share variables, hereby reducing the complexity of combining the test suites of different machines. It is interesting that the test case generation strategy proved scalable, even through the heavy use of hierarchical composition in the Controller main machine. This situation would not have been possible using model checking approaches, unless the model was altered as described in Listing 8.13.

8.2 Electronic Throttle Controller:

High Level Model

The Electronic Throttle Controller (ETC) case study is based on a Simulink model [167] developed by Griffiths et al. and by an industrial automotive manufacturer [111]. The case study is described in details in Section 2.8.2. The case study is used to illustrate the modeling capabilities of the TASM language, to exercise the analysis features of the framework, to illustrate the bi-directional traceability approach, and to demonstrate the test case generation capabilities, including regression testing. The case study is presented in three different sections. The first version of the model, described in this section, describes a high level model of the ETC for the mode switching
logic of the controller and for the calculation of the desired current. The following section, Section 8.3, presents a tasking model and a scheduler which are used to implement the ETC functionality. Finally, Section 8.4 presents the combination of the tasking model with the high level model presented in this section, and adds resource consumption to the model.

As a reminder, the ETC operates based on “modes”, which are set by the controller based on environmental factors such as vehicle parameters, driver inputs, and climate conditions. The operation of the ETC is divided into major modes of operation and minor modes of operation. During nominal operation, the major modes of the controller are grouped into “driving modes” and “limiting modes”. The limiting modes, defined as undesirable vehicle conditions that need to be remedied by the controller, take precedence over driving modes. Limiting modes are divided in minor modes, namely “traction control”, where the wheels rotate with too little friction, and “revolution control”, where the engine operates over a threshold rotation per minute. The driving modes are also divided into minor modes of operation, namely “human control”, where the driver dictates the behavior of the controller, and “cruise control”, where the behavior of the controller is determined using set parameters. The different modes are shown in Figure 8-4, adapted from [111], represented visually as a statechart variant [120]. The “XOR” label indicates mutual exclusion between modes and the “AND” label indicates parallel composition of modes.

As a reminder, the ETC uses the major and minor modes of operation to calculate the output of the ETC, the desired current, which is output to the throttle. The desired current dictates the throttle angle and controls how much air enters the engine and, consequently, on much torque and RPM the engine produces. The high level requirements governing the logic for determining the modes of operation and the associated calculation of the desired current can be summarized as follows:

- **Req 1.1**: The controller shall operate in two major modes, the *driving* mode and the *limiting* mode
  - **Req 1.1.1**: The driving mode shall be active when the *limiting condition*
Figure 8-4: ETC modes
is False.

- **Req 1.1.2:** The limiting mode shall be active when the *limiting condition* is True.

- **Req 1.1.3:** The limiting mode and the driving mode shall be mutually exclusive and collectively exhaustive.

- **Req 1.2:** The limiting mode shall be divided into over revolution mode and traction control mode
  
  - **Req 1.2.1:** The over revolution mode shall be active when the engine RPM is over 6000 rotations per minute
  
  - **Req 1.2.2:** The traction limiting mode shall be active when the engine torque is over 110 kPa

- **Req 1.3:** The driving mode shall be divided into human mode and cruise control mode
  
  - **Req 1.3.1:** The cruise control mode shall be active when the gear is in drive, the vehicle speed is over 30 miles per hour, the break pedal is depressed, and the cruise switch is on
  
  - **Req 1.3.2:** In all other conditions, the control mode shall be inactive

- **Req 1.4:** When calculating the desired current, the limiting modes shall take precedence over the driving modes
  
  - **1.4.1:** When the limiting mode and the driving modes are active, the desired current is calculated using the limiting mode
1.4.1.1: When the over revolution limiting mode and the traction limiting mode are active, the desired current is calculated using the minimum value of the desired current calculated using these two modes separately.

1.4.1.2: When only one of the limiting modes is active, this mode is used to calculate the desired current.

1.4.2: When the limiting mode is inactive, the desired current is calculated using the driving mode.

1.4.2.1: When both the human driving mode and the cruise control driving modes are active, the desired current is calculated using the maximum value of the desired current calculated using these two modes separately.

1.4.2.2: When only one of these modes is active, this mode is used to calculate the desired current.

8.2.1 Model

The Simulink model of the ETC is adapted into the TASM language by modeling the control of the desired current as a main machine. This main machine, called CONTROLLER, implements the requirements described above by performing 5 main steps: reading the state of the environment (vehicle, driver inputs, and climate) through sensors, setting the mode of the controller (major and minor), calculating the output current, and monitoring the health of the system. When the car is turned on, this sequence of operations executes indefinitely in a loop, until the car is turned.
off. The rules of the CONTROLLER main machine are shown in Listing 8.14.

### Listing 8.14 Rules of the CONTROLLER main machine

**R1: Controller loop when nominal**

```plaintext
if control_mode = sample then
    SAMPLE_STATE();
    control_mode := mode_set;
```

**R2: Controller loop to set major mode**

```plaintext
if control_mode = mode_set_major then
    SET_MAJOR_MODE();
    control_mode := mode_set_minor;
```

**R3: Controller loop to set minor mode**

```plaintext
if control_mode = mode_set_minor then
    SET_MINOR_MODE();
    control_mode := output;
```

**R4: Controller loop to output current**

```plaintext
if control_mode = output then
    CALCULATE_OUTPUT();
    control_mode := health;
```

**R5: Controller loop to find failure**

```plaintext
if control_mode = health then
    MONITOR_HEALTH();
    control_mode := sample;
```

Per the requirements, the mode of operation of the controller is set using a major mode and a minor mode. The steps of the actions of the controller are captured through the Control.mode data type. Since this version of the ETC model is a high level model, the output current is abstracted through a user-defined type called Desired_Current, as shown in Listing 8.15. The current is abstracted using the type because it eases verification and makes explicit what actual current is being output based on the logic. This simplification is justified for a high level model, and can later be refined when the calculation of the current is implemented using a specification type of controller.

The Mode datatype is used to set the major mode of operation. The Binary_Mode datatype is used to set the cruise, limiting, over revolution, and over torque minor
Listing 8.15 User-defined types of the ETC high level model

<table>
<thead>
<tr>
<th>Type</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary_Mode</td>
<td>{active, inactive}</td>
</tr>
<tr>
<td>Binary_Status</td>
<td>{on, off}</td>
</tr>
<tr>
<td>Health_Status</td>
<td>{nominal, fault_detected}</td>
</tr>
<tr>
<td>Mode</td>
<td>{off, startup, shutdown, driving, limiting, faulty}</td>
</tr>
<tr>
<td>Gear_Status</td>
<td>{park, drive}</td>
</tr>
<tr>
<td>Control_Mode</td>
<td>{sample, mode_set_major, mode_set_minor, output, health}</td>
</tr>
<tr>
<td>Desired_Current</td>
<td>{none_c, human_c, cruise_c, traction_c, rev_c, min_limiting_c, max_driving_c, fault_c, error_c}</td>
</tr>
<tr>
<td>Simulation_Mode</td>
<td>{begin_s, drive_s, random_s, stop_s}</td>
</tr>
</tbody>
</table>

The high level ETC model does not contain time or resource annotations since the model describes high level behavior. The model makes heavy use of hierarchical composition to structure the logic for mode switching and for the logic to calculate the desired current. The `Simulation_Mode` datatype is used to express various simulation scenarios, as explained in the functional analysis section, Section 8.2.2.

Complete Model

The complete TASM model contains 3 main machines, 13 function machines, and 10 sub machines. The complete electronic throttle controller high level model is documented in Appendix E, Section E.1, where the list of all machines is shown in Table E.1.

8.2.2 Functional Analysis

The functional analysis of the high level model concerns the correct transitions between modes and the correct calculation of the desired current based on the mode of operation. The analysis of the model is achieved through both simulation scenarios, model checking, and verification of completeness and consistency.

Scenario Modeling

The electronic throttle controller reacts to changes in the state of the vehicle (vehicle speed, wheel traction, etc.) and operator inputs (gas pedal angle, cruise control switch, ignition, gear position, etc.). In order to exercise the various modes of the
ETC, different simulation scenarios were devised. For example, the throttle controller always begins in the “off” mode, until ignition is turned on. Because the throttle controller will do nothing until the ignition is turned on, the functionality of the ETC can be exercised by either selecting different initial conditions e.g., starting the ETC in “driving” mode, or by modeling environment behavior to trigger the different modes. For example, nominal operation of the driver would turn on the ignition, put the car in drive, and start driving by pressing the gas pedal. The cruise control mode can only be initiated by the driver, by setting the cruise switch to the on position, when the other conditions of the vehicle are met. Traction mode and engine revolution mode are triggered through a combination of driver input and environmental conditions such as a slippery or uneven road surface.

In order to exercise the behavior of the controller, a main machine modeling driver behavior and a main machine modeling the car behavior have been designed. The first machine, called DRIVER, simply performs nominal initiation actions by turning on the ignition, setting the car gear in drive, and activating the gas pedal. Once the driver has transitioned the car into nominal driving mode, the driver can arbitrarily press the inputs – the cruise control switch, the break pedal, and the gas pedal. The second machine, called VEHICLE, arbitrarily varies the vehicle speed, engine speed, and vehicle traction. The detailed dynamics of the vehicle and the driver transfer function are not modeled in details, but are encoded into hardcoded values. As such, the behavior of the driver and the behavior of the vehicle are not directly linked. For example, if the driver presses the gas pedal, it won’t necessarily directly translate to an increase in the speed of the vehicle. While this lack of causality seems nonintuitive, it leads to a much more simplified model. Furthermore, the behavior of the driver and the behavior of the vehicle, as modeled in the two machines, provide an overapproximation of the true behavior of the vehicle and driver. For example, it is possible for the driver to press the gas pedal and for the vehicle to decrease its velocity. This behavior might seem counterintuitive, but it captures a richer set of scenarios and makes few assumptions about the behavior of both the driver and the vehicle. The only restrictions on the reachable states of both the driver and the
The DRIVER main machine will arbitrarily affect the driver inputs. Three sample rules of the DRIVER main machine are shown in Listing 8.16. These rules will non-deterministically change the status of the cruise switch with nominal speed, rule \( R_4 \), and with speed that is too low for the cruise control to take effect in the ETC, through rule \( R_3 \). The complete DRIVER main machine is documented in Listing E.4 and in Listing E.5.

**Listing 8.16 Two rules of the DRIVER main machine**

\( R_3 \): Turn on cruise, slow speed

```
{ if driver_s = random_s and cruise_switch = off then
     cruise_switch := on;
     vehicle_speed := 10;
 }
```

\( R_4 \): Turn on cruise, normal speed

```
{ if driver_s = random_s and cruise_switch = off then
     cruise_switch := on;
     vehicle_speed := 30;
 }
```

\( R_5 \): Turn off cruise

```
{ if driver_s = random_s and cruise_switch = on then
     cruise_switch := off;
 }
```

The VEHICLE main machine will arbitrarily affect the state of the vehicle and will wait for the proper action by the controller to return the vehicle to a nominal state. The combination of the DRIVER main machine and the VEHICLE main machine exercise the full behavior of the controller. Two sample rules of the VEHICLE main machine are shown in Listing 8.17. These rules will non-deterministically change the engine speed and the vehicle torque over the desired threshold, through rule \( R_4 \), and wait until the correct desired current is output to return them to nominal values, as
achieved through rule $R_7$. The complete $VEHICLE$ main machine is documented in Listing E.6 and in Listing E.7.

**Listing 8.17** Two rules of the $VEHICLE$ main machine

$R_4$: Randomly change both

```c
if driver_s = random_s and vehicle_over_rev_s = False and
    vehicle_over_tor_s = False then
    engine_speed := MAX_ENGINE_SPEED + 1;
    vehicle_over_rev_s := True;
    vehicle_torque := MAX_TORQUE + 1;
    vehicle_over_tor_s := True;
}
```

$R_7$: Randomly change both, correct

```c
if driver_s = random_s and vehicle_over_rev_s = True and
    vehicle_over_tor_s = True and desired_current = min_limiting_c then
    vehicle_torque := MAX_TORQUE;
    vehicle_over_tor_s := False;
    engine_speed := MAX_ENGINE_SPEED;
    vehicle_over_rev_s := False;
}
```

**Safety and Liveness Properties**

Verifying the safety properties of the controller involves asserting that certain states are not reachable while certain states must be reached after a certain condition is met. Since the controller operates in steps, it is important to formulate the state conditions over the "cached" state in order to avoid writing queries over the state that could change during the controller sequence of steps. The safety properties to be verified fall into two distinct categories – verifying that the correct mode is set depending on environmental conditions and verifying that the correct output current is set depending on the mode of operation.

In the first category of properties, verifying the that the limiting mode is correctly set involves checking that, whenever the engine revolution is over the maximum threshold or the vehicle torque is over the maximum threshold, the controller is in the limiting mode. These two properties can be easily formulated as temporal logic formulas:
These two properties are stated over the "cached" values of the state `c.engine_speed` and `c.vehicle_torque` to avoid cases involving non-deterministic state changes during controller operation. Furthermore, the `control_mode` variable is added to the query to ensure that the mode is correctly set after the controller has finished setting the mode. In the temporal logic queries, for the properties of interest, the `control_mode` variable should set to `output` to denote that the mode has already been set. Similar queries can be formulated for the driving mode and for the other minor modes such as the cruise control mode being set when the cruise condition is enabled. The second category of properties involves verifying that the correct desired current is output based on the controller mode. The correct desired current is defined according to the requirements listed in Section 8.2. Some basic properties can be stated about the desired current to ensure that minimal guarantees exist. For example, whenever the controller mode is driving, the desired current is either the human current, the cruise control current, or the minimum value of the two currents. In temporal logic, this property can be stated as:

- $A \ G (c.engine\_speed > MAX\_ENGINE\_SPEED \land control\_mode = output) \rightarrow (controller\_mode = limiting)$

- $A \ G (c.vehicle\_torque > MAX\_TORQUE \land control\_mode = output) \rightarrow (controller\_mode = limiting)$

- $A \ G (controller\_mode = driving \land control\_mode = health) \rightarrow (desired\_current = human\_c \lor desired\_current = cruise\_c \lor desired\_current = max\_driving\_c)$

The query uses the `control_mode` variable to ensure that the desired current is correctly calculated after the controller has finished calculating the current. This is achieved by ensuring that the `control_mode` variable is set to `health`, which occurs only after the desired current has been calculated. The query concerning the desired
current also illustrate the benefits of abstracting away the actual numerical value of the current being output. If a real variable were output, it would be difficult to determine exactly what numerical value the current should be without taking into account the actual speed and dynamics of the vehicle. A similar query can be formulated for the limiting major mode. More complex properties can be verified by querying based on both major and minor modes and ensuring that the current calculation logic is correct with respect to the requirements. For example, the limiting mode takes precedence over the driving mode and if both the over revolution mode and the traction mode are active, the minimum current of both limiting modes is used as the desired current output. This property can be formulated as:

\[
\text{A} \quad G \ (\text{controller\_mode} = \text{limiting} \land \text{cruise\_mode} = \text{active} \land \text{rev\_limiting\_mode} = \text{active} \land \text{traction\_mode} = \text{active} \land \text{control\_mode} = \text{health}) \rightarrow (\text{desired\_current} = \text{min\_limiting\_c})
\]

Similar properties can be formulated for the other combination of modes. After establishing that the modes are correctly set based on environmental conditions and establishing that the output current is correctly calculated based on the controller mode, it naturally follows that the ETC behaves correctly according to the requirements.

**Uppaal Model**

In order to verify the TASM model for the aforementioned safety assertions, the ETC TASM model leverages the UPPAAL model checker, using the translation approach documented in Appendix C. Because the timed automata used in UPPAAL do not have hierarchical composition facilities, the TASM main machines need to be “flattened” per the approach used in the proof of Theorem 4.1 and in the proof of Theorem 4.2. The removal of hierarchical composition leads to exponential growth in the number of states in the “flattened” machine where multiple units of hierarchical composition happen in parallel. In the ETC model, only the **CONTROLLER**
main machine uses hierarchical composition and is the only machine that needs to be flattened. In the definition of the CONTROLLER main machine, the invocation of the SET_MINORMODE_WORK sub machine is the only place where hierarchical composition is performed in parallel using multiple sub machines. Consequently, this is the only place in the model that leads to exponential growth in the number of rules of the flattened machine. However, this growth is tractable since it leads to only 8 rules ($2 \times 2 \times 2$). The number of rules for each flattened main machine of the TASM model is shown in Table 8.8.

The complete UPPAAL model contains 5 timed automata, including 3 automata for each main machine of the TASM model and 2 automata to enforce the “Else rules” of the DRIVER main machine and of the VEHICLE main machine. The safety properties given as temporal logic formulas can be easily translated to UPPAAL ’s TCTL query language. The UPPAAL queries corresponding to the safety properties stated above are shown below, in the order in which they were introduced:

- $A[] \ (c_{engine.speed} > MAX\_ENGINE\_SPEED \land control.mode == 4 \land system.health == 1) \implies (controller.mode == 5)$

- $A[] \ (c_{vehicle.torque} > MAX\_TORQUE \land control.mode == 4 \land system.health == 1) \implies (controller.mode == 5)$

- $A[] \ (controller.mode == 4 \land control.mode == 5) \implies$
  $(desired.current == 2 \lor desired.current == 3 \lor desired.current == 7)$

Table 8.8: Number of rules for flattened main machines for the high level ETC model
A[] (controller_mode == 5 && cruise_mode == 1 && rev_limiting_mode == 1 && traction_mode == 1 && control_mode == 5) imply (desired_current == 6)

These properties were successfully verified by running the queries through the UPPAAL verifier. The first two properties differ slightly from the original stated assertions because if a fault is present, the controller mode will be set to the faulty mode instead of being set to the limiting mode. The detection of a fault takes precedence over all the other modes of operation. The extended query adds a condition to state that the limiting mode is set when one of the two limiting conditions are true and the system health is nominal, through the system_health variable. The model can also be queried to verify certain liveness properties, to ensure that the model behaves correctly. For example, the property “eventually, the car is in cruise control” can be verified. This property can be formulated as the liveness property “E<> cruise_mode == 1”. Other liveness and safety properties can be formulated in a similar fashion, as needed.

Completeness and Consistency

The analysis of completeness and consistency was performed using the approach described in Section 5.1. The results of verifying completeness are shown in Table 8.9. The table shows, for each machine, the number of propositions, the number of clauses, and whether or not the machine is complete. For machines that are trivially complete, the number of propositions and clauses is listed as “N/A”. A similar table, Table 8.10, presents the results of verifying the consistency of each machine.

In Table 8.9, all machines are complete. In Table 8.10, machines DRIVER and VEHICLE are not consistent, as expected. These components model the environment of the controller and hence the lack of consistency uncovers assumptions about the behavior of the environment. For the DRIVER machine, one of the generated counterexamples by the SAT solver is the state where “driver_s = random, cruise_switch
Table 8.9: Completeness analysis results for the ETC high level model

<table>
<thead>
<tr>
<th>Name</th>
<th>Propositions</th>
<th>Clauses</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONTROLLER</td>
<td>5</td>
<td>32</td>
<td>Yes</td>
</tr>
<tr>
<td>DRIVER</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>VEHICLE</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Cruise</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Cruise_Mode</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Cruise.Throttle_C</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Driver.Throttle_C</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Driving.Throttle_C</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Fault</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Limiting.Throttle_C</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Over_Rev</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Over_Rev_Mode</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Over_Rev.Throttle_C</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Over_Torque</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Over_Torque_Mode</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Over_Torque.Throttle_C</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>CALCULATE_OUTPUT</td>
<td>6</td>
<td>64</td>
<td>Yes</td>
</tr>
<tr>
<td>DO_SHUTDOWN</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>DO_STARTUP</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>HANDLE_FAULT</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>MONITOR_HEALTH</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>SAMPLE_STATE</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>SET_MAJOR_MODE</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>SET_MAJOR_MODE_WORK</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>SET_MINOR_MODE</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>SET_MINOR_MODE_WORK</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
</tbody>
</table>

In this state, rule $R_3$ and rule $R_4$ are both enabled. This behavior is expected since it was modeled this way, to simulate driver behavior where the cruise switch is set to on and the driver speeds up over the cruise speed threshold, and to simulate the driver behavior where the cruise switch is set to on and the driver slows down under the cruise speed threshold. For the $VEHICLE$ machine, the generated counterexample is the state where “$\text{driver.s} = \text{random}, \text{vehicle}\_\text{over}\_\text{rev}\_\text{s} = \text{False}, \text{vehicle}\_\text{over}\_\text{tor}\_\text{s} = \text{False}$”. In this state, rule $R_1$ and rule $R_2$ are both enabled.

In a similar fashion, this behavior is expected since these two rules were designed to model vehicle behavior which stays nominal, and vehicle behavior which arbitrarily transitions to an engine RPM over the maximum threshold.

Since the high level ETC model does not contain time or resource annotations, this version of the model does not contain analysis results for execution time and for
<table>
<thead>
<tr>
<th>Name</th>
<th>Propositions</th>
<th>Clauses</th>
<th>Consistent</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONTROLLER</td>
<td>5</td>
<td>32</td>
<td>Yes</td>
</tr>
<tr>
<td>DRIVER</td>
<td>18</td>
<td>88</td>
<td>No</td>
</tr>
<tr>
<td>VEHICLE</td>
<td>19</td>
<td>529</td>
<td>No</td>
</tr>
<tr>
<td>Cruise</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Cruise_Mode</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Cruise_Throttle_C</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Driver_Throttle_C</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Driving_Throttle_C</td>
<td>5</td>
<td>11</td>
<td>Yes</td>
</tr>
<tr>
<td>Fault</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Limiting_Throttle_C</td>
<td>4</td>
<td>7</td>
<td>Yes</td>
</tr>
<tr>
<td>Over_Rev</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Over_Rev_Mode</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Over_Rev_Throttle_C</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Over_Torque</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Over_Torque_Mode</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Over_Torque_Throttle_C</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>CALCULATE_OUTPUT</td>
<td>6</td>
<td>64</td>
<td>Yes</td>
</tr>
<tr>
<td>DO_SHUTDOWN</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>DO_STARTUP</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>HANDLE_FAULT</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>MONITOR_HEALTH</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>SAMPLE_STATE</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>SET_MAJOR_MODE</td>
<td>8</td>
<td>63</td>
<td>Yes</td>
</tr>
<tr>
<td>SET_MAJOR_MODE_WORK</td>
<td>16</td>
<td>78</td>
<td>Yes</td>
</tr>
<tr>
<td>SET_MINOR_MODE</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>SET_MINOR_MODE_WORK</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 8.10: Consistency analysis results for the ETC high level model

resource consumption.

8.2.3 Test Case Generation

In the ETC case study, all the machines describe the behavior of the software except for the DRIVER and the VEHICLE main machines which describe environmental behavior. Consequently, test suites are generated for all the machines except for the DRIVER and VEHICLE machines, using the algorithm described in Listing 7.8. The results of the test case generation are shown in Table 8.7. In Table 8.7, the first column provides the machine name, the second column lists the number of test case templates in the test suite template for the machine, and the third column lists the number of test cases from the test suite required for unit testing of the machine. Per the approach described in Chapter 7, the test cases are generated using the rule
coverage criterion, explained in Section 7.1.1. Because the ETC high level model contains multiple function machines, some transformations need to be applied to the model in order to generate test cases, as explained in Section 7.4. For example, when function machines are used in a rule guard, the guard needs to be rewritten so that the function machine is removed, per the approach described in the proof of Theorem 4.1. Furthermore, function machines used in effect expressions are converted to sub machines, as described in Section 7.4. The CONTROLLER main machine contains the most test cases in its test suite, 33 in total, because it is the most complex machine, since it uses hierarchical composition. Because the machine uses hierarchical composition in many of its rules, the total number of rules required to cover the rules of the CONTROLLER main machine and the rules of the sub machines it uses will be approximately the sum of the number of rules of all the machines in the model. The total number of rules is slightly lower than the total summation because certain rules can be covered in parallel during the invocation of the SET.MINOR.MODE.WORK sub machine, which uses multiple units of hierarchical composition in its rules.

A sample test case template from the CONTROLLER main machine test suite is shown in Table 8.12.

8.2.4 Discussion

Adapting the Simulink ETC model into the TASM language enabled the verification of consistency and completeness for the mode switching logic and desired current calculation logic. Determining these properties was helpful during the early modeling stages to ensure that no cases were missed and that no cases were conflicting. Some of this analysis uncovered inconsistencies and incompleteness in the Simulink model. For example, the cruise control throttle current calculation was unreachable in the Simulink model. Furthermore, the Simulink model does contain the modeling of non-deterministic driver behavior to set the cruise switch or to activate the break pedal. The Simulink model contains driver behavior for gas pedal input only, which is modeled as a deterministic scenario using a hardcoded transfer function.

The completeness and consistency verification was established in isolation, by
Machine | Test Suite | Unit Testing
--- | --- | ---
CONTROLLER | 33 | 5
Cruise | 2 | 2
Cruise.Mode | 3 | 3
Cruise.Throttle.C | 1 | 1
Driver.Throttle.C | 1 | 1
Driving.Throttle.C | 3 | 3
Fault | 2 | 2
Limiting.Throttle.C | 6 | 4
Over_Rev | 2 | 2
Over_Rev.Mode | 3 | 2
Over_Rev.Throttle.C | 1 | 1
Over_Torque | 2 | 2
Over_Torque.Mode | 3 | 2
Over.Torque.Throttle.C | 1 | 1
CALCULATE_OUTPUT | 15 | 6
DO_SHUTDOWN | 2 | 2
DO_STARTUP | 2 | 2
HANDLE_FAULT | 2 | 2
MONITOR_HEALTH | 3 | 2
SAMPLE_STATE | 1 | 1
SET_MAJOR.MODE | 11 | 3
SET_MAJOR.MODE_WORK | 9 | 7
SET_MINOR.MODE | 3 | 2
SET_MINOR.MODE_WORK | 3 | 1

Table 8.11: Test case generation results for the ETC high level model

<table>
<thead>
<tr>
<th>Pre State</th>
<th>Post State</th>
<th>Coverage Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>control.mode{health}, fault{False}</td>
<td>control.mode{sample}, system.health{nominal}</td>
<td>CONTROLLER.R5, MONITOR_HEALTH.R2</td>
</tr>
</tbody>
</table>

Table 8.12: Sample test case template from the test suite for the CONTROLLER main machine

verifying the properties on a machine-by-machine basis. The hierarchical composition of the TASM language and toolset ensures that systems can be designed bottom-up using pre-verified auxiliary machines that are known to be complete and consistent. The completeness and consistency results will be reused in the following sections, where the ETC model developed in this section is extended and implemented using a set of tasks and a scheduler.

By translating the TASM model to UPPAAL, safety properties were verified to ensure that the controller behaves correctly with respect to the requirements. The
original verification of the controller also uncovered corner cases that the Simulink model did not cover, such as the injection of a fault overriding the limiting and driving controller modes. This case study provided a good example of an embedded controller and how a high level model can be analyzed using the proposed framework. The refined version of this model, presented in the following sections builds on the model and analysis of this section and illustrates other features of the presented framework, including the bi-directional traceability capabilities and the generation of test cases for regression testing.

8.3 Electronic Throttle Controller:

Tasking Model

The high level version of the electronic throttle controller, presented in Section 8.2, focused on the logic used to set the mode of operation of the controller and focused on the logic used to calculate the desired current. In this section, the tasking model and the scheduler used to implement the ETC are presented and analyzed using the framework. The tasking model and scheduler presented in this section are later used, in Section 8.4, to implement the mode setting logic and desired current calculating functionality of the ETC. The model presented in this section introduces the time-dependent behavior of the throttle controller.

In the Simulink model described in [111], the functionality of the throttle controller is implemented using three tasks – a manager task, a monitor task, and a servo task. The manager task is responsible for setting the major and minor mode of the controller. The monitor task is responsible for detecting failures and monitoring the health of the system. The servo task is responsible for calculating and outputting the desired current. The three tasks operate at different frequencies, based on the performance requirements of the ETC. The servo task is responsible for the closed-loop control of the ETC and must operate at a rate of 300 Hz. The manager task must operate at a rate of 100 Hz. The monitor task is less critical with an operation
frequency of 30 Hz being acceptable. The tasks are driven by a scheduler which operates at a clock speed of 1 kHz. The performance requirements have been obtained from [111].

In order to model the tasks and to perform analysis of the scheduling strategy, the Best-Case Execution Time (BCET) and Worst-Case Execution Time (WCET) of each task must be estimated. These calculations have been performed in past research in [48] by aggregating the operations from the Simulink model and calculating the number of clock cycles required for each operation on a PowerPC 405. The number of clock cycles for each operation is shown in Table 8.13.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Execution Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branch</td>
<td>1-3</td>
</tr>
<tr>
<td>Division</td>
<td>120</td>
</tr>
<tr>
<td>Multiplication</td>
<td>20</td>
</tr>
<tr>
<td>Addition</td>
<td>4-8</td>
</tr>
</tbody>
</table>

Table 8.13: Execution time for floating point operations for a PowerPC 405 (in clock cycles)

For each task, the number of operations is compiled and the resulting BCET and WCET can be estimated using the PowerPC 405 processor operating at 10MHz. The resulting values of BCET and WCET are shown in Table 8.14.

<table>
<thead>
<tr>
<th>Task</th>
<th>Manager</th>
<th>Monitor</th>
<th>Servo</th>
</tr>
</thead>
<tbody>
<tr>
<td>#Branches</td>
<td>2-5</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>#Divisions</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>#Multiplications</td>
<td>0</td>
<td>80</td>
<td>30</td>
</tr>
<tr>
<td>#Additions</td>
<td>0-1</td>
<td>24</td>
<td>32</td>
</tr>
<tr>
<td>BCET (cycles)</td>
<td>2</td>
<td>1700</td>
<td>854</td>
</tr>
<tr>
<td>WCET (cycles)</td>
<td>23</td>
<td>1804</td>
<td>994</td>
</tr>
<tr>
<td>BCET (ms)</td>
<td>0.0002</td>
<td>0.17</td>
<td>0.0854</td>
</tr>
<tr>
<td>WCET (ms)</td>
<td>0.0023</td>
<td>0.1804</td>
<td>0.0994</td>
</tr>
<tr>
<td>Period (ms)</td>
<td>10</td>
<td>30</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 8.14: Timing properties for the ETC tasks

These timing estimates are a bit coarse and rely on the details of the implementation. While this level of analysis might seem inappropriate for the level of modeling performed in this section, the coarseness of the analysis yields realistic upper and
lower bounds on the timing of the tasks, bounds which can readily be used for modeling at the task level. Furthermore, for BCET execution, certain properties such as pipelining, instruction caching, and data caching were ignored. Sophisticated tools and algorithms for execution time analysis exist, as documented in [89], and can later be used when the functionality is implemented to validate the early estimates. Furthermore, the bi-directional strategy can be leveraged to track the assumptions about the BCET and WCET of each task. Afterall, the goal of this model is not to derive precise metrics, but to demonstrate the capabilities of the TASM language and associated framework. Consequently, it is justifiable to round the execution time estimates into safe and tight bounds. In order to discuss the timing data in terms of integers, $\mu s$ are used. For the manager task, the execution time bounds can be rounded to $[0, 5] \mu s$. For the monitor task, the execution time bounds can be rounded to $[100, 200] \mu s$. For the servo task, the execution time bounds can be rounded to $[70, 100] \mu s$. The scheduling algorithm used in the Simulink model does not follow the optimal and widely used Rate Monotonic Analysis (RMA) [58] scheduling algorithm. Instead, the Simulink model gives precedence to the manager task first, followed by the monitor task, followed by the servo task. The priority scheme is statically assigned and hardcoded in Stateflow. Furthermore, the scheduler is non-preemptive, meaning that tasks cannot be interrupted once they have begun execution.

Since the execution times of each task are much smaller than the periods of each task, it is obvious with simple analysis to observe that the set of tasks is schedulable. Furthermore, given the priority scheme, the major cycle, that is, the amount of time required for all tasks to complete and start repeating the pattern, is 30 ms; the major cycle is clearly identified since the combined worst-case execution time of all tasks, $305 \mu s$, fits inside of the period of the task with the fastest rate, the servo task, whose period is 3 ms. Furthermore, taking into account the resolution of the scheduler, 1 ms, the worst-case execution time for each individual tasks will fit inside the 1 ms blocks meaning that the maximum delay before the beginning of the execution of a task will be 2 ms. Since the worst-case execution time of the servo task is $100 \mu s$, taking into account the potential $2 \mu s$ block delays, the worst-case completion time
for the servo task would be 2100 \mu s, which still falls under the deadline of 3 ms.

### 8.3.1 Model

The tasking structure and the scheduler are modeled in the TASM language to perform various forms of analysis, including schedulability analysis. The 1 ms clock is modeled as a main machine, named *SCHEDULER* which constantly performs steps in 1 ms increments. The tasks are modeled as a single main machine, named *TASKS*, to reflect the single processor implementation. Tasks can be in 4 possible states—waiting, released, executing, and finished. The waiting state denotes a task that is waiting for the next period to begin its execution. The released state denotes a task that is ready to execute. The executing state denotes a task that is currently executing. The finished state denotes a task that has finished execution for the current release. The *TASKS* main machine is purely reactive and will perform steps if one of the tasks is in the executing state. Otherwise, the machine waits for a task to be granted execution. The main machine representing the task execution is given in Listing 8.18. In Listing 8.18, the time annotations correspond to the BCET and WCET estimates derived in the previous subsection.

The states of the tasks are manipulated by the scheduler, which is also modeled as a main machine. The scheduler follows the ticks of the 1 ms clock, releases tasks when the periods expire, and sends tasks to execute on the processor based on the priority scheme. There are no stoppage conditions for the model. The complete model of the scheduler and tasks contains 3 main machines, 1 function machine, and 10 sub machines. The complete scheduler model is documented in Appendix E, Section E.2, where the complete list of all machines is given in Table E.2.

### 8.3.2 Functional Analysis

Modeling the ETC tasking model in the TASM language enables analysis through model checking by translating the TASM model to *UPPAAL*. The properties that can be verified within *UPPAAL* include schedulability, that is, the absence of missed
Listing 8.18 TASKS main machine

R1: Execute manager {
    t := [0, 5];
    if manager_s = executing then
        manager_s := finished;
}

R2: Execute monitor {
    t := [100, 200];
    if monitor_s = executing then
        monitor_s := finished;
}

R3: Execute servo {
    t := [70, 100];
    if servo_s = executing then
        servo_s := finished;
}

R4: Else, do nothing, wait for an event {
    t := next;
    else then
        skip;
}


<table>
<thead>
<tr>
<th>Machine</th>
<th>Rules</th>
<th>Flattened Rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLOCK</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>SCHEDULER</td>
<td>4</td>
<td>28</td>
</tr>
<tr>
<td>TASKS</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 8.15: Number of rules for flattened main machines

deadlines, and safety and liveness properties of the scheduler logic.

**Uppaal Model**

In order to model check the TASM model for safety assertions and schedulability properties, the ETC TASM model leverages the Uppaal model checker, using the translation approach documented in Appendix C. Because the timed automata used in Uppaal do not have hierarchical composition facilities, the TASM main machines need to be “flattened” per the approach in the proof of Theorem 4.1 and in the proof of Theorem 4.2. The removal of hierarchical composition leads to exponential growth in the number of states in the “flattened” machine where multiple units of hierarchical composition happen in parallel. In the ETC tasking model, the Clock main machine and the Scheduler main machine both use hierarchical composition and need to be flattened. In the definition of the Clock main machine both rules utilize hierarchical composition in parallel, but the growth is tractable since it leads to only 16 rules \((2 \times 2 \times 2 \times 2)\). A similar growth occurs in the SCHEDULER main machine when executing the rule to wake up the various tasks. The number of rules for each flattened main machine of the TASM model is shown in Table 8.15.

The complete Uppaal model contains 4 timed automata, including 3 automata for each main machine of the TASM model and 1 automata to enforce the “Else rule” of the TASKS main machine.

The Uppaal verifier can be used to ensure that the scheduler behaves correctly according to expected functionality. For example, simple liveness queries can involve verifying that each task is eventually finished. For example, verifying that the manager task eventually executes can be expressed in the Uppaal query language as “A<> manager_s == 4”. Similar queries were formulated for the other tasks as well. An im-
portant safety property of the scheduler is that it enforces the single processor nature of the execution platform by not setting more than one task to the executing state. This safety assertion can be formulated as “A[] !(monitor_s == 3 & manager_s == 3) || (monitor_s == 3 & servo_s == 3) || (manager_s == 3 & servo_s == 3)”. Other safety and liveness properties can be formulated as well, as needed.

Completeness and consistency

The completeness and consistency of the tasking model was verified successfully following the approach presented in 5.1. The results of the completeness analysis, for the machines which are not trivially complete in shown in Table 8.16. The consistency analysis results are shown in Table 8.17.

<table>
<thead>
<tr>
<th>Name</th>
<th>Propositions</th>
<th>Clauses</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLOCK</td>
<td>3</td>
<td>7</td>
<td>Yes</td>
</tr>
<tr>
<td>SCHEDULER</td>
<td>4</td>
<td>15</td>
<td>Yes</td>
</tr>
<tr>
<td>SET_EXECUTION_PRIORITY</td>
<td>12</td>
<td>46</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 8.16: Completeness analysis results for the ETC tasking model

<table>
<thead>
<tr>
<th>Name</th>
<th>Propositions</th>
<th>Clauses</th>
<th>Consistent</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLOCK</td>
<td>3</td>
<td>7</td>
<td>Yes</td>
</tr>
<tr>
<td>SCHEDULER</td>
<td>4</td>
<td>15</td>
<td>Yes</td>
</tr>
<tr>
<td>TASKS</td>
<td>12</td>
<td>39</td>
<td>Yes</td>
</tr>
<tr>
<td>SET_EXECUTION_PRIORITY</td>
<td>12</td>
<td>46</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 8.17: Consistency analysis results for the ETC tasking model

For the tasking TASM model, most machines are trivially complete because the “Else rule” is used extensively, except for the CLOCK main machine and for the SET_EXECUTION_PRIORITY sub machine. Most machines are also trivially consistent, since most machines have very few rules, except for the 3 main machines and the SET_EXECUTION_PRIORITY sub machine. The TASKS main machine is the only machine that is not consistent and the counterexample generated by the SAT solver is the case where two tasks are executing simultaneously. Clearly, this case is not reachable in the model since the tasking structure is executed on a single proces-
8.3.3 Execution Time Analysis

The execution time analysis of the tasking structure concerns whether any of the 3 tasks could ever miss a deadline given the scheduling priority and the execution time of individual tasks. For the servo task, analyzing whether there is a possibility that the task could miss a deadline can be obtained by measuring the longest running time from the task being released to the task being finished. This model path can be easily formulated using the approach described in Section 5.3.3. The resulting observer automaton to measure the time necessary to complete this path is shown in Figure 8-5.

![Observer automaton to verify the execution time of the servo task](image_url)

After 2 iterations, the worst-case execution time of the servo task is measured to be 2100 $\mu$s, which is congruent with the preliminary analysis in the tasking model description. For the monitor task, the worst-case execution time is measured to be 1200 $\mu$s, corresponding to a one block execution delay and the worst-case execution time of the task. For the manager task, the worst-case execution time is 5 $\mu$s, with no delay before starting execution. This result is also expected since the manager task has the highest priority of all the tasks and the other tasks’ execution times will fit inside the 1 ms blocks.
8.3.4 Test Case Generation

In the ETC tasking model, the TASM machines describe the behavior of a scheduler and a set of tasks with different periods. For the test case generation, it is assumed that all the machines in the TASM model represent software components. Consequently, for all the machines in the model, test suites are generated using the algorithm described in Listing 7.8. The results of the test case generation are shown in Table 8.18. In Table 8.18, the first column provides the machine name, the second column lists the number of test case templates in the test suite template for the machine, and the third column lists the number of test cases from the test suite required for unit testing of the machine. Per the approach described in Chapter 7, the test cases are generated using the rule coverage criterion, explained in Section 7.1.1.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Test Suite</th>
<th>Unit Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLOCK</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>SCHEDULER</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>TASKS</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>finished_to_waiting</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>MANAGER_TICK</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>MONITOR_TICK</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>SERVO_TICK</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>SET_EXECUTING_TASK</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>SET_EXECUTION_PRIORITY</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>UPDATE_TASK_STATUSES</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>WAKE_UP_MANAGER</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>WAKE_UP_MONITOR</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>WAKE_UP_SERVO</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>WAKE_UP_TASKS</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 8.18: Test case generation results for the ETC tasking model

A sample test case template from the SCHEDULER main machine test suite is shown in Table 8.19.

8.3.5 Discussion

Modeling the tasking structure and scheduler in the TASM language enabled the verification of safety and liveness of the scheduler. Furthermore, the analysis of completeness and consistency uncovered missing cases in the model during the development
Table 8.19: Sample test case template from the test suite for the SCHEDULER main machine stages. While the scheduler is fairly straightforward since it uses a static fixed priority scheduling scheme with no preemption, modeling it in the TASM language shows the versatility of the language. Furthermore, analyzing the TASM tasking model using the framework uncovered errors in the Simulink model which were not immediately apparent. The Simulink model did not model the mutual exclusion of each task correctly. In part, this is due to the confusion surrounding the semantics of Stateflow; however, Simulink and Stateflow do not provide any verification facilities to ensure that these cases cannot happen. By modeling the scheduler and tasks in TASM and by using the proposed framework, the scheduler was verified to ensure that all tasks are executed while ensuring mutual exclusion.

The execution time analysis displays another application of the observer automaton paradigm, to evaluate whether certain deadlines are missed. The worst-case execution times for each task to complete its execution, while taking into account the priority scheme, were obtained to make sure that no deadlines are missed. Once again, this type of analysis is not possible with Simulink and Stateflow. In this case, the schedulability analysis was quite simple, and could have been done with pen and paper; however, more complex schedulability problems would not require many changes to the TASM model and the analysis approach could be reused without any modifications. The execution time analysis also uncovers some limitations in the observer automaton described in Section 5.3. Since the form of the automaton observes only simple paths between a fixed start state and a fixed final state, certain properties

<table>
<thead>
<tr>
<th>Pre State</th>
<th>Post State</th>
<th>Coverage Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>scheduler.s{wakeup}, oldtick[3], tick[5],</td>
<td>scheduler.s{execute}, oldtick[5],</td>
<td>SCHEDULER.R1, WAKEUP_TASKS.R1,</td>
</tr>
<tr>
<td>manager.s{released}, managertick{MANAGER.PERIOD},</td>
<td>manager.s{released},</td>
<td>WAKEUP_MANAGER.R1, WAKEUP_MONITOR.R1,</td>
</tr>
<tr>
<td>monitor.s{released}, monitortick{MONITOR.PERIOD},</td>
<td>monitor.s{released},</td>
<td>WAKEUP_MONITOR.R1, WAKEUP_SERVO.R1</td>
</tr>
<tr>
<td>servos.s{released}, servotick{SERVO.PERIOD}</td>
<td>servos.s{released}</td>
<td></td>
</tr>
</tbody>
</table>
cannot be expressed in this paradigm. For example, it is not possible to formulate a path to measure the execution time required for all tasks to complete their execution. Formulating this property is possible through a custom observer automaton with a structure more complex than the basic structure presented in Figure 5-2. Other properties that cannot be estimated using the proposed observer automaton structure include determining the major cycle. Nevertheless, the proposed approach has yielded interesting results in verifying the absence of missed deadlines for the tasking model. Furthermore, by translating the TASM model to UPPAAL, an end-user is free to use UPPAAL freely without imposing limits to the functionality provided by the framework which is usable and flexible, but represents only a subset of the capabilities of UPPAAL.

8.4 Electronic Throttle Controller: Low Level Model

The high level version of the electronic throttle controller, presented in Section 8.2, focused on the logic used to set the mode of operation of the controller and focused on the logic used to calculate the desired current. In this version of the ETC model, the throttle controller functionality modeled in Section 8.2 is implemented using the tasking model and the scheduler modeled in Section 8.3. This model combines time-dependent behavior with the mode switching logic and with the current calculation logic. The model presented in this section also extends previous models by adding resources that are consumed by the throttle controller. The analysis presented in this section is used to illustrate the bi-directional traceability capabilities of the presented framework, as described in Chapter 6, and the generation of unit test cases, as described in Section 7.6.
8.4.1 Model

In order to model the implementation of the throttle controller using the tasking structure described in the previous section, the functional model developed in Section 8.2.1, referred to as model $\mathcal{F}_0$, is combined with the tasking model developed in Section 8.3.1, referred to as model $\mathcal{T}_0$. For the most part, the machines of model $\mathcal{F}_0$ and the machines of model $\mathcal{T}_0$ can be combined directly without changes, except for the $\text{CONTROLLER}$ main machine of model $\mathcal{F}_0$ and the $\text{TASKS}$ main machine of model $\mathcal{T}_0$. The datatypes and environment variables can also be combined without modification.

The resources that are included in the model are "memory" and "power". The amount of memory available for the throttle controller is 2048 kilobytes, per the properties of the target platform implementation platform [251]. For power consumption, there is typically no upper bound, so a large value is chosen as the resource upper bound, 1 Mega Watt. The case of power consumption is interesting because analyzing the power consumption is not done to establish whether a finite amount will be exhausted, but is done to understand what the peak power consumption will be. The modeling of resources is included in the "final" model resulting from the combination of model $\mathcal{F}_0$ and model $\mathcal{T}_0$, a model called model $\mathcal{FT}_1$. The "final model" is obtained through successive refinements of each model. The following subsections describe the refinements used to obtain model $\mathcal{FT}_1$.

Refined Tasking Model Level 1: $\mathcal{T}_1$

The first step of combining model $\mathcal{F}_0$ and model $\mathcal{T}_0$ is to divide the manager task of model $\mathcal{T}_0$ into two steps – one step to set the major mode and one step to set the minor mode. To maintain the semantics of the manager task, the steps should be consecutive and atomic within the manager task execution. This refinement is achieved through a "step expansion refinement", as described in Section 6.2.1. The step expansion is achieved by dividing rule $R_2$ of the $\text{TASKS}$ main machine, shown in Listing 8.18, into 2 rules, $R_{11}$ and $R_{12}$. The consecutive execution of the two
refined rules is achieved by introducing a new variable called \texttt{manager.s.step}, whose responsibility is to ensure that rule \( R_{11} \) and rule \( R_{12} \) are executed in sequence. The modified rules of the refined model, called model \( T_1 \), are shown in Listing 8.19.

\textbf{Listing 8.19} Rules of the \textit{TASKS} main machine of model \( T_1 \) (partial)

\begin{verbatim}
R11: Execute manager - set major mode
{ 
  t := [0, 3];

  if manager_s = executing and manager_s_step = major_mode then
    manager_s_step := minor_mode;
}

R12: Execute manager - set minor mode
{ 
  t := [0, 2];

  if manager_s = executing and manager_s_step = minor_mode then
    manager_s_step := major_mode;
    manager_s := finished;
}
\end{verbatim}

The traceability relationship from model \( T_0 \) to model \( T_1 \) is simply the identity mapping of all rules of all machines except for rule \( R_1 \) of the \textit{TASKS} main machine, whose traceability mapping is included in the set of "step expansion refinements". The complete traceability relationship can be expressed as:

\[ T = T_0 \leftrightarrow T_1 = T_{id} \cup T_{sexp} \]

Where:

- \( T_{id} \) = identity mappings for all rules of all machines except for rule \( R_1 \) of machine \textit{TASKS}

- \( T_{sexp} = \{ \{\text{TASKS}.R_1\}, \{\text{TASKS}.R_{11}, \text{TASKS}.R_{12}\} \} \)
It is fairly obvious to see that the correctness criteria of Section 6.2.2 for the step expansion refinement is met since the time annotations of rule $R_{11}$ and rule $R_{12}$ are contained within the time annotation of rule $R_1$. Furthermore, the guards of the refined rules also meet the correctness criteria, as shown by the truth table shown in Table 8.20.

<table>
<thead>
<tr>
<th>manager_s executing</th>
<th>manager_s_step major_mode</th>
<th>manager_s_step minor_mode</th>
<th>$G_1$</th>
<th>$G_{11}$</th>
<th>$G_{12}$</th>
<th>$(G_{11} \lor G_{12})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>T</td>
<td>F</td>
<td>T</td>
<td>T</td>
<td>F</td>
<td>T</td>
</tr>
<tr>
<td>T</td>
<td>F</td>
<td>T</td>
<td>T</td>
<td>F</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>F</td>
<td>T</td>
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<tr>
<td>F</td>
<td>F</td>
<td>T</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>

Table 8.20: Truth table for the step expansion refinement between rule $R_1$ of model $T_0$ and rules $R_{11}$ and $R_{12}$ of model $T_1$.

Furthermore, no other rule changes the value of manager_s from executing to another value, no other rule changes the value of manager_s_step, the two rules are sequential through manager_s_step, and the result of executing both rules in sequence is the same as the result of executing rule $R_1$. Because the correctness criteria holds for the step expansion refinement, the analysis performed on model $T_0$, in Section 8.3, still holds in model $T_1$. Since the time annotations in both models are equivalent through equality bounds, the analysis results that are preserved from model $T_0$ include the functional analysis, the schedulability analysis, and the worst-case execution time analysis. Consequently, the absence of deadlines and the safety of the scheduler, as determined in Section 8.4.4, are preserved through the refinement, in model $T_1$.

Refined Tasking Model Level 2: $T_2$

In the second refinement level, elements manipulating the state from model $T_0$ are introduced into model $T_1$. The first refinement for this level happens with the SCHEDULER main machine. The refinement is of the type “step expansion”, performed by adding rule $R_0$ to the rules of the SCHEDULER main machine to be executed after rule $R_4$ and before rule $R_1$. The refinement is achieved by expanding the Scheduler
datatype by adding an extra member, called `update_state`. The refinement occurs so that the scheduler reads the state of the sensors at 1 ms intervals, at the beginning of each tick. This is achieved by reusing the `SAMPLE_STATE` sub machine defined in Section 8.2. The added rule, rule $R_0$, and the modified version of rule $R_4$ are shown in Listing 8.20. The refinement adds a step to the scheduler execution, at the beginning, by caching the state at the beginning of each execution cycle. The state updating rate is congruent to the functionality of the Simulink model described in [111], which is driven by a 1 ms clock.

<table>
<thead>
<tr>
<th>Listing 8.20 Modified rules of <code>SCHEDULER</code> main machine of model $T_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_0$: Step 0, update state</td>
</tr>
<tr>
<td>{</td>
</tr>
<tr>
<td>if scheduler_s $=\text{update_state}$ then</td>
</tr>
<tr>
<td><code>SAMPLE\_STATE();</code></td>
</tr>
<tr>
<td>scheduler_s := update_tasks;</td>
</tr>
</tbody>
</table>
|}

|...|

|$R_4$: Wait for a tick |
|{ |
|  $t := \text{next}$; |
|  if scheduler $=\text{wait}$ then |
|    scheduler_s := update_state; |
|}

Using a structure and an argument similar to the step expansion refinement for the `TASKS` main machine in model $T_1$, it can be shown that the step expansion refinement preserves the semantics of model $T_1$ and, by associativity, the semantics of model $T_0$. The refinement meets the correctness criteria of Section 6.2.2, since the refined rules follow sequentially, and the updates introduced by the `SAMPLE_STATE` sub machine affect only the expanded state space and no other rule in model $T_1$.

The second refinement that occurs at this level is the addition of state manipulating functionality for the task executions. Analogously to the refinement of the `SCHEDULER` main machine, this refinement is achieved by reusing sub machines from model $F_0$, namely the `SET\_MAJOR\_MODE`, `SET\_MINOR\_MODE`, `MONITOR\_HEALTH`, and `CALCULATE\_OUTPUT` sub machines. The refined `TASKS`
main machine is shown in Listing 8.21. For this refinement, the refinement is of type "rule expansion", where each rule $R_i$ of the TASKS main machine of model $T_1$ is mapped one-to-one to each rule of the TASKS main machine of model $T_2$. It is easy to see that, in the mapping, each time annotation and each guard is equivalent. The difference happens in the effect expressions. Since the sub machines that are used in the refinement do not depend or modify the state of model $T_1$, it can be shown that the refinement preserves the semantics of model $T_1$, and by associativity, the semantics of model $T_0$. The equivalence of the guards in the mapping can be easily visualized through previous analysis. Per the analysis presented in Table 8.9, all the sub machines introduced in Listing 8.21 are complete. Consequently, the equivalent "flattened" machine for Listing 8.21 will yield a machine where the guards between the mapped rules will also be complete since completeness is preserved through hierarchical composition per the proof of Theorem 5.1. The extra rules introduced by the use of sub machines are included in the rule expansion refinement since the equivalent "flattened" machine would yield the one-to-many mapping that includes the extra rules.

The traceability relationship for this refinement level can be expressed as:

$$T = T_1 \leftrightarrow T = T_1 \cup T_{\text{id}} \cup T_{\text{sexp}} \cup T_{\text{exp}}$$

Where:

- $T_{\text{id}}$ = identity mappings for all rules of all machines except for rule $R_4$ of machine $SCHEDULER$, and rules $R_{11}$, $R_{12}$, $R_2$, and $R_3$ of machine $TASKS$

- $T_{\text{sexp}} = (\{SCHEDULER.R_4\}, \{SCHEDULER.R_4, SCHEDULER.R_0\})$

- $T_{\text{exp}} = (\{TASKS.R_{11}\}, \{TASKS.R_{11}\}, \{TASKS.R_{12}\}, \{TASKS.R_{12}\})$
**Listing 8.21** Modified TASKS main machine of model $T_2$

R11: Execute manager
{
  \( t := [0, 3]; \)
  
  if manager_s = executing and manager_s_step = major_mode then
    SET_MAJOR_MODE();
    manager_s_step := minor_mode;
}

R12: Execute manager
{
  \( t := [0, 2]; \)
  
  if manager_s = executing and manager_s_step = minor_mode then
    SET_MINOR_MODE();
    manager_s_step := major_mode;
    manager_s := finished;
}

R2: Execute monitor
{
  \( t := [100, 200]; \)
  
  if monitor_s = executing then
    MONITOR_HEALTH();
    monitor_s := finished;
}

R3: Execute servo
{
  \( t := [70, 100]; \)
  
  if servo_s = executing then
    CALCULATE_OUTPUT();
    servo_s := finished;
}

R4: Else, do nothing, wait for event
{
  \( t := \text{next}; \)
  
  else then
    skip;
}
\[
\{\text{TASKS}.R_2\}, \{\text{TASKS}.R_2\} , \{\text{TASKS}.R_3\}, \{\text{TASKS}.R_3\} \}
\]

Through this sequence of refinements of model \( T_0 \), the refinements have conformed to the correctness criteria described in Section 6.2.2. Consequently, the analysis results performed on model \( T_0 \) are preserved for model \( T_2 \).

**Refined Functional Model Level 1: \( \mathcal{F}_1 \)**

The refinement of model \( T_0 \) from a tasking model to a combination of tasking and functional model was performed in appropriately defined steps to show that the refinements were performed to preserve the analysis performed on model \( T_0 \). In this section, an attempt is made to refine model \( \mathcal{F}_0 \) stepwise to preserve its semantics all the while introducing scheduling. The first step of the refinement introduces time annotations into the \( \text{CONTROLLER} \) main machine using the task execution times. The modified rules of the \( \text{CONTROLLER} \) machine are shown in Listing 8.22. In Listing 8.22, the only difference in the refinement is the addition of time annotations for rules \( R_2 \), \( R_3 \), \( R_4 \), and \( R_5 \), using the task execution times. This refinement corresponds to a rule expansion refinement between the \( \text{CONTROLLER} \) main machine of model \( \mathcal{F}_0 \) and the \( \text{CONTROLLER} \) main machine of model \( \mathcal{F}_1 \).

Because the guards and effect expressions are equivalent between model \( \mathcal{F}_0 \) and model \( \mathcal{F}_1 \), the correctness criteria of the rule expansion refinement for the guards and effect expressions are met. However, the correctness criteria regarding the time annotations between model \( \mathcal{F}_0 \) and model \( \mathcal{F}_1 \) are not met. Consequently, if timing analysis was performed in model \( \mathcal{F}_0 \), the analysis results would not necessarily hold in \( \mathcal{F}_1 \). However, while the addition of time annotations affects the timing of the model, the sequence of execution of the rules remains unchanged between model \( \mathcal{F}_0 \) and model \( \mathcal{F}_1 \). Consequently, the functional analysis performed on model \( \mathcal{F}_0 \), in Section 8.2.2 still holds in model \( \mathcal{F}_1 \). This can be established using the argument that the \( \text{CONTROLLER} \) main machine executes a “full loop” using the cached state. In the case of model \( \mathcal{F}_1 \), the performance of the controller will be lower since the
Listing 8.22 Rules of the CONTROLLER main machine of model $F_1$

R1: Controller loop when nominal
{
   if control_mode = sample then
      SAMPLE_STATE();
      control_mode := mode_set;
}

R2: Controller loop to set major mode
{
   t := [0, 3];
   
   if control_mode = mode_set_major then
      SET_MAJOR_MODE();
      control_mode := mode_set_minor;
}

R3: Controller loop to set minor mode
{
   t := [0, 2];
   
   if control_mode = mode_set_minor then
      SET_MINOR_MODE();
      control_mode := output;
}

R4: Controller loop to output current
{
   t := [70, 100]
   
   if control_mode = output then
      CALCULATE_OUTPUT();
      control_mode := health;
}

R5: Controller loop to find failure
{
   t := [100, 200];
   
   if control_mode = health then
      MONITOR_HEALTH();
      control_mode := sample;
}
actions are not instantaneous, but the safety and liveness of the ETC are preserved because the correctness criteria hold. The traceability relationship between model $F_0$ and model $F_1$ can be expressed as:

$$T = F_0 \leftrightarrow F_1 = T_{id} \cup T_{exp}$$

Where:

- $T_{id}$ = identity mappings for all rules of all machines except for rules $R_1$, $R_2$, $R_3$, $R_4$, and $R_5$ of machine CONTROLLER

- $T_{exp}$ = $\langle\langle\{\text{CONTROLLER}.R_1\}, \{\text{CONTROLLER}.R_1\}\rangle,$
  $\langle\{\text{CONTROLLER}.R_2\}, \{\text{CONTROLLER}.R_2\}\rangle,$
  $\langle\{\text{CONTROLLER}.R_3\}, \{\text{CONTROLLER}.R_3\}\rangle,$
  $\langle\{\text{CONTROLLER}.R_4\}, \{\text{CONTROLLER}.R_4\}\rangle,$
  $\langle\{\text{CONTROLLER}.R_5\}, \{\text{CONTROLLER}.R_5\}\rangle)$

**Refined Functional Model Level 2: $F_2$**

The refinement of model $F_1$ into model $F_2$ involves adding the scheduler and the tasking structure of model $T_0$ to model $F_1$. The refined version of the CONTROLLER main machine resembles the machine of Listing 8.21, with the variable control_mode removed from the rules. Since model $F_2$ is drastically different from model $F_1$, the functional properties analyzed in model $F_0$ no longer hold in model $F_2$. Nevertheless, the rules can be traced syntactically using rule expansion refinements with an identical mapping from model $F_1$ to model $F_2$ as in the mapping between model $F_0$ and model $F_1$. 

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Final Refined Model: $\mathcal{FT}_1$

The two refinement branches converge at a common model called $\mathcal{FT}_0$ that is traceable to model $\mathcal{F}_2$ and, by associativity, to model $\mathcal{F}_0$. Furthermore, model $\mathcal{FT}_0$ to model $\mathcal{T}_2$. The final step in refining the ETC low level model, resulting in model $\mathcal{TF}_1$, adds resource annotations to model $\mathcal{FT}_0$. The model contains 2 resources - memory and power consumption. The resources are modeled to estimate the maximum power consumption of the throttle controller, and to ensure that the memory used by the controller is adequately bounded. The power consumption resource utilization was estimated using the characteristics of the Xilinx Virtex II Pro implementation platform, which uses a PowerPC 405 processor operating at 10 MHz [251]. The memory consumption was also estimated using the properties of the Xilinx Virtex II Pro, using a combination of the operations listed in Table 8.14 and the Simulink model. Both resources are consumed only by the functional aspects of the model, that is, mode setting, desired current calculation, and health monitoring. The resource consumption of the scheduler and the clock are assumed to be negligible.

In order to estimate the memory necessary to set the mode and to calculate the desired current, the Simulink model is abstracted using the list of Simulink blocks, variables, and parallel operations performed in each subsystem. For example, the sliding mode controller used to calculate the throttle controller current commanded by the driver input is shown in Figure 8-6. In Figure 8-6, there are 6 parallel lines of computation and the computations are achieved through 26 variables of type float, 3 integrators, 9 gains, 7 additions, 1 saturation, 2 sign reversals, 1 discrete filter, and a summation at the end of the computation. The memory usage is estimated using the number of variables necessary to perform the calculation and the properties of the execution platform. The power consumption is estimated using the parallel branches of computation, the number of maximum number of clock cycles required to perform on each branch, and the properties of the implementation platform. For most current calculations in the Simulink model, there are multiple calculation paths that can be followed to obtain the desired current. Consequently, it is possible to obtain
Table 8.21: Resource usage estimates for the ETC low level model

<table>
<thead>
<tr>
<th>Calculated Current</th>
<th>Min Power (mW)</th>
<th>Max Power (mW)</th>
<th>Min Memory (bytes)</th>
<th>Max Memory (bytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human</td>
<td>769</td>
<td>895</td>
<td>196</td>
<td>360</td>
</tr>
<tr>
<td>Cruise</td>
<td>800</td>
<td>800</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>Human + Cruise</td>
<td>864</td>
<td>1695</td>
<td>324</td>
<td>826</td>
</tr>
<tr>
<td>Traction</td>
<td>800</td>
<td>800</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>Rev</td>
<td>800</td>
<td>800</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>Traction + Rev</td>
<td>1425</td>
<td>1425</td>
<td>648</td>
<td>648</td>
</tr>
<tr>
<td>Fault</td>
<td>855</td>
<td>895</td>
<td>512</td>
<td>512</td>
</tr>
</tbody>
</table>

minimum and maximum values for both resource calculations. The results of the resource usage estimation for the desired current calculations are shown in Table 8.21. Similar estimates were made for the health monitoring logic and for the startup and shutdown modes. The results of the estimates serve as resource annotations in the TASM model. The modified machines containing resource annotations are provided in Section E.3.

Complete Model

The complete ETC low level TASM model contains 5 main machines, 14 function machines, and 20 sub machines. The complete low level ETC model is documented in Appendix E where the list of all machines is shown in Table E.3 and in Table E.4.

8.4.2 Traceability

The sequence of refinements performed in Section 8.4.1 yields a tree of models that can be navigated through the relation of rules of machines. The complete traceability relationship can be visualized as illustrated in Figure 8-7. In Figure 8-7, model $\mathcal{F}_0$ corresponds to the model described and analyzed in Section 8.2, model $\mathcal{L}_0$ corresponds to the model described and analyzed in Section 8.3, and model $\mathcal{FT}_1$ corresponds to the model described and analyzed in this section.
This is a standard sliding mode controller design. The (known) nonlinear dynamics are subtracted off the system and a signum or saturation function is then used along with a tunable gain, $K$, to achieve the control objective. In this case, the control objective is to bring the error between the desired throttle angle and the actual throttle angle to zero.

Figure 8-6: Simulink sliding mode controller to calculate driver throttle current
Figure 8-7: Traceability between different versions of the ETC model
8.4.3 Functional Analysis

Since the steps of the refinements performed to combine the functional model presented in Section 8.2 with the model presented in Section 8.3 do not preserve the semantics of model $F_0$, the functional analysis performed in Section 8.2.2 must be performed again on model $TF_1$. The safety properties verified in $F_0$ utilized the sequential nature of the controller execution to ensure that the mode was always set correctly according to the requirements, based on the state cached by the controller and based on the step of operation of the controller. However, in model $TF_1$, since the functionality is implemented using a tasking model where the manager task executes at a slower rate (every 10 ms) than the controller resolution (1 ms), some controller iterations do not meet the safety properties expressed in Section 8.2.2. The properties verified in Section 8.2.2 assumed that the controller would set the mode at every controller iteration, which is not true for model $TF_1$. Consequently, the queries from Section 8.2.2 need to be modified. The queries can capitalize on the subtleties of the execution, where the state is cached at the beginning of the controller iteration and each task will be in the finished state in an iteration only if the task has executed during the previous iteration. Furthermore, since it has been established through the execution time analysis of model $T_0$ that the execution of each task will complete within a controller iteration, the safety property to verify that the limiting mode is always set correctly, when the engine speed or the torque is above the predefined threshold, can be formulated as:

- $A \ G (system\_health = nominal \land c\_engine\_speed > MAX\_ENGINE\_SPEED \land scheduler\_s = update\_state \land manager\_s = finished) \rightarrow (controller\_mode = limiting)$

- $A \ G (system\_health = nominal \land c\_vehicle\_torque > MAX\_TORQUE \land scheduler\_s = update\_state \land manager\_s = finished) \rightarrow (controller\_mode = limiting)$
The scheduler will be in the “update state” step after an iteration has completed and before the cached state is updated. Consequently, at that step, if the manager task has executed, the mode should be set correctly. The requirement that no fault be present is necessary because if a fault is detected, it will override all other modes. Similar queries can be formulated to verify that the mode is set correctly for the driving mode and for the minor modes. To verify the calculation of the desired current, the queries from Section 8.2.2 can be adapted in a similar fashion:

- \[ A \; G \; (controller\_mode = \text{driving} \land scheduler\_s = \text{update\_state} \land servo\_s = \text{finished}) \rightarrow (\text{desired\_current} = \text{human\_c} \lor \text{desired\_current} = \text{cruise\_c} \lor \text{desired\_current} = \text{max\_driving\_c}) \]

- \[ A \; G \; (controller\_mode = \text{limiting} \land cruise\_mode = \text{active} \land rev\_limiting\_mode = \text{active} \land traction\_mode = \text{active} \land scheduler\_s = \text{update\_state} \land servo\_s = \text{finished}) \rightarrow (\text{desired\_current} = \text{min\_limiting\_c}) \]

The status of the servo task also needs to be queried because the servo task will not execute at every controller iteration and will execute in an iteration only if it is the only released task since it has the lowest priority of all the tasks. Other similar queries could be written to verify that the minor modes are set properly and that the current is calculated correctly for all the combination of major and minor modes. Those queries would follow a pattern similar to the queries presented in this section and are omitted for brevity. In order to verify the safety properties, the TASM model is translated to UPPAAL's timed automata.

**UPPAAL Model**

In order to model check the TASM model for safety assertions, the ETC TASM model leverages the UPPAAL model checker, using the translation approach documented in Appendix C. Because the timed automata used in UPPAAL do not have hierarchical
composition facilities, the TASM main machines need to be "flattened" per the approach in the proof of Theorem 4.1 and in the proof of Theorem 4.2. In the low level ETC model, model $T \mathcal{F}_1$, 3 main machines use hierarchical composition and need to be flattened – the \textit{CLOCK} main machine, the \textit{SCHEDULER} main machine, and the \textit{TASKS} main machine. The number of rules for each flattened main machine of the TASM model is shown in Table 8.22.

The complete \textsc{Uppaal} model contains 9 timed automata, including 5 automata for each main machine of the TASM model and 4 automata to enforce the "Else rules" of the \textit{DRIVER}, \textit{SCHEDULER}, \textit{TASKS}, and \textit{VEHICLE} main machines. The safety properties given as temporal logic formulas can be easily translated to the TCTL query language of \textsc{Uppaal}. The \textsc{Uppaal} queries corresponding to the safety properties stated above are shown below, in the order in which they were introduced:

- $A[] (c\_engine\_speed > \text{MAX\_ENGINE\_SPEED} \&\& \text{system\_health} == 1 \&\& \text{scheduler\_s} == 5 \&\& \text{manager\_s} == 4) \imply (\text{controller\_mode} == 5)$

- $A[] (c\_vehicle\_torque > \text{MAX\_TORQUE} \&\& \text{system\_health} == 1 \&\& \text{scheduler\_s} == 5 \&\& \text{manager\_s} == 4) \imply (\text{controller\_mode} == 5)$

- $A[] (\text{controller\_mode} == 4 \&\& \text{scheduler\_s} == 5 \&\& \text{servo\_s} == 4) \imply (\text{desired\_current} == 2 \text{ || } \text{desired\_current} == 3 \text{ || } \text{desired\_current} == 3)$

<table>
<thead>
<tr>
<th>Machine</th>
<th>Rules</th>
<th>Flattened Rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLOCK</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>DRIVER</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>SCHEDULER</td>
<td>5</td>
<td>29</td>
</tr>
<tr>
<td>TASKS</td>
<td>5</td>
<td>33</td>
</tr>
<tr>
<td>VEHICLE</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 8.22: Number of rules for flattened main machines
desired_current == 7)

- A[] (controller_mode == 5 && cruise_mode == 1 && rev_limiting_mode == 1 && traction_mode == 1 && scheduler_s == 5 && servo_s == 4) imply (desired_current == 6)

These properties were successfully verified by running the queries through the UPPAAL verifier. The model can also be queried to verify certain liveness properties, to ensure that the model behaves correctly. For example, the property "eventually, the car can be in cruise control" can be verified. This property can be formulated as the liveness property "E<> cruise_mode == 1". Other liveness and safety properties can be formulated in a similar fashion, as needed.

Completeness and Consistency

The completeness and consistency of the low level ETC model was verified successfully following the approach presented in 5.1. The results of the completeness analysis are shown in Table 8.23. The consistency analysis results are shown in Table 8.24. The completeness and consistency analysis was performed only for the machines whose rules were changed from the model presented in Section 8.2 and the model presented in Section 8.3. For the machines in the low level model, model $\mathcal{F}_1$, whose rules were not modified, the completeness and consistency results are available in Table 8.9, Table 8.16, Table 8.10, and Table 8.17.

<table>
<thead>
<tr>
<th>Name</th>
<th>Propositions</th>
<th>Clauses</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCHEDULER</td>
<td>5</td>
<td>32</td>
<td>Yes</td>
</tr>
<tr>
<td>TASKS</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 8.23: Completeness analysis results for the ETC low level model

For the low level ETC TASM model, the only machines whose completeness and consistency need to be verified are the SCHEDULER main machine and the TASKS
Table 8.24: Consistency analysis results for the ETC low level model

<table>
<thead>
<tr>
<th>Name</th>
<th>Propositions</th>
<th>Clauses</th>
<th>Consistent</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCHEDULER</td>
<td>5</td>
<td>32</td>
<td>Yes</td>
</tr>
<tr>
<td>TASKS</td>
<td>14</td>
<td>42</td>
<td>No</td>
</tr>
</tbody>
</table>

main machine. The other machines which were modified were altered to include resource consumption annotations to the rules. Because the rule guards were not changed, the completeness and consistency of the machines are not affected. According to the results presented in Table 8.24, the TASKS main machine is not consistent. The counterexample generated by the SAT solver is the same state as the one described in the analysis of the consistency results presented in Table 8.10. The counterexample is the state where two tasks are executing simultaneously, a state which is clearly not reachable since the functionality is implemented on a single processor architecture. It can be easily verified that this state is not reachable, through the safety invariant query \( A[] !((\text{monitor.s} == 3 \&\& \text{manager.s} == 3) \sqcup (\text{monitor.s} == 3 \&\& \text{servo.s} == 3) \sqcup (\text{manager.s} == 3 \&\& \text{servo.s} == 3)) \) against the timed automata UPPAAL model. Interestingly enough, this safety invariant was verified for model \( T_0 \) in Section 8.3.1 and given the nature of the refinements, this property is guaranteed to hold in model \( TF_1 \).

### 8.4.4 Execution Time Analysis

Given that the refinements of the tasking model, model \( T_0 \), presented in Section 8.3, meet the correctness criteria, the execution time analysis results from Section 8.3.3 are preserved in model \( FT_1 \). Consequently, the schedulability analysis and the absence of missed deadlines analysis performed on model \( T_0 \) are guaranteed to hold in model \( TF_1 \). Using the approach presented in Section 5.3, other execution time properties of model \( TF_1 \) can be verified. For example, execution time properties for a combination of functional properties and scheduling properties can be verified.
End-to-End Latency

End-to-end latency refers to the amount of time that it takes for the system to react to a change in the environment. In terms of the ETC, end-to-end latency could refer to the amount of time required for the controller to output the appropriate current to remedy a given situation. For example, the end-to-end latency of mitigating the torque rising over the critical threshold would be the BCET and WCET of the ETC setting the desired current to "traction limiting", taking into account the effects of scheduling to set the appropriate controller mode and to calculate the desired current based on the mode. The DRIVER and VEHICLE main machines model the behavior of the surroundings of the ETC and are modeled so that changes in the vehicle torque and in the engine RPM can occur at any point. Consequently using the iterative bounded liveness approach against the UPPAAL model derived in Section 8.4.3 can yield the desired measures through an appropriately defined observer automaton.

For example, the observer automaton shown in Figure 8-8 is used to measure the end-to-end latency of the ETC outputting current to mitigate a vehicle torque over the critical threshold. In the observer, it is important to include the health of the system in the path formula. Otherwise, the timing of the path could be unbounded because a fault could occur after the torque rise and the ETC would enter the "faulty" mode and would never handle the torque condition.

Figure 8-8: Observer automaton to measure the end-to-end latency of the ETC for the vehicle torque being over the critical threshold

After two iterations of verifying $\phi_{max}$ against the UPPAAL model, the WCET of the end-to-end latency corresponding to the behavior observed through the automaton
shown in Figure 8-8 is determined to be $12100\mu s$. This WCET corresponds to the rise in torque occurring at the same time as the manager task beginning execution, after the state has been cached. $10000\mu s$ elapse until the next execution of the manager task (10 ms period), where the appropriate controller mode is set after the manager task has completed its execution. However, the desired current will not be calculated until the servo task completes its execution. Since the period of the servo task is (3 ms), the servo task will be released $2000\mu s$ after the beginning of the execution of the manager task. Since the servo task has a WCET of $100\mu s$, the desired current to handle the torque limiting will occur $100\mu s$ after the beginning of the execution of the servo task, resulting in an end-to-end latency WCET of $12100\mu s$. It is interesting to notice that the WCET occurs only if the torque rise occurs at the beginning of the first execution of the manager task within the major cycle. Since the major cycle is 30 ms, the manager task executes 3 times per major cycle, at the beginning, 10 ms into the cycle, and 20 ms into the cycle. The WCET occurs this way because the second execution provides the largest gap between the end of the manager task and the beginning of the servo task, when the mode is set and the desired current is calculated.

The BCET of the same end-to-end latency is verified to be $2070\mu s$, also after two iterations, but through verifying $\phi_{min}$. This BCET corresponds to the rise in torque occurring immediately before the beginning of the major cycle, when all tasks are released. Given the task priority, the manager task executes first, followed by the monitor task, $1000\mu s$ later, followed by the servo task, $1000\mu s$ later. Given that the BCET of the servo task is $70\mu s$, the total BCET reaches $2070\mu s$.

For the situation where the ETC remedies a rise in engine RPM, the BCET and WCET of the end-to-end latency is exactly the same as for the torque case. The similarity occurs because the reaction delay is purely a result of the scheduling properties of the various tasks. The time required to set the controller mode and the time required to calculate the desired current is independent of what mode is being set and which desired current is being output.

Another interesting situation to consider, and which yields different timing results,
is the BCET and WCET of the end-to-end latency for the ETC to remedy a fault. The
WCET for this situation is 42100\(\mu s\) and the BCET is 12070\(\mu s\). The BCET is achieved
when the fault occurs right before the beginning of the major cycle. However, since
the manager task has a higher priority than the monitor task, it runs first, without
the fault having been detected. The monitor task runs second and detects the fault.
However, the manager task does not set the appropriate fault handling mode until
10 ms after the beginning of the major cycle. Furthermore, the appropriate desired
current does not get output until the next execution of the servo task, 2 ms after
the beginning of execution of the manager task. The WCET occurs when the fault
happens right after the beginning of the major cycle, once the state has been cached.
The fault will not be detected until the beginning of the following major cycle, 30 ms
later, and, given the priority of the manager task and the same argument as in the
BCET case, the fault is not handled until 12100\(\mu s\) later, resulting in the WCET of
42100\(\mu s\). The summary results for the end-to-end latency analysis of model \(\mathcal{F}_1\) are
summarized in Table 8.25.

<table>
<thead>
<tr>
<th>Po</th>
<th>P1</th>
<th>WCET</th>
<th>Iter</th>
<th>BCET</th>
<th>Iter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>system.health = nominal,</td>
<td>12100(\mu s)</td>
<td>2</td>
<td>2070(\mu s)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>vehicle.torque &gt; MAX.TORQUE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(desired.current = traction.c or</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>desired.current = min.limiting.c),</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>system.health = nominal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>system.health = nominal, engine.speed &gt; MAX.ENGINE.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SPEED</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(desired.current = rev.c or</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>desired.current = min.limiting.c),</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>system.health = nominal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>fault = True</td>
<td>42100(\mu s)</td>
<td>2</td>
<td>12070(\mu s)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>desired.current = fault.c</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8.25: End-to-end latency analysis results for the ETC low level model

### 8.4.5 Resource Consumption Analysis

The resource consumption analysis provided by the proposed framework provides
calculations for the best-case and worst-case amounts of resources consumed, as ex-
plained in Section 5.4. The algorithm iterates through combinations of rules that can
be executed in parallel in order to find a combination of rules who are satisfiable and
which yield maximal and minimal resource usage. Per TASM semantics, resource usage is additive through parallel rule execution. The parallelism can be achieved
either through main machines executing simultaneously, or through multiple units of hierarchical composition. In the ETC model, the implementation of the functionality is fairly simple, on a single processor architecture, and there are few interactions between the tasks. Furthermore, the calculation logic for the desired current is also of low complexity.

Because the ETC implementation does not contain any parallel consumption of resources through the use of multiple main machines, the minimum and maximum amounts of resources consumed will correspond to the minimum and maximum amounts contained in an individual rule. For the maximum amount of power consumed, 1695 milliWatts, it occurs when rule $R_1$ of the Driving.Throttle.C machine is executed. The minimum amount of power consumed is trivially 0 milliWatts, before the ETC initializes or after shutdown. The minimum non-zero power consumption is 769 milliWatts, which occurs when rule $R_1$ of the Driver.Throttle.C machine is executed. Similar reasoning can be applied to the memory consumption. The results of the analysis, alongside the complete state of the “flattened” machine yielding the minimum and maximum values are shown in Table 8.26.

<table>
<thead>
<tr>
<th>Resource</th>
<th>Type</th>
<th>Amount</th>
<th>State</th>
</tr>
</thead>
</table>
| power   | min  | 769    | $\text{servo.s = executing,}$  
$\text{controller.mode = driving,}$  
$\text{cruise.mode = inactive,}$  
$\text{c\_pedal\_angle \neq 0}$ |
| power   | max  | 1695   | $\text{servo.s = executing,}$  
$\text{controller.mode = driving,}$  
$\text{cruise.mode = active,}$  
$\text{c\_pedal\_angle \neq 0}$ |
| memory  | min  | 128    | $\text{servo.s = executing,}$  
$\text{c\_vehicle\_speed = 0,}$  
$\text{c\_break\_pedal = active,}$  
$\text{c\_cruise\_switch = off}$ |
| memory  | max  | 1024   | $\text{monitor.s = executing,}$  
$\text{fault = True}$ |

Table 8.26: Resource usage analysis results for the ETC low level model
8.4.6 Test Case Generation

Since the ETC low level model, model $\mathcal{FT}_1$, combines features of the high level model, model $\mathcal{F}_0$, and features of the tasking model, $\mathcal{T}_0$, through a series of refinements, the test cases generated previously can be reused. More specifically, test suites have already been generated for these two models, in Section 8.2.3 and in Section 8.3.4. In this section, test cases are generated for the combined model using the set of refinements and the regression test case strategy described in Section 7.6. The results of the test case generation are shown in Table 8.27 and in Table 8.28. In the tables, the first column provides the machine name, the second column lists the number of test case templates in the test suite for the machine, and the third column lists the number of test cases from the test suite required for unit testing of the machine. The fourth column denotes how many test cases were regenerated and the fifth column describes the number of test cases that need to be executed, under the assumption that the test suites generated in Section 8.2.3 and in Section 8.3.4 were already executed on the respective models. Per the approach described in Chapter 7, the test cases are generated using the rule coverage criterion, explained in Section 7.1.1.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Test Suite</th>
<th>Unit Testing</th>
<th>New</th>
<th>Execute</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLOCK</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SCHEDULER</td>
<td>21</td>
<td>5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>TASKS</td>
<td>33</td>
<td>5</td>
<td>32</td>
<td>4 (32)</td>
</tr>
<tr>
<td>Cruise</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cruise_Mode</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cruise_Throttle_C</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Driver_Throttle_C</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Driving_Throttle_C</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fault</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Limiting_Throttle_C</td>
<td>6</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Over_Rev</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Over_Rev_Mode</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Over_Rev_Throttle_C</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Over_Torque</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 8.27: Test case generation results for the ETC low level model (part 1)

For the $SCHEDULER$ main machine, a test case template is added to the test suite, using the approach for the step expansion refinement. The new test case tem-
<table>
<thead>
<tr>
<th>Machine</th>
<th>Test Suite</th>
<th>Unit Testing</th>
<th>New</th>
<th>Execute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over_Torque_Mode</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Over_Torque_Throttle_C</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>finished_to_waiting</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CALCULATE_OUTPUT</td>
<td>15</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DO_SHUTDOWN</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DO_STARTUP</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HANDLE_FAULT</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MANAGER_TICK</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MONITOR_HEALTH</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MONITOR_TICK</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SAMPLE_STATE</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SERVO_TICK</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SET_EXECUTING_TASK</td>
<td>9</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SET_EXECUTION_PRIORITY</td>
<td>8</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SET_MAJOR_MODE</td>
<td>11</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SET_MAJOR_MODE_WORK</td>
<td>9</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SET_MINOR_MODE</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SET_MINOR_MODE_WORK</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>UPDATE_TASK_STATUSES</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WAKE_UP_MANAGER</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WAKE_UP_MONITOR</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WAKE_UP_SERVO</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WAKE_UP_TASKS</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 8.28: Test case generation results for the ETC low level model (part 2)

...
Table 8.29: Sample test case template from the test suite for the TASKS main machine

<table>
<thead>
<tr>
<th>Pre State</th>
<th>Post State</th>
<th>Coverage Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>manager_s{executing},</td>
<td>manager_s.step{minor_mode},</td>
<td>TASKS.R$_{11}$,</td>
</tr>
<tr>
<td>manager_s.step{major_mode},</td>
<td>controller.mode{driving}</td>
<td>SET.MAJOR=R$_{1}$,</td>
</tr>
<tr>
<td>system.health{nominal},</td>
<td></td>
<td>SET.MAJOR=MODE.R$_{1}$</td>
</tr>
<tr>
<td>controller.mode{startup},</td>
<td></td>
<td>MODE.WORK=R$_{2}$</td>
</tr>
<tr>
<td>startup.done{True}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

8.4.7 Discussion

The Electronic Throttle Controller (ETC) proved to be an interesting cases study because it combined different facets of real-time systems such as scheduling aspects and functional aspects. Furthermore, the ETC lent itself nicely to the traceability approach described in Chapter 6. The low level model of the ETC provided insightful analysis results, especially with regards to end-to-end latency. As was uncovered in Section 8.4.4, the latency for fault detection is unnecessarily high in both the worst case and the best case. The reason for this situation is because the monitor task has a lower priority than the manager task. It would be quite simple to modify the TASM model and associated UPPAAL model such that the monitor task has higher priority than the manager task. With this change, the impact on end-to-end latency could be immediately analyzed. Measuring end-to-end latency is not possible with Simulink and it would need to be obtained through an appropriate simulation scenario or through separate analysis.

While the presented framework, the TASM language, and the associated toolset do not have the rich library of mathematical components from control theory provided by Simulink, the analysis capabilities of the framework proved to be a useful complement to the Simulink model. Matlab and Simulink provide robust facilities for control-theoric analysis of control systems, through simulation scenarios. However, the ETC analysis, as performed on the high level model, tasking model, and low level model, is not possible with Matlab and Simulink. Matlab also does not provide traceability or refinement capabilities.

The ETC low level model was derived by combining the high level model of Section 8.2 with the tasking model of Section 8.3, and through the addition of resource
consumption. The traceability approach from the tasking model to the functional model proved useful as properties from the tasking model, such as schedulability analysis and execution time analysis, were preserved through the refinements. This situation occurred because the various refinements from the tasking model complied with the correctness criteria described in Section 6.2.2. While the set of correctness criteria seemed a bit restrictive when they were defined, they proved useful in this case study. However, for the traceability branch starting at the functional model and ending at the low level model, the sequence of refinements did not comply with the correctness criteria from Section 6.2.2. This situation occurred because the functional model didn’t have quite the same structure as the tasking model.

In terms of functional analysis, the majority of the completeness and consistency results were preserved through the chain of models. This situation occurred because most of the machines used in the low level model were taken verbatim from the tasking model and from the functional model. The functional analysis performed on the low level UPPAAL model started to stretch the performance of the UPPAAL engine. Some of the verification queries took over 30 minutes to complete and consumed over 500 MB of memory on a Pentium 4 operating at 2.4GHz with 512 MB of memory. This situation became slightly worse for execution time analysis with the addition of the observer automaton and the iterative nature of the analysis algorithm. Nevertheless, the analysis was completely automated, meaning that the UPPAAL verifier could be left alone to explore the state space. Using a mature verification engine like UPPAAL proves practical because the UPPAAL verifier contains various options for how the state space is explored [156]. For example, there are different state space reduction techniques which can be used to obtain better performance, at the cost of the exactness of solutions. Depending on the property to be verified, an overapproximation or an underapproximation of the solution might be acceptable if an exact solution is not feasible given the problem size.

Because the ETC is an industrial application, the implementation of the functionality and the tasking model is not overly complex. Consequently, the amount of resources consumed is rather limited. The resource consumption analysis performed
on the low level ETC model did not yield terribly insightful results, but was useful to validate the resource analysis approach. Overall, the ETC case study was an interesting application to study using the framework because it exercised the majority of the components of the framework, while stretching the performance limits of the analysis algorithms. The case study also demonstrated the versatility of the TASM modeling language as the language was used to model a tasking structure, a functional model, and a combination of the two.

8.5 The Timeliner Script Executor: Plant Control System

The Timeliner system has been developed as a scripting environment to automate procedural tasks typically performed by human operators [61]. The system is composed of a high-level input language, a compiler, a run-time system, and a user interface. The Timeliner system is described in details in Section 2.8.3.

The plant control system is a Timeliner application that contains a script used to regulate the cabin temperature and the cabin humidity level of a plant, as shown in Figure 2-12. The Timeliner script uses three actuators to regulate the cabin environment – a heating system, a cooling system, and a humidifier system [238]. The control script is composed of two sequences. The first sequence, called TEMP_MONITOR, shown in Listing 8.23, is used to maintain the temperature of the cabin between 20 and 25 Celsius degrees. The second sequence, called HUMIDITY_MONITOR, shown in Listing 8.24, is used to maintain the humidity of the cabin between 40 and 60 percent. When the temperature is greater than or equal to 26 Celsius degrees, the sequence starts the cooling system. When the temperature is lower than or equal to 19 Celsius degrees, the sequence starts the heating system. In both instances, the sequence will wait for the temperature to reach an acceptable level before continuing. When the cabin humidity is over 60 percent, the HUMIDITY_MONITOR sequence starts the cooling system. When the cabin humidity is lower than 40 percent, the HUMIDITY_MONITOR
sequence starts the humidifier system. The variable TRYING_TO_COOL_SYSTEM is used to notify the HUMIDITY_MONITOR sequence not to turn off the cooling system if the TEMP_MONITOR sequence is cooling the cabin. The HUMIDITY_MONITOR sequence uses the cooling system to reduce the humidity of the cabin and shares usage of the cooling system with the TEMP_MONITOR sequence.

Listing 8.23 Timeliner TEMP_MONITOR sequence [238]

SEQUENCE TEMP_MONITOR
EVERY 1
  IF TEMPERATURE >= 26 THEN
    SET TRYING_TO_COOL_SYSTEM TO TRUE
    COMMAND COOLING, NEW_STATE=>ON
    WHEN TEMPERATURE <= 22
      SET TRYING_TO_COOL_SYSTEM TO FALSE
      COMMAND COOLING, NEW_STATE=>OFF
    END WHEN
  END IF
  IF TEMPERATURE <= 19 THEN
    COMMAND HEATING, NEW_STATE=>ON
    WHEN TEMPERATURE >= 22
      COMMAND HEATING, NEW_STATE=>OFF
    END WHEN
  END IF
END EVERY
CLOSE SEQUENCE

Listing 8.24 Timeliner HUMID_MONITOR sequence [238]

SEQUENCE HUMID_MONITOR
EVERY 1
  IF HUMIDITY >= 61 THEN
    COMMAND COOLING, NEW_STATE=>ON
    WHEN HUMIDITY <= 50
      IF NOT TRYING_TO_COOL_SYSTEM
        COMMAND COOLING, NEW_STATE=>OFF
      END IF
    END WHEN
  END IF
  IF HUMIDITY <= 39 THEN
    COMMAND HUMIDIFIER, NEW_STATE=>ON
    WHEN HUMIDITY >= 50
      COMMAND HUMIDIFIER, NEW_STATE=>OFF
    END WHEN
  END IF
END EVERY
CLOSE SEQUENCE
The plant control system case study is an interesting case study because it involves the modeling of a software program with time annotations for the program. This case study differs from the production cell case study where the software actions are assumed to be instantaneous and also differs from the electronic throttle controller case study where the timing of actions is contained in the tasking model.

8.5.1 Model

The execution times of various Timeliner statements have been heavily studied by the Charles Stark Draper Laboratory, with timing results documented in [62]. The measures were performed using the Timeliner Testbed, with version CL024 of the Timeliner Executor, using an embedded real-time 16MHz Intel 80836sx VME board with an 80387 floating point coprocessor. The execution times contained in document [62] are used to model the scripts in the TASM language. The scripts are modeled in the TASM language for the sake of performing timing analysis and to generate test cases. More specifically, the static timing analysis of Timeliner scripts provides execution time guarantees. Traditionally, the Best-Case Execution Time (BCET) and Worst-Case Execution Time (WCET) of one pass of a Timeliner script were obtained through manual analysis and through systematic testing. By modeling the script in TASM and using the iterative bounded liveness approach presented in Section 5.3, exact values of the BCET and WCET can be obtained automatically.

To model the scripts in the TASM language, the scripts are augmented with labels where the statements contained in the script either block or branch. For example, the IF statement is a branching statement; the WHEN statement is a blocking statement which will block until its condition becomes true. The structural view of both augmented sequences is shown in Listing 8.25. The possible executions of the sequence can be illustrated using the labels. For example, under nominal conditions, the TEMP_MONITOR sequence will execute through the sequence of labels $b_0$, $b_1$, $b_3$, $b_0$ in one pass. At the next pass, if the temperature is greater than or equal to 26 Celsius degrees, the sequence will execute through the sequence of labels $b_0$, $b_1$, $b_2$ in one pass. Eventually, the sequence will leave $b_2$ when the temperature is below 22
Celsius degrees. Until that condition is met, the sequence will stay at label $b_2$ at each pass.

**Listing 8.25** Labeled TEMP_MONITOR sequence

$b_0$: EVERY 1

$b_1$: IF TEMPERATURE $\geq$ 26 THEN

$b_2$: WHEN TEMPERATURE $\leq$ 22

$b_3$: IF TEMPERATURE $\leq$ 19 THEN

$b_4$: WHEN TEMPERATURE $\geq$ 22

**Listing 8.26** Labeled HUMID_MONITOR sequence

$c_0$: EVERY 1

$c_1$: IF HUMIDITY $\geq$ 61 THEN

$c_2$: WHEN HUMIDITY $\leq$ 50

$c_3$: IF NOT TRYING_TO_COOL SYSTEM

$c_4$: IF HUMIDITY $\leq$ 39 THEN

$c_5$: WHEN HUMIDITY $\geq$ 50

The duration of one step transitions from one label to another label have been calculated using the execution times documented in [62]. The results are shown in Table 8.25 for the TEMP_MONITOR sequence and in Table 8.26 for the HUMIDITY_MONITOR sequence. Entries in the table marked with a "-" denote that the transition is not possible in one step. It is important to remember that multiple transitions can be taken in one pass, until a blocking statement is reached.

The time of the transitions are used to build the TASM model. The transitions are naturally encoded into rules, and the durations from Table 8.30 and Table 8.31 become the durations of the rule executions.
Table 8.30: Duration of transitions (in $\mu$s) between labels of Listing 8.25

<table>
<thead>
<tr>
<th></th>
<th>$b_0$</th>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
<th>$b_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_0$</td>
<td>685</td>
<td>685</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$b_1$</td>
<td>-</td>
<td>-</td>
<td>2285</td>
<td>1730</td>
<td>-</td>
</tr>
<tr>
<td>$b_2$</td>
<td>-</td>
<td>-</td>
<td>1625</td>
<td>3725</td>
<td>-</td>
</tr>
<tr>
<td>$b_3$</td>
<td>1950</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2390</td>
</tr>
<tr>
<td>$b_4$</td>
<td>1630</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3195</td>
</tr>
</tbody>
</table>

Table 8.31: Duration of transitions (in $\mu$s) between labels of Listing 8.26

<table>
<thead>
<tr>
<th></th>
<th>$c_0$</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$c_3$</th>
<th>$c_4$</th>
<th>$c_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_0$</td>
<td>685</td>
<td>685</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$c_1$</td>
<td>-</td>
<td>-</td>
<td>2395</td>
<td>-</td>
<td>1730</td>
<td>-</td>
</tr>
<tr>
<td>$c_2$</td>
<td>-</td>
<td>-</td>
<td>1625</td>
<td>1625</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$c_3$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2160</td>
<td>-</td>
</tr>
<tr>
<td>$c_4$</td>
<td>1950</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2390</td>
<td>-</td>
</tr>
<tr>
<td>$c_5$</td>
<td>3195</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1630</td>
</tr>
</tbody>
</table>
The Environment

The labels introduced in Listing 8.25 and in Listing 8.26 are encoded in the TASM model in the type Temp.Sequence.Block and in the type Humid.Sequence.Block. The types are used as a program counter to keep track of the location of each sequence through each pass of execution. The Processor.Status type is used to allocate processor usage to Timeliner and to the control task. The TASM model contains only 1 bundle, the plantsim bundle, which contains 2 sequences. Other bundles and sequences can be easily added to the model by extending the Bundle and Sequence types. The list of types is shown in Listing 8.27.

Listing 8.27 User-defined types of the model

<table>
<thead>
<tr>
<th>Type</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status</td>
<td>{active, inactive};</td>
</tr>
<tr>
<td>Device</td>
<td>{on, off};</td>
</tr>
<tr>
<td>Temp.Sequence.Block</td>
<td>{b0, b1, b2, b3, b4};</td>
</tr>
<tr>
<td>Humid.Sequence.Block</td>
<td>{c0, c1, c2, c3, c4, c5};</td>
</tr>
<tr>
<td>Processor.Status</td>
<td>{timeliner, controltask};</td>
</tr>
<tr>
<td>Execution.Status</td>
<td>{done, not_done};</td>
</tr>
<tr>
<td>Bundle</td>
<td>{plantsim};</td>
</tr>
<tr>
<td>Sequence</td>
<td>{temp_monitor, humid_monitor};</td>
</tr>
</tbody>
</table>

The variables that make up the environment contain status variables for the bundles and sequences, the program counters for each sequence, which task has control of the processor, and whether a given pass is done or not done. The environment variables are shown in Appendix F, in Listing F.2.

Timeliner Bundles and Sequences

The execution semantics of the Timeliner language are such that only active bundles are executed and only active sequences are executed, per the organization of Figure 2-11. Given the hierarchical nature of the execution semantics, sub machines are a natural fit to describe this behavior. The sub machine EXECUTE_BUNDLES executes all bundles in sequential order. The sub machine PLANTSIM_BUNDLE executes all sequences in its bundle, in sequential order, through the EXECUTE_PLANTSIM_SEQUENCES sub machine, if the bundle is active. The rules of the PLANTSIM_BUNDLE sub machine are shown in Listing 8.28, where the active status of the bundle
dictates whether or not the sequences are executed.

Listing 8.28 Rules of the PLANTSIM.Bundle sub machine

R1: Bundle Active
{ 
    if plantsim_bundle_status = active then
        EXECUTE_PLANTSIM_SEQUENCES();
}

R2: Bundle Inactive
{ 
    if plantsim_bundle_status = inactive then
        plantism_s := done;
}

Each sequence is also wrapped into a sub machine so that the sequences are executed only if they are active. The SEQUENCE.TEMP.MONITOR sub machine and the SEQUENCE.HUMID.MONITOR sub machine are wrapper sub machines that will execute the work of the sequences only if the given sequence is active. The SEQUENCE.TEMP.MONITOR is shown in Listing 8.29.

Listing 8.29 Rules of the SEQUENCE.TEMP.MONITOR sub machine

R1: Sequence Active
{ 
    if temp_seq_status = active then
        SEQUENCE.TEMP.MONITOR.WORK();
}

R2: Sequence Inactive
{ 
    if temp_seq_status = inactive then
        temp_seq_s := done;
}

TEMP.MONITOR Sequence

The SEQUENCE.TEMP.MONITOR.WORK sub machine describes the logic of the temperature monitor sequence. Listing 8.30 shows 2 of the 11 rules that make up the machine. Each rule represents a durative transition between the sequence labels, as shown in Table 8.30. The names of each rule are of the form “bi -> bj” to indicate that the rule describes the transition between the label bi to the label bj. For example,
rule $R_5$ of Listing 8.30 describes the transition between label $b_2$ and label $b_3$. Referring to Listing 8.23 and Listing 8.25, the rule is fired only if the temperature is less than or equal to 22 Celsius degrees. If the temperature is above 22 Celsius degrees, the sequence will stay on the WHEN statement until the temperature falls below 22 Celsius degrees. This behavior is captured by rule $R_4$. The time annotations of each rule are congruent to the calculations summarized in Table 8.30. The complete list of rules of the $SEQUENCE.TEMP.MONITOR.WORK$ are given in Listing F.12 and in Listing F.13.

**Listing 8.30** Rules of the $SEQUENCE.TEMP.MONITOR.WORK$ sub machine (partial)

```
R4: b2 -> b2
{
    t := 1625;
    if temp_seq_b = b2 and temperature > 22 then
        temp_seq_b := b2;
        temp_seq_s := done;
}

R5: b2 -> b3
{
    t := 1730;
    if temp_seq_b = b2 and temperature <= 22 then
        temp_seq_b := b3;
        trying_to_cool_system := False;
        cooling := off;
}
```

The $HUMIDITY.MONITOR$ sequence is built analogously to the $TEMP.MONITOR$ sequence through the $SEQUENCE.HUMIDITY.MONITOR$ sub machine and the $SEQUENCE.HUMIDITY.MONITOR.WORK$ sub machine. The structure of the two sequences is identical with regards to the status of the sequence and the list of rules is built based on Table 8.31.

**Control Task**

In order to model the dynamics of script execution, a separate "control task" is modeled, which shares the processor with Timeliner. The control task is modeled in
TASM as a main machine which acts as a "dummy" task which performs no function other than consume time. The execution time of the control task is set between 3500 \( \mu s \) and 5000 \( \mu s \). The rules of the \textit{Control Task} main machine are shown in Listing 8.31.

\begin{verbatim}
Listing 8.31 Rules of the Control Task main machine
R1: Control Task
{  
  t := [3500, 5000];

  if processor = controltask and execution = not_done then
    execution := done;
}

R2: Else
{  
  t := next;

  else then
    skip;
}
\end{verbatim}

Scheduler

The scheduler is the component responsible for switching processor control between Timeliner and the control task. The processor is allocated to the two competing tasks on a round-robin basis. The scheduler waits for the task that owns the processor to signal that it has finished execution for the round. In terms of Timeliner, a round of execution corresponds to a pass. The scheduler is modeled without preemption in order to verify the maximum execution time of a single pass of Timeliner. The scheduler uses the \texttt{processor} variable and the \texttt{execution} variable to determine which task has control of the processor. The context switching time is assumed to be 1000 \( \mu s \). The functionality is wrapped in a main machine, called \textit{Scheduler}. The rules of this main machine are shown in Listing 8.32.

The Plant Cabin - Temperature and Humidity

The behavior of the humidity and the temperature inside the plant cabin influences the Timeliner sequence execution. For example, if the temperature is below 20 Celsius
Listing 8.32 Rules of the Scheduler main machine

R1: Controller
{
    t := 1000;

    if processor = controltask and execution = done then
        processor := timeliner;
        execution := not_done;
    }

R2: Timeliner
{
    t := 1000;

    if processor = timeliner and execution = done then
        processor := controltask;
        execution := not_done;
    }

R3: Else
{
    t := next;

    else then
        skip;
    }

degrees, the TEMPERATURE_MONITOR sequence will turn on the heating system in order to warm the cabin. In order to verify all the potential behaviors of the Timeliner script, the behavior affecting the execution of the script must be modeled. The behavior of the environment is non-deterministic and it is assumed that the temperature and humidity can vacillate unexpectedly. The restrictions on the vacillation of the atmosphere are such that the temperature and humidity will not vary unexpectedly if any of the actuating systems, namely heating, cooling, and humidifier are turned on. The behavior of the atmosphere is encoded in two main machines to represent the behavior of the two environment variables. The non-deterministic behavior of the temperature variable is encoded in a main machine called Temperature. Three of the rules of the machines are shown in Listing 8.33. In Listing 8.33, since the guards of the first two rules are identical, when both guards are enabled, one of the rules is selected non-deterministically and is executed. The first rule, rule R₁, describes nominal behavior, where the temperature does not change. The second rule, rule R₂, switches the temperature from nominal to “too low” per the behavior of the Timeliner script. The time annotations are selected to ensure that all the behaviors of the script are exercised. The time annotation of 685 μs represents the smallest step in each sequence. The third rule shown in Listing 8.33, rule R₅, describes the behavior of the temperature variable when the heating system is turned on to remedy a drop in temperature below the critical threshold. The duration of the interval to return the temperature to nominal is between 0 and 1500 μs. This annotation was selected to exercise the different behaviors of the script. For example, an instantaneous return to nominal will cause the script to execute all the sequences in a pass. If the duration to return the temperature to nominal is higher than 685 μs, Timeliner will block on the WHEN statement, while waiting for the temperature to return to the nominal value. Furthermore, the upper bound on the duration, 1500 μs ensures that it is possible for the script to execute on pass where the only statement in the pass is the execution of the blocking WHEN statement. A value higher than 1500 μs would cause the script to execute multiple passes where the script executes only the blocking WHEN statement. This situation would be redundant from an analysis and simulation perspective since...
it would not exercise different script behavior. The behavior of the humidity variable is encoded in an analogous main machine called *Humidity*.

The model of the temperature and humidity variables is simplistic and does not adequately reflect the differential equation relationship between humidity, temperature, and the heating, cooling, and humidifier. However, the goal of the model is to analyze the behavior of the Timeliner script and the model of the temperature and humidity is sufficient to exercise the necessary behavior of the script.

**Listing 8.33 Rules of the *Temperature* main machine (partial)**

R1:
```
{ 
  t := 685; 
  if temperature > 19 and temperature < 26 and cooling = off and heating = off and humidifier = off then skip; 
}
```

R2:
```
{ 
  t := 685; 
  if temperature > 19 and temperature < 26 and cooling = off and heating = off and humidifier = off then temperature := 18; 
}
```

R5: Heating on
```
{ 
  t := [0, 1500]; 
  if temperature < 20 and heating = on and cooling = off then temperature := 24; 
}
```

**Complete Model**

The complete TASM model contains 5 main machines, no function machines, and 7 sub machines. The complete Timeliner plant control system model is documented in Appendix F where the list of all machines is provided in Table F.1.
The TASM model is translated to UPPAAL to perform model checking of safety and liveness properties and to perform execution time analysis. The first step of the translation to the timed automata of UPPAAL removes hierarchical composition from the main machines. In the TASM model, only the *Timeliner* main machine uses hierarchical composition, as it uses 7 sub machines. The flattened version of the *Timeliner* main machine contains 27 rules. The complete UPPAAL model yields 10 timed automata – 1 automaton for the *Timeliner* script and execution, 1 automaton for the scheduler, 1 automaton for the control task, 3 automata to enforce the urgent channel transitions of the 3 aforementioned machines, 2 automata to describe the evolution of the *temperature* and *humidity* variables (the environment). The timed automaton for the scheduler machine is shown in Figure 8-9. In the scheduler automaton, the *processor* variable is used to denote whether the control task (*processor == 2*) or *Timeliner* (*processor == 1*) has control of the processor. The variable *execution* is used to denote whether the component currently using the processor has completed (*execution == 1*) or not (*execution == 2*). The variable *Scheduler_else* is an urgent channel that is used to keep the scheduler waiting in the *SchedulerELSE* location until it needs to switch the processor context. The *pivot* location is used to either perform an action, if applicable, or to move to the *SchedulerELSE* location if no action is enabled. The *SchedulerELSE* location is the only location where time can elapse because of actions of other automata.

The most complex automaton of the translated model is the automaton describing the behavior of the *Timeliner* main machine. The complete automaton contains 27 locations and 54 transitions, and retains the general form of the Scheduler automaton shown in Figure 8-9. As for the automaton in Figure 8-9, all locations have invariants, except for the *SchedulerELSE* location, which is guarded by an urgent channel called *Scheduler_else*.
Figure 8-9: Automaton for the Scheduler main machine
8.5.2 Functional Analysis

The UPPAAL model can be used to verify safety and liveness properties of the Timeliner script. Safety properties that can be verified include the mutual exclusion of the different actuators:

- The cooling system and the humidifier should not be on simultaneously
- The heating system and the cooling system should not be on simultaneously

If any of these properties hold, they signal a conflict between the logic in the two scripts. The reason why these situations are undesirable is because these two systems contradict each other and hence would cancel the desired effect. If such a situation occurs, both sequences will end up waiting forever for the environment to change, a situation that can't happen under these circumstances, which would result in the system being deadlocked. These two safety properties can be translated into the temporal logic query language of UPPAAL:

- $A[] \neg (\text{cooling} == 1 \land \text{humidifier} == 1)$
- $A[] \neg (\text{heating} == 1 \land \text{cooling} == 1)$

Executing the first query in the UPPAAL verifier shows that the safety property holds. However, executing the second property in the UPPAAL verifier unveils that the property does not hold in the model. In the model, it is possible for the humidity to be over 60% and for the temperature to be under 20 Celsius degrees. In this situation, the TEMPERATURE_MONITOR sequence would turn on the heating system to raise the temperature. In turn, the HUMIDITY_MONITOR sequence would turn on the cooling system to reduce the ambient humidity. In the model, this case does not result in the heating and cooling system canceling their effects because the humidity variable is unaffected by the heating system. When the heating system and the cooling system are on simultaneously, the humidity would decrease while the temperature stays constant. Once the humidity reaches the nominal level, the HUMIDITY_MONITOR sequence will turn off the cooling system, at which point the cabin temperature will
start to rise and eventually reach a nominal level. Since this safety property does not hold in the model, it raises an interesting question about whether this situation is a reachable state in the environment. Perhaps there are unstated assumptions about the behavior of the temperature and the humidity variables.

The liveness properties of the Timeliner script which can be verified include the behavior of the script in the face on off-nominal values of the cabin variables:

- If the temperature falls below 20 Celsius degrees, the heating system will eventually be turned on
- If the temperature rises over 25 Celsius degrees, the cooling system will eventually be turned on
- If the humidity falls below 40%, the humidifier system will eventually be turned on
- If the humidity rises over 60%, the cooling system will eventually be turned on

All of these properties are expected to hold because they describe the basic requirements of the monitor sequences. These properties can be stated using the temporal logic query language of UPPAAL:

- $(temperature < 19) \rightarrow (heating == 1)$
- $(temperature > 26) \rightarrow (cooling == 1)$
- $(humidity < 39) \rightarrow (humidifier == 1)$
- $(humidity > 61) \rightarrow (cooling == 1)$

These properties can be run through the UPPAAL verifier and can be shown to hold for the given model. Other liveness properties can also be verified, to ensure that the model behaves as expected, as needed. For example, it can be verified that if the temperature is below 20 Celsius degrees and the heating system is on, the temperature will eventually return to the nominal level.
Completeness and Consistency

The analysis of completeness and consistency was performed using the approach described in Section 5.1. The results of verifying completeness are shown in Table 8.32. The table shows, for each machine, the number of propositions, the number of clauses, and whether or not the machine is complete. For machines that are trivially complete, the number of propositions and clauses is listed as "N/A". A similar table, Table 8.33, presents the results of verifying the consistency of each machine.

<table>
<thead>
<tr>
<th>Name</th>
<th>Propositions</th>
<th>Clauses</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control.Task</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Scheduler</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Timeliner</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Temperature</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Humidity</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>EXECUTE.BUNDLES</td>
<td>3</td>
<td>5</td>
<td>Yes</td>
</tr>
<tr>
<td>PLANTSIM.BUNDLE</td>
<td>2</td>
<td>4</td>
<td>Yes</td>
</tr>
<tr>
<td>EXECUTE.PLANTSIM.SEQUENCES</td>
<td>6</td>
<td>10</td>
<td>Yes</td>
</tr>
<tr>
<td>SEQUENCE.TEMP.MONITOR</td>
<td>2</td>
<td>4</td>
<td>Yes</td>
</tr>
<tr>
<td>SEQUENCE.TEMP.MONITOR_WORK</td>
<td>10</td>
<td>34</td>
<td>Yes</td>
</tr>
<tr>
<td>SEQUENCE.HUMID.MONITOR</td>
<td>2</td>
<td>4</td>
<td>Yes</td>
</tr>
<tr>
<td>SEQUENCE.HUMID.MONITOR_WORK</td>
<td>11</td>
<td>46</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 8.32: Completeness analysis results for the Timeliner plant control system

<table>
<thead>
<tr>
<th>Name</th>
<th>Propositions</th>
<th>Clauses</th>
<th>Consistent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control.Task</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Scheduler</td>
<td>4</td>
<td>8</td>
<td>Yes</td>
</tr>
<tr>
<td>Timeliner</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>Temperature</td>
<td>9</td>
<td>25</td>
<td>No</td>
</tr>
<tr>
<td>Humidity</td>
<td>9</td>
<td>25</td>
<td>No</td>
</tr>
<tr>
<td>EXECUTE.BUNDLES</td>
<td>3</td>
<td>7</td>
<td>Yes</td>
</tr>
<tr>
<td>PLANTSIM.BUNDLE</td>
<td>2</td>
<td>4</td>
<td>Yes</td>
</tr>
<tr>
<td>EXECUTE.PLANTSIM.SEQUENCES</td>
<td>6</td>
<td>10</td>
<td>Yes</td>
</tr>
<tr>
<td>SEQUENCE.TEMP.MONITOR</td>
<td>2</td>
<td>4</td>
<td>Yes</td>
</tr>
<tr>
<td>SEQUENCE.TEMP.MONITOR_WORK</td>
<td>10</td>
<td>34</td>
<td>Yes</td>
</tr>
<tr>
<td>SEQUENCE.HUMID.MONITOR</td>
<td>2</td>
<td>4</td>
<td>Yes</td>
</tr>
<tr>
<td>SEQUENCE.HUMID.MONITOR_WORK</td>
<td>11</td>
<td>46</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 8.33: Consistency analysis results for the Timeliner plant control system
8.5.3 Execution Time Analysis

The execution time of the model is analyzed using the approach described in Section 5.3. The first goal is to verify the WCET and BCET for one pass of the Timeliner script executor. In the model, the beginning of one pass of the script executor begins with the state “processor = timeliner, execution = not done”. Consequently, the state predicate for the beginning of the path, \( p_0 \), is the UPPAAL state (\( \text{processor} == 1 \&\& \text{execution} == 2 \)). Conversely, the state predicate for the final state of the path, \( p_1 \), is the UPPAAL state (\( \text{processor} == 1 \&\& \text{execution} == 1 \)), which states that Timeliner still has control of the processor, but that its execution is done for the current pass. Consequently, the goal is to analyze the execution time of the path (\( \text{processor} == 1 \&\& \text{execution} == 2 \)) \( \rightarrow \) (\( \text{processor} == 1 \&\& \text{execution} == 2 \)). The observer automaton to measure the execution time of one pass of Timeliner is shown in Figure 8-10. Using \( \phi_{\text{init}} \), the trace stored in the simulator for the observer automaton yields \( t_{\text{init}} = 11030\mu s \). In terms of the Timeliner script, this trace corresponds to execution of labels \( b_0, b_1, b_2 \) in one pass for the TEMP_MONITOR sequence, followed by execution of labels \( c_0, c_1, c_4 \) for the HUMID_MONITOR sequence. \( t_{\text{init}} \) is used to iteratively establish the satisfiability of \( \phi_{\text{max}} \).

Using the approach explained in Section 5.3, the WCET, \( t_{\text{max}_{p_0-p_1}} \), was established to be 16815\( \mu s \) after 4 iterations. The iterations are shown in Table 8.34. The behavior corresponding to the WCET of one pass is the sequence of execution of labels \( b_0, b_1, b_3, b_4, b_0 \) in one pass for the TEMP_MONITOR sequence, followed by execution of labels \( c_0, c_1, c_2, c_3, c_4, c_0 \) for the HUMID_MONITOR sequence.

Figure 8-10: Observer automaton to measure the execution time of one pass of Timeliner, for the scripts of Listing 8.23 and of Listing 8.24
Table 8.34: Execution time analysis results for the WCET of one pass of Timeliner

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>11030µs</td>
</tr>
<tr>
<td>1</td>
<td>12870µs</td>
</tr>
<tr>
<td>2</td>
<td>14435µs</td>
</tr>
<tr>
<td>3</td>
<td>15250µs</td>
</tr>
<tr>
<td>4</td>
<td>16815µs</td>
</tr>
</tbody>
</table>

To establish the BCET, $t_{\text{min}_{p_0 \rightarrow p_1}}$, a similar iterative strategy is used using $\phi_{\text{min}}$. $t_{\text{min}_{p_0 \rightarrow p_1}}$ is established to be 3255µs after 2 iterations. The iterations are shown in Table 8.35. The trace which yields the BCET of one pass of Timeliner is the simple case of executing a single statement in each sequence. This trace corresponds to the execution of one blocking WHEN statement for the TEMP.MONITOR sequence, and the execution of one blocking WHEN statement for the HUMID.MONITOR sequence. One example displaying the BCET of one pass is the execution of label $b_2$ in the TEMP.MONITOR sequence followed by the execution of label $c_2$ in the HUMID.MONITOR sequence.

Table 8.35: Execution time analysis results for the BCET of one pass of Timeliner

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>11030µs</td>
</tr>
<tr>
<td>1</td>
<td>8960µs</td>
</tr>
<tr>
<td>2</td>
<td>3255µs</td>
</tr>
</tbody>
</table>

End-to-End Latency

End-to-end latency refers to the amount of time that it takes for the system to react to a change in the environment. In the context of the plant control system, one example of end-to-end latency involves the amount of time required for the plant control system to turn on the heating system when the temperature falls under 20 Celsius degrees. In terms of a predicate over state variables, this behavior corresponds to the path between a state where “temperature <= 19, heating = off” to a state where “heating = on”. The observer automaton to verify this property is shown in Figure 8-11. The WCET of the end-to-end latency corresponding to this automaton is
22570µs, reached after 2 iterations. The BCET of the end-to-end latency corresponding to this automaton is 2390µs. Since this property is a system property, the time used in the calculation of the WCET and the BCET involves delays in the scheduler and the execution time of the control task. The behavior corresponding to the WCET is the behavior where the temperature drop occurs after rule $R_6$ has just started executing in the `TEMP_MONITOR_SEQUENCE_WORK` sub machine. The WCET is calculated using rule $R_6$ (1950µs) of the `TEMP_MONITOR_SEQUENCE_WORK` sub machine, followed by rules $R_1$ (685µs), $R_2$ (2395µs), $R_3$ (1625µs), $R_6$ (2160µs), $R_9$ (1950µs) of the `HUMID_MONITOR_SEQUENCE_WORK` sub machine, followed by a context-switch by the scheduler (1000µs), the maximum execution time of the control task (5000µs), a context switch by the scheduler (1000µs), and rules $R_1$ (685µs), $R_3$ (1730µs), $R_7$ (2390µs) of the `TEMP_MONITOR_SEQUENCE_WORK` sub machine.

In terms of Listing 8.23 and Listing 8.24, the maximum end-to-end latency will occur when the temperature drop occurs when the `TEMP_MONITOR` sequence has started executing label $b_3$, the `HUMID_MONITOR` sequence is at label $c_0$, and the humidity is over 60%. For the minimum end-to-end latency, the value 2390µs corresponds to execution of rule $R_7$ of the `TEMP_MONITOR_SEQUENCE_WORK` sub machine. This means that the temperature drop happens just before the rule begins executing. In terms of Listing 8.23, this corresponds to the temperature drop occurring just before the sequence is at label $b_3$.

![Observer automaton](image)

Figure 8-11: Observer automaton to measure the end-to-end latency of Timeliner for a temperature drop, for the scripts of Listing 8.23 and of Listing 8.24

Similar observers were formulated for the other conditions leading to the heating, cooling, and humidifier systems being turned on. The end-to-end latency results, alongside the number of iterations needed to converge on the values are reported in
Table 8.36.

<table>
<thead>
<tr>
<th>$p_0$</th>
<th>$p_1$</th>
<th>WCET</th>
<th>Iterations</th>
<th>BCET</th>
<th>Iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>heating = off, temperature &lt; 20</td>
<td>heating = on</td>
<td>11030µs</td>
<td>3</td>
<td>2390µs</td>
<td>10</td>
</tr>
<tr>
<td>cooling = off, temperature &gt; 25, humidity &gt;= 40, humidity &lt;= 60</td>
<td>cooling = on</td>
<td>21650µs</td>
<td>4</td>
<td>2285µs</td>
<td>8</td>
</tr>
<tr>
<td>cooling = off, humidity &gt; 60, temperature &gt;= 20, temperature &lt;= 25</td>
<td>cooling = on</td>
<td>21760µs</td>
<td>6</td>
<td>2285µs</td>
<td>7</td>
</tr>
<tr>
<td>humidifier = off, humidity &lt; 40</td>
<td>humidifier = on</td>
<td>21755µs</td>
<td>6</td>
<td>2390µs</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 8.36: End-to-end latency analysis results for the plant control system

Since both sequences share the usage of the cooling system, extra conditions need to be added to $p_0$. Otherwise, the BCET would be trivially 0. For example, if the end-to-end latency of the Timeliner script turning on the cooling system, to remedy a rise in temperature, is to be measured, the condition that the humidity be nominal at the beginning of the path is necessary. Otherwise, the BCET would result when the rise in temperature occurs right after the HUMID_MONITOR sequence has turned on the cooling system to remedy a rise in humidity.

8.5.4 Test Case Generation

In the Timeliner case study, the Temperature and the Humidity main machines are used to simulate environmental behavior and are not included in the generation of test cases. Consequently, test cases are generated for all other machines, using the algorithm described in Listing 7.8. The results of the test case generation are shown in Table 8.37. In Table 8.37, the first column provides the machine name, the second column lists the number of test case templates in the test suite template for the machine, and the third column lists the number of test cases from the test suite required for unit testing of the machine. Per the approach described in Chapter 7, the test cases are generated using the rule coverage criterion, explained in Section 7.1.1.
Table 8.37: Test case generation results for the plant control system

<table>
<thead>
<tr>
<th>Machine</th>
<th>Test Suite</th>
<th>Unit Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control_Task</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Scheduler</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Timeliner</td>
<td>27</td>
<td>2</td>
</tr>
<tr>
<td>EXECUTE_BUNDLES</td>
<td>26</td>
<td>2</td>
</tr>
<tr>
<td>PLANTSIM_BUNDLE</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>EXECUTE_PLANTSIM_SEQUENCES</td>
<td>24</td>
<td>4</td>
</tr>
<tr>
<td>SEQUENCE_TEMP_MONITOR</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>SEQUENCE_TEMP_MONITOR_WORK</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>SEQUENCE_HUMIDITY_MONITOR</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>SEQUENCE_HUMIDITY_MONITOR_WORK</td>
<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 8.38: Sample test case template from the test suite for the Timeliner main machine

A sample test case template from the Timeliner main machine test suite is shown in Table 8.38.

8.5.5 Discussion

The Timeliner plant control system case study focused on execution time analysis for various properties of the Timeliner script. More specifically, the analysis performed enabled the calculation of the minimum and maximum execution times for a single pass of the Timeliner script. Furthermore, end-to-end latency analysis uncovered the worst case and best case response time that the system can provide for a change in the environment. The analysis was performed for four different conditions that affect the execution of the script. The interesting point to note is that the execution time analysis was performed automatically and without modifying the generated UPPAAL model. The use of observer automata, as described in Section 5.3, provides a generic
and unintrusive means of analyzing the system model. This case study modeled an example at the detailed software level, using lab measurements for various statements of the language. The modeling and analysis of Timeliner scripts could certainly be generalized to support the entire Timeliner language.

The functional analysis performed on the plant control system involved verifying safety properties and a different type of liveness property than in other case studies. The “\( \phi_1 \rightarrow \phi_2 \)” UPPAAL path quantifier states that, in all paths, if \( \phi_1 \) holds at some point for a state in the path, then \( \phi_2 \) will eventually hold for a later state in the path. This type of property is important to determine that the script achieves its basic functionality, such as turning on the heating system after a temperature drop. This property is different than a simple reachability property which can state that a particular state is reachable in some path, or in all paths. By using the “\( \rightarrow \)” operator of UPPAAL, the properties of sequences of states in all paths can be formulated. As in other case studies, the analysis of consistency and completeness proved useful during model development and model debugging, but the end results of the analysis are not terribly insightful. Nevertheless, the plant control system case study proved to be a case study of manageable size to illustrate in details the capabilities of the framework in terms of execution time analysis and test case generation.

### 8.6 Segue into Chapter 9

This chapter presented three case studies used to evaluate the capabilities of the proposed framework and the TASM language. The case studies were used to illustrate the modeling facilities of the language, the analysis capabilities of the framework, the traceability approach, and the test case generation strategy. In the following chapter, Chapter 9, the contributions of the presented research are reviewed in light of the presented framework and the results of the case studies. Chapter 9 also provides guidance for future work related to the presented research.
Chapter 9

Conclusion

This chapter reexamines the objectives of the research, described in Chapter 1, in light of the presented framework and the experimental results obtained through the case studies. The research contributions of the thesis are also revisited in light of the information presented in the previous chapters. This chapter also provides a synthesized critique of the various components of the presented framework and describes additional developments that could be achieved as part of future research.

9.1 Research Objectives and Contributions

The research objectives of the presented thesis were first described in Chapter 1. The objectives sought to address key challenges in the engineering of embedded real-time systems. These challenges, alongside proposed solutions, are repeated below:

- The high complexity of modern software systems by providing a model-based approach to software-intensive system engineering.

- The high cost of Verification and Validation (V & V) activities by leveraging the use of models to automate engineering activities.

- The challenges in using formal methods in an engineering context by providing a novel literate specification language and hiding verification details in a push-button approach.
• The lack of integration between models by providing bi-directional traceability across levels of abstraction.

• The lack of integration of the state-of-the art in individual disciplines by providing an overarching engineering framework.

Certainly, the framework presented in this thesis was flexible enough to model and analyze archetypical case studies from the embedded real-time system domain. The case studies concerned applications from the manufacturing industry, the automotive industry, and the aerospace industry. Furthermore, the framework proved versatile enough to model and study the three key aspects of the systems of interest – function, time, and resources. The framework succeeded in tackling some of the complexity issues of these systems by providing a building block approach to system construction and analysis. The high cost of V & V activities was addressed by reusing well-established analysis engines that provided automated analysis, namely the UPPAAL tool suite and the SAT4J SAT solver, and by performing verification and test case generation activities automatically. The challenges of using formal methods in an engineering context was addressed in two ways. The first approach built on the success of Abstract State Machines (ASM), which have been used successfully in an engineering context [41]. Furthermore, the TASM toolset provides an integrated tool suite that hides many of the details involved in the translation and the verification using the analysis engines. The experience in the Embedded System Laboratory, at conferences, and through outside evaluation has been positive among the engineering community. The integration of models has been addressed through the bi-directional traceability strategy, which has proved to be versatile enough to handle the incorporation of seemingly disparate models, such as a tasking model and a functional model. The presented framework incorporates ideas from a number of communities, including the formal methods community, the test case generation community, and the scheduling community. Incorporating these different disciplines into the framework provides an integrated approach for end-to-end embedded real-time system engineering.
The research contributions of the presented thesis were first described in Chapter 1. These contributions are reiterated below:

- A new specification language for embedded real-time systems, the Timed Abstract State Machine (TASM) language, which extends the theory of Abstract State Machines (ASM). The TASM language integrates the specification of functional and non-functional properties – function, time, and resources.

- A set of verification procedures for automated analysis of models using generally available analysis engines. The analysis procedures include completeness and consistency, execution time, and resource consumption.

- An approach to traceability of system models that incorporates syntactic change and semantic integrity.

- A generic and extensible approach to automatically generate test cases for unit testing, integration testing, and regression testing.

- An integrated framework for modeling, simulation, verification, and test-case generation for embedded real-time systems.

- An integrated toolset implementing the capabilities of the framework

The Timed Abstract State Machine (TASM) language proved a versatile language to express different aspects of embedded real-time systems. Furthermore, the language proved to be a formal yet literate specification language, based on the experience using the language. The verification procedures for consistency and completeness improved on previous approaches by formulating the problem in a generic way and providing verification using an existing analysis engine, instead of requiring language-specific algorithms. For execution time analysis, the use of observer automata to formulate the timing properties to be verified proved flexible enough to analyze interesting facets of models such as end-to-end latency, without requiring changes to the model. The provided traceability approach supplies a unique combination of syntactic traceability and semantic equivalence, two concepts typically
treated separately. The test case generation strategy introduced the concepts of test case templates to define generic test cases and to provide a scalable and reusable approach to test case generation. The traceability approach was utilized successfully to identify invalidated test cases based on model changes and to generate the necessary test cases to test the changes according to the rule coverage criterion. All of the functionality of the framework is provided in the context of the TASM language, thereby integrating various facets of model building and various engineering functionality, all under the TASM umbrella. Furthermore, the capabilities of the framework were successfully implemented into an integrated toolset, the TASM toolset, to provide end-to-end system engineering tool support, hiding numerous implementation details and removing the need to gain a deep understanding of different languages and tools, such as the UPPAAL tool suite.

9.2 Framework Evaluation

The presented framework was exercised using 3 case studies, as described in Chapter 8. This section provides a “post-mortem” analysis of each feature of the presented research, in light of the experience gained during the case studies. This section summarizes and expands on the discussions following each case study in Chapter 8.

9.2.1 The TASM Language

Based on the case studies, the TASM language proved versatile in modeling a wide variety of system behavior. For example, the language was used successfully to model software and hardware components in the production cell case study. Furthermore, at the software level, the software proved adequate to model software code, as evidenced in the Timeliner case study, control-theoric behavior, and a task/scheduler abstraction, as evidenced in the electronic throttle controller case study. All three facets of the TASM language, namely function, time, and resources, were used successfully to model system behavior in the case studies. The hierarchical composition facilities of the language proved useful to structure and reuse specifications. Further-
more, the composition facilities were instrumental in performing analysis in isolation, as was shown in the electronic throttle controller case study. The use of sub machines in parallel within a step made model construction easier in the case of the production cell case study, but led to exponential growth during the translation to UPPAAL. In terms of usability of the syntax and understanding of the semantics, the language proved relatively easy to learn for someone with a standard programming background. Experience with undergraduate researchers, experience with visiting scientists in the embedded systems laboratory, experience presenting the language at various conferences and workshops, and experience working with engineers from the Charles Stark Draper laboratory all provided evidence that the TASM language is understandable and usable by a user with a standard programming background. These anecdotal results surrounding the use of the TASM language are in line with similar past experiences with ASM [41].

Some aspects of the TASM language were not as easily grasped and were slightly clumsier to use than initially anticipated. The first facet which led to confusion is the parallel nature of update sets within a step. Since the updates happen atomically after the step has finished executing, users were slightly confused that the results of updates which happen sequentially in a rule definition are not available to sub machines or other expressions within the same step. This was especially true for users who were expecting the same semantics as that of a programming language. In certain cases, this situation lead to clumsy specifications, as is the case in the production cell case study, where the arm position is set based on the robot angle. However, situations such as this one were the exception more than the rule and users grasped the importance and subtleties of the step concept with a simple explanation. Another area that led to confusion was the synchronization of parallel main machines with respect to one another. Since the communication between machines happen through shared variables only, wait states had to be devised in the production cell case study and in the electronic throttle controller case study in order to let the environment (other machines) make progress. However, after creating a few models, communication through shared variables became more natural and proved to be ad-
equate. Possible extensions to the TASM language, to enable other synchronization and communication mechanisms, are discussed in Section 9.3.1. Overall, the TASM language proved simple and easy to use and learn, both from a personal experience perspective and from the perspective of peers and colleagues.

9.2.2 Static Analysis

The static analysis capabilities of the framework include functional analysis, execution time analysis, and resource consumption analysis. The functional analysis provided by the framework includes the automated verification of completeness and consistency, and the automated analysis of safety and liveness properties. While the end results of the completeness and consistency analysis did not yield terribly insightful results, the analysis proved indispensable during the model building stage. The verification of functional properties achieved through the UPPAAL verifier was instrumental, both to debug the TASM model and to gain insight into the subtleties of the case studies. The execution time analysis also proved insightful, especially the analysis of end-to-end latency. In the electronic throttle controller case study, the end-to-end latency analysis uncovered an interesting inefficiency in the fault detection strategy. The resource consumption analysis provided an interesting window into the possible parallel behavior of the modeled system.

The bridge between the TASM model and the SAT4J SAT solver is quite clear and the counterexample translation is straightforward since it simply maps a Boolean state to a state in the TASM model. However, the bridge between the TASM model and the UPPAAL model is less clear. If a property does not hold in the UPPAAL model, the tool suite returns a path leading to the state which contradicts the property. Since the UPPAAL model is derived using the "flattened" version of the TASM model, the sequence of rule executions wasn’t always clear from the generated trace. Furthermore, when a property did not hold in the UPPAAL model, three possibilities were encountered – the TASM model was incorrect, the translation to UPPAAL was incorrect, or the design logic was incorrect. When errors were present in the TASM model, the verification proved insightful to ensure the correctness of the model, especially after
simulation scenarios were designed to validate the model. Design logic errors were uncovered using the analysis through UPPAAL although the design errors were often related to the stated property making invalid assumptions about the semantics of the model. For example, in the electronic throttle controller, it is possible to reach a state where the engine revolution is over the critical RPM but the controller is not in the limiting mode. This reachability property is not so much a design error as much as it is a byproduct of the physical reality that there is a delay between an event of interest in the environment and a corrective action by the controller.

9.2.3 Bi-Directional Traceability

The traceability approach presented in Chapter 6 was used on the electronic throttle controller case study in Chapter 8. The benefits of traceability have been established in the software engineering community [217] and the presented approach should provide a usable and flexible means to achieved traceability between models. The theory of refinement has always been intriguing to engineers and mathematicians alike since the seminal paper by Niklaus Wirth [250]. The idea of performing program and system development in a provably correct fashion is an attractive proposition. However, it remains unclear whether such a proposition is realizable in practice since theories of refinement require a fairly strict correspondence between model semantics. In doing so, it is always easier to build models that comply with the refinement theory after the fact instead of building models independently and later try to relate their semantics. Perhaps theories of refinement are best applied in a verification context where the system has been designed and implemented, such as the verification of the Java virtual machine in [237]. Nevertheless, the set of refinement types presented in Section 6.2.1 provide a basis for a disciplined approach to model development. While the correctness criteria presented in Section 6.2.2 seem to apply only to a set of restricted special cases, they proved useful in the electronic throttle controller case study to avoid repeating verification activities unnecessarily, resulting in reduced V & V cost.
9.2.4 Test Case Generation

The test case generation strategy proved fairly straightforward for the case studies. The algorithms presented in Chapter 7 were applied directly without too much trouble. The regression testing strategy was applied to the Electronic Throttle Controller (ETC) case study successfully using the traceability strategy. Unlike the semantic guarantees provided by the correctness criteria, the regression testing approach does not make assumptions about the restrictions of the changes made through the refinement. Consequently, the approach used to regenerate, create, identify, and execute the necessary test cases is applicable at large, where the worst-case corresponds to applying the test case generation algorithm anew.

Since the test case generation is performed in the context of the model, the generated test cases need to be related to a system under test in some way. The ability to apply test cases generated based on the model to the system under test is discussed as possible enhancements to the framework in Section 9.3. Furthermore, when generating test cases, it was assumed that the model could be started in any state and that the effect of executing a single step could be observed at the end of the step. While these assumptions might be valid for a TASM model, they might not be valid for the system under test, which might need to be started in a specific initial state and whose output would not be observable until after a number of steps have been performed. Nevertheless, the test case generation approach provided by the framework provides a strong basis for developing a theory relating the test cases generated by the model to the system under test. As is discussed in Section 7.5.1, the proposed approach can be extended to create test sequences that could be applied to a specific system being tested.

Finally, the coverage criterion used for test case generation is the rule coverage criterion [103]. Rule coverage in the TASM model is analogous to structural coverage for implemented code but weaker than transition coverage or state coverage in finite state automata [102]. More fine grained analysis of the rule guards might be needed to comply with more complex coverage criteria such as the Modified Condition/Decision
Coverage (MD/DC) criterion or with specification-based coverage criteria [143]. Nevertheless, the test case generation strategy provided by the framework presents an intuitive and flexible approach to automatically generate test cases based on TASM models, with acceptable scalability.

9.2.5 Scalability

The topic of scalability is an important one in formal methods and in model-based software engineering [124]. For specification and simulation, scalability does not pose problems since the TASM language provides ample mechanisms for structuring specifications into reusable units using sub machine and function machines. However, if a large number of environment variables are used, the lack of namespaces could present inconvenience to avoid name clashes. In the presented framework, scalability issues arise in the translation of TASM models to the input language of the third party analysis engines. The complexity of the translation algorithm for the mapping to SAT is analyzed in Section B.3.1 and the complexity of the mapping to UPPAAL is analyzed in Section C.2.3. For the translation to SAT, the use of multiple integer variables in the specification can lead to exponential growth in the size of the Boolean formula. For the translation to the timed automata of UPPAAL, the number of generated automata grows linearly with the number of main machines. However, as evidenced in the production cell case study, the use of multiple sub machine calls within a given rule can lead to exponential growth in the number of locations in the generated timed automata. This occurs because the timed automata of UPPAAL do not contain facilities for hierarchical composition and hence the TASM model needs to be “flattened” by removing the hierarchical composition, essentially taking the cross product of the hierarchical units of composition.

Aside from the scalability of the translation, the static analysis features of the presented framework also lead to scalability issues. SAT solving is a well known NP-Complete problem [232], meaning that the performance of the analysis grows exponentially with linear growth of the Boolean formula. For the case of consistency, this problem is exacerbated by the need to verify all pairs of rules against one another.
For the case studies presented in Chapter 8, the analysis of completeness and consistency did not present scalability issues. Nevertheless, the nature of SAT solving, combined with the need to iteratively solve a number of SAT problems presents an important limitation of the proposed approach to perform completeness and consistency analysis. The use of the UPPAAL tool suite for safety and liveness analysis also creates scalability hurdles. However, these scalability issues are directly related to the use of a model checker and not to the TASM language. While model checkers have improved their scalability through heuristics and through the constant increase in computing power [69], model checking as a technology will always face challenges in terms of scalability. The advent of bounded model checking [126] can aid to remedy this situation and will be considered in future work. The analysis of execution time also suffers from scalability issues on two counts. First, by using an observer automaton in addition to the system model, the addition of a parallel automaton creates multiplicative growth in the resulting system model in terms of locations. Since the observer automaton used in the iterative bounded liveness approach contains only 3 locations, this growth is manageable. Second, the approach to measure execution time of the system model uses a combination of the UPPAAL verifier and the UPPAAL simulator, in an iterative fashion to converge on a WCET and on a BCET. Clearly, for a problem of challenging size where verifying a single iteration would prove expensive, doing so iteratively would prove even more intractable. As mentioned in the discussion in Section 8.4.7, when scalability issues arise, the sophistication of UPPAAL can be leveraged to use the heuristics for state space approximation instead of obtaining exact solutions. Whether an approximate solution is feasible or desirable depends on the nature of the problem and the goal of the analysis.

For the analysis of resource consumption behavior, the algorithm provided in Section 5.4 uses brute-force search to iterate through all combinations of rule guards to converge on the minimum and maximum resource consumptions. Clearly, the performance of this algorithm grows exponentially with the number of main machines in the TASM model. Furthermore, the algorithm also relies on the main machines to be "flattened", which could lead to the exponential growth observed in the pro-
duction cell case study. However, given the case studies analyzed in Chapter 8 and other related experience with modeling resources, the number of resource annotations throughout the entire model is typically limited. As was the case in the production cell case study, if a machine does not contain annotations, it can be removed from the iteration algorithm, leading to improved performance.

The last facet of the presented framework where scalability could influence the feasibility of the approach is in the generation of test cases. The test case generation approach is afflicted by the same scalability issues related to the translation to SAT and the use of SAT solvers. However, since the rule coverage criterion is used, the number of necessary test cases in a unit test suite for a given machine will always be equal to the number of rules of the machine. Furthermore, for integration testing and the use of sub machines, the number of required test cases to satisfy the rule coverage criterion should be equal to the largest number of rules of an individual machine in the sub machines used in the hierarchical composition. For the case of regression testing, the worst-case behavior would require that every test case of all test suites be generated anew. In this situation, the number of generated test cases will be linear in the total number of rules in the model. However, each test cases will be generated using the translation to SAT and running the instance through the solver.

9.2.6 Overall Limitations

The scalability of the proposed framework, especially in terms of static analysis capabilities, presents limitations to the applicability of the framework to large case studies. Furthermore, the translation to the timed automata of UPPAAL and to the Boolean formulas for SAT solvers require that a finite version of the TASM model be computable. This is most easily achieved by removing the use of decimal datatypes in the TASM specification. In Section 9.3.3, other analysis engines are surveyed as candidates for use in the framework. More specifically, the use of Satisfiability Modulo Theory (SMT) solvers [21] could provide a viable solution to remedy the limitations regarding the use of decimal datatypes.

Another limitation of the framework is the lack of a generic translation mechanism
to easily incorporate novel analysis engines in the framework, as provided through
model transformation [179]. In the current version of the framework, the addition of a
new input language for another analysis engine would require that the TASM syntax
be parsed into the syntax of the new input language, inside of the toolset. Integrating
model transformation concepts into the framework could remedy the need to manually
hardcode syntax parsing inside of the toolset. Finally, as explained in the evaluation of
the TASM language, the language does not currently include features for specifying
continuous behavior. Consequently, the proposed framework cannot model hybrid
systems. This limitation could be remedied by integrating an environment for hybrid
system modeling and analysis, such as the ones presented in [3] and in [147].

9.2.7 Lessons Learned

Creating formal models of system behavior requires discipline and intellectual invest-
ment. Throughout the model development process in the case studies, different levels
of model “correctness” were required. For example, having a model written on paper
is fairly straightforward to achieve and one can be easily convinced that the model
is correct, using simple arguments. However, when the model is captured through
a tool and the model is simulated, various flaws in the model were encountered, in-
cluding syntax errors, deadlocks, and errors in the control logic. Once these errors
were ironed out through simulation scenarios and rational arguments, the model was
analyzed for completeness and consistency and through the UPPAAAL tool suite. Dur-
ing the static analysis process, even more errors were encountered, requiring a deeper
understanding of the model. The layers of required discipline was interesting to expe-
rience because it validates two basic principles of the presented research – the benefits
of modeling and the necessity of tool support. Making the necessary effort to create a
model will undoubtedly lead to a deeper understanding of the system being designed.
This understanding is independent of the language or the specific design approach
and is purely a byproduct of the intellectual investment required for modeling. But,
as was experienced throughout the case studies, creating a model is only the first
step in gaining understanding of the system behavior. The automated analysis tools
certainly provided sanity checks to ensure that assumptions about the system can be easily verified. The automated tool support certainly keeps the modeler honest.

9.3 Opportunities for Future Research

This section provides an overview of extensions that can be made to the presented research. Since the research presents a framework, it is extensible by definition. The extensions are grouped into features of the TASM language, features of the framework, and other types of analysis engines that can be integrated into the framework.

9.3.1 Language Extensions

The TASM language provides a minimal syntax to describe system behavior in the form of an abstract machine. Simple extensions to ease the writing of specifications could include the definition of arrays and data structures, common facilities which have proved useful in programming language [239]. Furthermore, in terms of ASM theory, the TASM language is expressed in “block form” [110]. The TASM language could equivalently be expressed in “free form”, introducing the step construct to delineate the content of a step, as used in [42]. It would be interesting to investigate usability issues in terms of “block form” versus “free form” even though the two forms are semantically equivalent [110]. Furthermore, in the TASM language, communication between different main machines is achieved via shared variables only. In certain contexts, making the interactions explicit can help understand the dependencies between parallel entities, all the while enabling stronger refinement theories through interaction subsetting and notions of trace equivalence [133, 147]. Common explicit communication mechanisms include synchronization channels, as used in UPPAAL’s timed automata, which are borrowed from Communicating Sequential Processes (CSP) [131] and from the Calculus of Communicating Systems (CCS) [170]. Other languages, such as Timed Input/Ouput Automata (TIOA), make interactions explicit by partitioning externally visible transitions into input and output actions [147]. Regardless of the mechanism selected to express cross-machine communication, it would be interesting
to investigate the effect on semantics and on usability.

Finally, the TASM language describes system behavior through discrete step transitions. While this behavior is adequate to describe the behavior of hardware and software components, embedded controllers often act on continuous dynamics described through differential equations. Future investigations could focus on how continuous dynamics could be integrated into the language and/or the framework, for the sake of hybrid system modeling, simulation, and verification. The ability to include continuous dynamics in the TASM language would most likely be better introduced through an appropriate modeling, simulation, and verification environment for hybrid systems, integrated in the framework, such as those provided by CHARON [3] and by TIOA [147].

9.3.2 Framework Features

The presented framework provides an integrated environment for modeling, validation, and verification of embedded real-time systems. The crux of the approach focuses on the design phase of the engineering lifecycle. Other features of the framework could include code generation and traceability of model features down to the implementation level. Ongoing research is currently performed in the Embedded Systems Laboratory (ESL) concerning code generation and extending the traceability approach to support the RavenSpark implementation language. The RavenSpark language is a combination of Spark Ada [20], a safe subset of Ada, and the Ada Ravenscar tasking profile, a safe set of tasking features [233]. The ability to trace model features down to the implementation level could help validate assumptions made in the model by comparing the assumptions embedded in the model, such as time annotations, to the running time of implemented code. The comparison could be achieved via measurements obtained through state-of-the-art WCET analysis tools for implementation code [90]. If a relation between the TASM language and an implementation such as RavenSpark exists, the test case generation approach can also be bridged between the language of the model and the language of the system being tested. The approach to test case generation presented in Chapter 8 could be tai-
lored to a specific system by piecing together the templates that cover specific rules to create test sequences. Such test sequences would take the form of executing a set of rules in sequence. The appropriate sequences of rules would depend on the system being tested, including the properties of initial states and the properties of observable states.

The exploration of alternate designs is an important part of the design activity [56]. The assumption in the presented research is that the functional decomposition and design alternatives have already been evaluated separately and that a design has been agreed upon. Facilities to provide design tradeoffs and to explore the design trade space would certainly complement the design features of the framework. Finally, most system engineering practice begins through requirements engineering [141]. The ability to integrate the presented framework with established requirement elicitation and classification methods could provide end-to-end traceability of requirements from high-level down to implementation [217]. Furthermore, using the traceability approach with the presented test case generation approach, requirement coverage could potentially be achieved [216]. By integrating with requirement engineering practice and an implementation platform, the presented framework could provide a true end-to-end system engineering framework from requirements to code.

9.3.3 Analysis Engines

The UPPAAAL tool suite and the SAT4J SAT solver were selected as the analysis engines integrated into the presented framework because they represent two mature engines from two popular branches of analysis – model checking and SAT solving. While both types of solvers proved appropriate for the type of analysis provided by the framework, the solvers also have important limitations. The first limitation involves the lack of support for decimal numerical values from the Reals domain. The TASM language provides the facilities for modeling and simulating models containing variables of type float, but the translation algorithms do not support the analysis of such TASM models because the relevant engines do not support the datatype. While some workarounds are possible, as suggested in Section B.3.1, the selected engines simply
do not provide native support. The second limitation involves the scalability of the selected analysis engines. The “state explosion problem” is a well-known limitation of the model checking approach [67] and also applies to SAT solving, which relies on systematically exploring a finite state space. However, with increasing computer power and improved state exploration heuristics, model checking can handle problems of increasing complexity [69]. Furthermore, Bounded Model Checking (BMC) provides an approach to model checking where scalability can be mitigated by controlling the length of paths to be verified [126]. Nevertheless, the need to generate and explore the state space of the model remains the cornerstone of model checking and SAT solving and will continue to present scalability challenges [68]. In the following subsections, different classes of analysis engines are explored as potential options to remedy the limitations of the engines currently used in the presented framework.

**Linear Programming Solvers**

Linear Programming (LP) solvers are a class of constraint solvers with support for solving linear constraints involving a mix of integer and decimal variables [215]. The use of LP solvers in the presented framework has been investigated in [206]. LP solvers provide an advantage over SAT solvers because they can handle symbolic constraints and provide native support for decimal variables. However, the constraints need to be linear and the solvers do not provide native support for the disjunction of constraints. Simulating disjunction of constraints is possible through the so-called “big-M” method [218]. While the “big-M” approach can simulate disjunction, the approach scales extremely poorly when multiple disjunctions are present, as is the case for the analysis of completeness and consistency. Furthermore, when the research was conducted, tool support for LP solving was relatively scarce, with the GNU Linear Programming Toolkit (GLPK) being one of the few mature offerings [96].

**Satisfiability Modulo Theory Solvers**

Satisfiability Modulo Theory (SMT) is a theory for solving constraints that involve Boolean formulas and arithmetic constraints [229]. The solvers that support the
automated analysis of constraints, called SMT solvers, extend SAT solvers with the ability to reason about arbitrary constraints over the integer domain and the Reals domain. In a sense, SMT solvers combine the benefits of SAT solvers and LP solvers. While non-linear constraints are supported by certain solvers, scalability issues arise in the presence of non-linear constraints. SMT solvers have been used as an alternative to traditional model checkers, especially for bounded model checking [14, 97].

At the time when the presented research was conducted, SMT was a relatively new theory and tool support was rather primitive. Nowadays, SMT solvers are gaining popularity and implementations are increasingly more reliable and more scalable [21]. Mature implementations include the MathSAT solver [53] and the Yices solver [142]. Nevertheless, most constraint solving problems are known to be NP-Complete and hence scalability issues will always be present in model checkers, SAT solvers, and SMT solvers [232].

Theorem Provers

During the early days of tool-supported formal verification, approaches to verification were polarized into theorem proving and model checking. Theorem proving differs from model checking in that it does not rely on generating a finite state space for the semantics of the model in order to prove properties [137]. Theorem provers use a set of axioms and rules of inference to prove properties of system models [191] syntactically, through symbolic manipulation. Because they do not rely on exhaustive exploration of the state space, theorem provers do not suffer from the same scalability issues as model checkers do. However, theorem provers present different challenges since the analysis typically needs to be guided by the user and is not completely automated [243]. Furthermore, encoding state transition system semantics into a logical theory is not readily achieved [11]. On the usability front, some progress has been made to use the PVS proof system to verify properties of automata models [13, 12]. Popular and mature theorem prover implementations include Coq [83], HOL [106], Isabelle [209], and PVS [207].
9.4 Closing Thoughts

Engineering complex systems is, by definition, a complex endeavor. While the growing sophistication of algorithms and tools, the constant increase in computing power, and the rigor of mathematical theories all provide attractive trends leaning toward automated engineering, the problem of system engineering remains very much a human problem about complexity management. Consequently, the design and development of solutions to address the challenges of engineering complex systems should target the augmentation of the capabilities of the human engineer, not the replacement of the engineer. The anecdotal experience surrounding ASM, combined with the experience with the TASM language and the presented framework has demonstrated that the modeling paradigm of ASM can be readily grasped by someone with minimal programming experience and synchronizes well with established programming practice.

Moreover, there exists a vast body of research in different, seemingly unrelated disciplines such as software engineering, formal methods, and control theory. Many of the research efforts in disparate disciplines cannot be readily aggregated and synthesized to achieve engineering goals. Hopefully, the research presented in this thesis will lead to increased integration of multi-disciplinary approaches to embedded real-time system engineering.

9.5 Segue into the Appendices

The conclusion presented in this chapter marks the end of the narrative of the thesis. The appendices following this chapter can be read in any order and do not follow a linear sequence. Summary descriptions of the content of each appendix is available in Section 1.4.
Appendix A

TASM Language Reference

This appendix explains the concrete constructs of the TASM language as implemented in the TASM toolset. This appendix can be consulted as a supplement to Chapter 4. More specifically, this appendix describes the logical objects that make up the TASM language in the toolset, the rules for constructing names, the list of reserved keywords, the list of operators, and the general typing rules. Furthermore, the context-free grammar of the TASM language, presented in Section A.2, has been used to implement the compiler for the TASM toolset. Semantic implementation topics, such as operator precedence and calling convention, are explained in Section A.3.

A.1 TASM Objects

The concepts described in Chapter 4 are implemented in a suite of logical objects in the TASM language. This section gives the list of logical objects and their properties, as implemented in the TASM toolset. The concrete syntax of how these objects are expressed is described in Section A.2.

A.1.1 Specification

In the logical objects, a specification is the overarching concept or object that includes all other logical objects. A specification is the complete document that results from
capturing a system design in a model expressed in the TASM language.

A.1.2 Project

The project is the top level object that contains the high level metadata of the system specification. The project has three attributes, the project name, the project description, and the version of the syntax. The name and description are self-explanatory. The version of the syntax is used to identify older versions of the syntax to preserve backwards compatibility. Other attributes of the project that might be added in the future might include modification times, authors, etc. There is only one project object per specification.

A.1.3 Environment

The environment is the object that is used to represent the "outside world". The environment object contains the list of user-defined types, which are finite enumerations, the list of resources, which are finite quantities, and the list of variables, which are the values that affect and are affected by the execution of the various machines in the specification. The environment is a global object that is accessible by all machine instances.

A.1.4 Main Machine Template

In the TASM language, a main machine definition is a template. A machine template is a parameterized version of a machine that needs to be instantiated through a constructor given as part of the template definition. The use of templates enables reuse of specifications and the ability to have multiple versions of a machine definition for a given system design. The concept of a machine template is analogous to the concept of a class in object-oriented programming languages [239]. Main machine templates are instantiated in a Configuration object.

A main machine template contains three attributes – a set of internal variables, a constructor, and a set of rules. The internal variables are typed variables that are
visible only inside the machine. The constructor is used to initialize the machine through instantiation and to assign default values to internal variables. The set of rules is a set of guarded commands that govern the machine execution and its effects on the environment. Each rule also specifies the duration of the rule application and the resources consumed during execution of the rule, according to the principles explained in Chapter 4. Additional attributes of a main machine template include a set of monitored variables and a set of controlled variables. The set of monitored variables is the list of environment variables that are used in the guarding conditions of the rules. The set of controlled variables is the list of environment variables that are used in the effect conditions of the rules.

The main machines are the top-level abstract machines that represent a thread of execution. If more than one main machine is present in a system configuration, the resultant specification contains parallelism, also called a multi-agent ASM in the Abstract State Machine community [47]. Instantiating multiple main machines is the way to obtain parallel composition of specifications with interleaving semantics.

### A.1.5 Function Machine

The idea behind a function machine is a machine with no side-effects that can be used to define abstractions and macros. A function machine is a machine that takes a set of typed inputs and returns a single typed output. A function machine contains a set of input variables and a single output variable. The set of input variables are typed variables that are used to invoke the machine. The output variable is a typed variable that is used to return a value from the machine when it is invoked. A function machine is not allowed to modify the environment and must compute its output solely based on the input values and the values of its monitored variables.

### A.1.6 Sub Machine

A sub machine is similar to a main machine except that the sub machine does not execute in its own thread of execution. Instead, a sub machine executes inside of a
main machine and shares the thread of execution of the main machine. Sub machines are used to achieve hierarchical composition. A main machine can use more than one sub machine as part of its definition. A sub machine definition contains the same attributes as a main machine except that it does not contain internal variables nor does it contain a constructor.

A.1.7 Configuration

A configuration corresponds to a simulation scenario. A configuration contains a name and a description so that it can be referenced during simulation. A configuration also contains a list of main machine instantiations, defined by invoking the constructors of the main machine templates. Furthermore, the configuration can contain initial values for the environment variables. The initial values specified in a configuration override the initial values of environment variables specified in the environment. Multiple configurations can exist for a given project and a configuration must be selected to perform simulation.

A.2 Syntax

This section describes the concrete syntax of the TASM language, expressed in plain-text format. The plain-text syntax is the format used to read and write specifications using the TASM toolset and it is the input format for the parser and compiler. In the TASM toolset, a system design can be shown across different windows and other user interface components and does not need to be gathered into a single location.

A.2.1 Notational Conventions

The following notational conventions are used in this section and subsequent sections.

- Each abstract type uses the prefix TASM
- Constants are enclosed in single quotes (e.g. 'a', '1', etc.), except where set-theoretic notation is used
- The formal grammar uses the basic symbols of Backus-Naur Form (BNF) [18] (e.g., {}, [], <>, etc.)

A.2.2 Names

The use of names is crucial in the TASM language; every type of object (variable, type, resource, machine, etc.) is uniquely identified by its name. We define the generic abstract type TASMName to express the restrictions on individual names. The type TASMName is used in the rest of this document when a name has the listed restrictions. The TASM language has a set of reserved keywords that cannot be used as names. The complete list of reserved keywords is shown in table A.1.

- TASMName is a string of characters
- Each character of TASMName can be either 'a'-'z' or 'A'-'Z' or '_' or '1'-'9' or '0'
- TASMName must start with 'a'-'z' or 'A'-'Z'
- TASMName has a length: 1-64
- TASMName is not a reserved keyword
- TASMName is case-sensitive
- Each TASMName is unique in a given TASM specification

The restrictions on the uniqueness of TASMName's might seem restrictive, especially in the absence of namespaces, but imposing this restriction removes potential ambiguities.

A.2.3 Types

The TASM language contains only simple types. There are no data structures, subtypes, or polymorphic types. The TASM language is also strongly typed; there are no dynamic types or type inference. All typing rules are enforced at compilation time.
### Table A.1: Reserved keywords

<table>
<thead>
<tr>
<th>Keyword</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>t</code></td>
<td>Used for time annotations</td>
</tr>
<tr>
<td><code>next</code></td>
<td>Used in time annotations to denote a special value of time</td>
</tr>
<tr>
<td><code>now</code></td>
<td>Used to obtain the value of the global clock</td>
</tr>
<tr>
<td><code>new</code></td>
<td>Used to instantiate a machine template</td>
</tr>
<tr>
<td><code>Integer</code></td>
<td>Denotes the integer datatype</td>
</tr>
<tr>
<td><code>Float</code></td>
<td>Denotes the float datatype</td>
</tr>
<tr>
<td><code>Boolean</code></td>
<td>Denotes the Boolean datatype</td>
</tr>
<tr>
<td><code>False</code></td>
<td>Denotes a constant in the Boolean datatype</td>
</tr>
<tr>
<td><code>True</code></td>
<td>Denotes a constant in the Boolean datatype</td>
</tr>
<tr>
<td><code>and</code></td>
<td>Denotes a logical connective</td>
</tr>
<tr>
<td><code>or</code></td>
<td>Denotes a logical connective</td>
</tr>
<tr>
<td><code>not</code></td>
<td>Denotes a unary operator</td>
</tr>
<tr>
<td><code>skip</code></td>
<td>Denotes the production of an empty update set</td>
</tr>
<tr>
<td><code>else</code></td>
<td>Denotes the special &quot;else rule&quot;</td>
</tr>
<tr>
<td><code>//</code></td>
<td>Used to comment out a given line</td>
</tr>
</tbody>
</table>
and type safety is assured if a TASM specification compiles correctly. The TASM language supplies three default types:

- Integers = {..., -1, 0, 1, ...}
- Floats = \textit{Rational Numbers} (e.g., -1.11, -0.5, 0.0, 10.45, etc.)
- Booleans = \{\textit{True}, \textit{False}\}

TASM also allows the definition of user-defined types, which are analogous to \textit{enumerations} in most programming languages. However, user-defined types are not assigned integer values and are unordered. A user-defined type is a named type that can be used to provide readable options and type safety. More specifically, a user-defined type is a named type that contains one or more named values. For example, user-defined types can be defined to denote the status of a light status or the mode of an airplane:

- \texttt{light\_status} = \{\texttt{ON}, \texttt{OFF}\}
- \texttt{airplane\_mode} = \{\texttt{Idle}, \texttt{Taxi}, \texttt{Takeoff}, \texttt{Cruise}, \texttt{Landing}\}

User-defined types are unordered sets of one or more elements where elements must be unique. Each member element is a TASMName. Furthermore, the name of the type is a TASMName.

The TASM language is a strongly typed language, meaning that all variables are typed and that type safety is enforced at compilation time. No type casting is allowed, even from \textit{Float} to \textit{Integer}. Future versions of the language might allow type casting through functions supplied by the TASM language.

**A.2.4 Arithmetic Operators**

For \textit{Integer} and \textit{Float} types, the TASM language provides the four basic arithmetic operators, applicable only to operands of the same type:

- addition: +
• subtraction: −

• multiplication: *

• division: /

Operations between operands of disparate types is undefined and results in a compilation error. For example, addition between an operand of type Float or an operand of type Integer results in a compilation error. The arithmetic operators are undefined for Boolean types and for user-defined types.

The assignment operator is the only operator which is defined for all types. Like for the other arithmetic operators, the assignment operator is defined only for operands of the same type:

• assignment: :=

The assignment operator does not return a value (denoted by the special character '⊥').

A.2.5 Logical Operators

The following two logical operators are defined for all types. The signature of the operators is Type1 × Type2 → Boolean where Type1 = Type2. Operators applied to operands of different types are undefined and result in a compilation error.

• equal: =

• not equal: !=

For Integer and Float types, the TASM language supplies an additional four logical operators:

• greater than: >

• greater than or equal to: >=
• less than: <

• less than or equal to: <=

The signature of these operators is also \( Type_1 \times Type_2 \rightarrow Boolean \) where \( Type_1 = Type_2 \). The logical operators are undefined when the operators are of different types or for \( Boolean \) and user-defined types. For \( Boolean \) types, the TASM language provides two logical connectives:

• conjunction: \textit{and}

• disjunction: \textit{or}

The signature of these operators is \( Boolean \times Boolean \rightarrow Boolean \) and is undefined for non \( Boolean \) types. For \( Boolean \) types, the TASM language supplies one unary operator:

• negation: \textit{not}

The signature of this operator is \( Boolean \rightarrow Boolean \) and is undefined for non \( Boolean \) types.

All operators are summarized in Table A.2.

\textbf{A.2.6 Context-Free Grammar}

The following section explains the formal grammar that is used to express the basic concepts from the previous section, such as types, constants, variables, expressions, etc. The formal grammar is given in Backus-Naur Form (BNF) \cite{18} where the syntactic symbol '|' means "or", '[' means "optional", and '{}' means 0 or more instances (Kleene closure). The special form of the closure operator, denoted '{}+' means 1 or more instances. Any constant is given inside of single quotation marks. For example, the keyword denoting the type integer is given as 'Integer'. It is important to distinguish between the syntactical "optional symbol" '|' and the constant denoting the right bracket "]".
Table A.2: Operators

<table>
<thead>
<tr>
<th>Operator</th>
<th>Signature</th>
<th>Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>( Type_1 \times Type_2 \rightarrow Type_3, Type_1 = Type_2 = Type_3 )</td>
<td>Integer, Float</td>
</tr>
<tr>
<td>-</td>
<td>( Type_1 \times Type_2 \rightarrow Type_3, Type_1 = Type_2 = Type_3 )</td>
<td>Integer, Float</td>
</tr>
<tr>
<td>*</td>
<td>( Type_1 \times Type_2 \rightarrow Type_3, Type_1 = Type_2 = Type_3 )</td>
<td>Integer, Float</td>
</tr>
<tr>
<td>/</td>
<td>( Type_1 \times Type_2 \rightarrow Type_3, Type_1 = Type_2 = Type_3 )</td>
<td>Integer, Float</td>
</tr>
<tr>
<td>:=</td>
<td>( Type_1 \times Type_2 \rightarrow \perp, Type_1 = Type_2 )</td>
<td>All</td>
</tr>
<tr>
<td>=</td>
<td>( Type_1 \times Type_2 \rightarrow \text{Boolean}, Type_1 = Type_2 )</td>
<td>All</td>
</tr>
<tr>
<td>!=</td>
<td>( Type_1 \times Type_2 \rightarrow \text{Boolean}, Type_1 = Type_2 )</td>
<td>All</td>
</tr>
<tr>
<td>&gt;=</td>
<td>( Type_1 \times Type_2 \rightarrow \text{Boolean}, Type_1 = Type_2 )</td>
<td>Integer, Float</td>
</tr>
<tr>
<td>&lt;</td>
<td>( Type_1 \times Type_2 \rightarrow \text{Boolean}, Type_1 = Type_2 )</td>
<td>Integer, Float</td>
</tr>
<tr>
<td>&lt;=</td>
<td>( Type_1 \times Type_2 \rightarrow \text{Boolean}, Type_1 = Type_2 )</td>
<td>Integer, Float</td>
</tr>
<tr>
<td>and</td>
<td>( \text{Boolean} \times \text{Boolean} \rightarrow \text{Boolean} )</td>
<td>Boolean</td>
</tr>
<tr>
<td>or</td>
<td>( \text{Boolean} \times \text{Boolean} \rightarrow \text{Boolean} )</td>
<td>Boolean</td>
</tr>
<tr>
<td>not</td>
<td>( \text{Boolean} \rightarrow \text{Boolean} )</td>
<td>Boolean</td>
</tr>
</tbody>
</table>
The BNF grammars describing the concepts of the TASM language is given below. The first part of the grammar supplies the rules for constructing names, constants, and types. The second part of the grammar supplies the rules for constructing expressions, variables, and formulas. The TASM language ignores whitespace unless whitespace is required. When whitespace is required, it is denoted by the token \(<TASMWhitespace>\), which represents a single whitespace character. Tab characters, space characters, new line characters, carriage return characters, and form feed characters all represent a single whitespace character.
Basic Concepts

\[
\begin{align*}
< \text{TASMUCaseLetter} > & ::= \ 'A' \mid 'B' \mid \ldots \mid 'Z' \\
< \text{TASMLCaseLetter} > & ::= \ 'a' \mid 'b' \mid \ldots \mid 'z' \\
< \text{TASMLetter} > & ::= < \text{TASMUCaseLetter} > \mid < \text{TASMLCaseLetter} > \\
< \text{TASMDigit} > & ::= \ '0' \mid '1' \mid '2' \mid '3' \mid '4' \mid '5' \mid '6' \mid '7' \mid '8' \mid '9' \\
< \text{TASMCharacter} > & ::= < \text{TASMLetter} > \mid < \text{TASMDigit} > \mid '.' \\
< \text{TASMASCIIChar} > & ::= \text{All standard ASCII characters} \\
< \text{TASMWhiteSpaceChar} > & ::= \ ' ' \mid '\t' \mid '\n' \mid '\r' \mid '\f' \\
< \text{TASMWhiteSpace} > & ::= \{ < \text{TASMWhiteSpaceChar} > \}^+ \\
< \text{TASMIntLit} > & ::= \['-']< \text{TASMDigit} >\{< \text{TASMDigit} >\} \\
< \text{TASMFloatLit} > & ::= \['-']< \text{TASMDigit} >\{< \text{TASMDigit} >\} '.' < \text{TASMDigit} >\{< \text{TASMDigit} >\} \\
< \text{TASMBinaryLit} > & ::= 'True' \mid 'False' \\
< \text{TASMStringLit} > & ::= \{ < \text{TASMASCIIChar} > \} \\
< \text{TASMName} > & ::= < \text{TASMLetter} >\{< \text{TASMCharacter} >\} \\
< \text{TASMDescription} > & ::= < \text{TASMStringLit} > \\
< \text{TASMVariable} > & ::= < \text{TASMName} >
\end{align*}
\]
< TASMUDTypeName > ::= < TASMName >

< TASMTypeName > ::= 'Integer' | 'Float' | 'Boolean' | < TASMUDTypeName >

< TASMUDTypeMember > ::= < TASMName >

< TASMUDTypeDef > ::= < TASMUDTypeName > ':='

'{'< TASMUDTypeMember > {','< TASMUDTypeMember >}'

< TASMFMachineCall > ::= < TASMMachineName > ' ('[< TASMArithExpr {','< TASMArithExpr >}]')

< TASMValueExpr > ::= < TASMArithExpr > | < TASMFMachineCall > | 'now'

< TASMArithOp > ::= '+' | '-' | '*' | '/'

< TASMArithExpr > ::= < TASMValueExpr > |

<TASMArithExpr><TASMArithOp><TASMArithExpr> |

'('<TASMArithExpr><TASMBinLogicOp><TASMArithExpr>')'

< TASMBinLogicOp > ::= '>=' | '>=' | '<=' | '<' | '=' | '<=' | '>=' | '!='

< TASMLogicExpr > ::= < TASMBooleanLit > |

<TASMArithExpr><TASMBinLogicOp><TASMArithExpr> |

'('<TASMArithExpr><TASMBinLogicOp><TASMArithExpr>')'

< TASMLogicBinConn > ::= 'and' | 'or'

< TASMLogicUnConn > ::= 'not'
< TASMLogicFormula > ::=  < TASMLogicExpr > |  
< TASMLogicFormula > < TASMLogicBinConn > < TASMLogicFormula > |  
< TASMLogicUnConn > < TASMLogicFormula > |  
'( '< TASMLogicExpr > ' ) ' |  
'( '< TASMLogicFormula > < TASMLogicBinConn > < TASMLogicFormula > ' ) ' |  
'( '< TASMLogicUnConn > < TASMLogicFormula > ' ) '  
< TASMExpr > ::=  < TASMArithExpr > | < TASMLogicExpr > | < TASMLogicFormula >  
< TASMVarDecl > ::=  < TASMTypename >< TASMWhitespace >< TASMVariable >';'  
< TASMVarDeclInit > ::=  < TASMTypename >< TASMWhitespace >< TASMVariable >  
' :=< TASMConstant >';'  
< TASMNameDescPair > ::=  'NAME:' < TASMName >< TASMWhitespace > 
' DESC:' < TASMDescription >  
< TASMVarInit > ::=  < TASMVariable >' :=< TASMConstant >';'  

Environment  

< TASMResourceName > ::=  < TASMName >  
< TASMResourceDef > ::=  < TASMResourceName >' :=' [ '< TASMIntLit >', '< TASMIntLit >' ]';'  
< TASMChannelName > ::=  < TASMName >  
< TASMChannelDef > ::=  'Channel' < TASMWhiteSpace > < TASMChannelName >';'  
< TASMEvironDef > ::=  'ENVIROMENT.' < TASMEnvTypeDef >  
< TASMEnvVarDef > < TASMEnvChannelDef >  
< TASMEnvResourceDef >
< TASMEnvTypeDef > ::= 'TYPES' {< TASMUDTypeDef >}

< TASMEnvVarDef > ::= 'VARIABLES' {< TASMVarDeclInit >}

< TASMEnvChannelDef > ::= 'CHANNELS' {< TASMChannelDef >}

< TASMEnvResourceDef > ::= 'RESOURCES' {< TASMResourceDef >}

Project

< TASMProjectDef > ::= 'PROJECT' {< TASMNameDescPair >}

Machine Templates

< TASMTemplateDef > ::= 'TEMPLATES' {< TASMTemplatesDef >}
    < TASMTemplatesDef >
    < TASMFTemplatesDef >

< TASMTemplatesDef > ::= 'MAIN MACHINES' {< TASMTemplateDef >}

< TASMTemplatesDef > ::= 'SUB MACHINES' {< TASMTemplateDef >}

< TASMFTemplatesDef > ::= 'FUNCTION MACHINES' {< TASMFTemplateDef >}

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Syntax Common to all Machines

\[
\begin{align*}
<TASMVariableList> &::= \{ <TASMVariable> \}'\}
\\
<TASMRuleName> &::= <TASMSName>
\\
<TASMRule> &::= <TASMRuleName>' \{ <TASMTTimeSpec>\} <TASMSResourceSpec> <TASMRuleDef>'
\\
<TASMTTimeSpec> &::= 't' ::= ' [ <TASMSIntLit> ', ', <TASMSIntLit> ] ' |
\\ &::= 't' ::= ' [ <TASMSIntLit> ', ', <TASMSIntLit> ] ' |
\\ &::= 't' ::= 'nextl'; |
\\ &::= 't' ::= 'dt'; |
\\
<TASMSResourceSpec> &::= <TASMSResourceName> ::= ' [ <TASMSIntLit> ', ', <TASMSIntLit> ] ' |
\\ &::= <TASMSResourceName> ::= ' [ <TASMSIntLit> ', ', <TASMSIntLit> ] ' |
\\
<TASMRuleDef> &::= <TASMRuleGuard><TASMSWhiteSpace><TASMRuleEffect>
\\
<TASMRuleGuard> &::= 'if' <TASMLogicFormula>' then' |
\\ &::= 'else' <TASMSWhiteSpace>' then'
\\
<TASMRuleEffect> &::= \{ <TASMEffectExpression>\}^*
\\
<TASMEffectExpression> &::= <TASMAssignment> | <TASMSubMachineCall> | <TASMSChannelExpr> | 'skip'
\\
<TASMAssignment> &::= <TASMVariable>' := '<TASMArithExpr>
\\
<TASMSubMachineCall> &::= <TASMMachineName> '(')
\\
<TASMSChannelExpr> &::= <TASMChannelName> <TASMChannelOpChar>
\\
<TASMChannelOpChar> &::= '?'; |
\\ &::= '}'
\end{align*}
\]
Main Machine

< TASMTemplatesDef > ::= 'MAIN MACHINE'! < TASMNameDescPair >
< TASMMVars > < TASMConstr > < TASMRules >

< TASMMVars > ::= < TASMContVars > < TASMMonVars > < TASMinVars >

< TASMContVars > ::= 'CONTROLLED VARIABLES'! < TASMVariableList >

< TASMMonVars > ::= 'MONITORED VARIABLES'! < TASMVariableList >

< TASMinVars > ::= 'INTERNAL VARIABLES'! { < TASMVarDeclInit > }

< TASMConstr > ::= 'CONSTRUCTOR'! < TASMMachineName > { '< TASMParamList >' } '{
{ '< TASMVarInit >' }

< TASMParamList > ::= < TASMParam > {',' < TASMParamList >}

< TASMParam > ::= < TASMTypename > < TASMWhiteSpace > < TASMVariable >

< TASMRules > ::= 'RULES'! < TASMRule > { < TASMWhiteSpace > < TASMRule > }

Sub Machine

< TASMSTemplateDef > ::= 'SUB MACHINE'! < TASMNameDescPair >
< TASMSVars > < TASMRules >

< TASMSVars > ::= < TASMMonVars > < TASMContVars >
A.3 Semantics

Three dominant approaches stand out when expressing programming language semantics - operational semantics, denotational semantics, and axiomatic semantics. Denotational semantics has been used successfully for sequential programs, but the
paradigm becomes difficult to work with when concurrency is introduced. Axiomatic semantics has been used on smaller programs, but it is not clear that it works well for larger programs or for languages with numerous concepts. Operational semantics could be used to express the TASM semantics because it has concepts analogous to the TASM language, namely, that of an abstract machine progressing through configurations. Operational semantics has been used extensively to specify language semantics, for both sequential and concurrent programs. However, because the ASM paradigm is close to the operational semantics paradigm, an attempt is made to express the semantics of the TASM language using Abstract State Machines (ASM). The motivation is twofold. First, ASMs have been used to specify the semantics of executable languages, including VHDL, Prolog, and SDL. Second, because the TASM language is built on top of the ASM language, it makes sense to use ASM to express the semantics. In a sense, if the semantics are expressed properly, the TASM language could be viewed as "syntactic sugar" on top of the ASM language.

A.3.1 Operator Precedence

The use of parentheses is strongly encouraged to disambiguate operator precedence for language users. However, the TASM language defines rules for operator precedence when parentheses are not used. The precedence rules are listed in Table A.3.

A.3.2 Calling Convention

In the TASM language, all function ASM calls machine instantiations, and variable references use "call-by-value" semantics. There are no pointers or no references in the TASM language, only distinct variables. Machine instances are all different from one another. When variables are assigned to each other, the value gets copied over to the assigned variable. No variable can be "linked" to the same value, using "pointer-like" semantics.
Table A.3: Operator precedence

<table>
<thead>
<tr>
<th>Operator</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>*</td>
<td>Multiplication</td>
</tr>
<tr>
<td>/</td>
<td>Division</td>
</tr>
<tr>
<td>+</td>
<td>Addition</td>
</tr>
<tr>
<td>-</td>
<td>Subtraction</td>
</tr>
<tr>
<td>&gt;=</td>
<td>Greater than or equal to</td>
</tr>
<tr>
<td>&gt;</td>
<td>Greater than</td>
</tr>
<tr>
<td>&lt;=</td>
<td>Less than or equal to</td>
</tr>
<tr>
<td>&lt;</td>
<td>Less than</td>
</tr>
<tr>
<td>=</td>
<td>Equal to</td>
</tr>
<tr>
<td>!=</td>
<td>Not equal to</td>
</tr>
<tr>
<td>and</td>
<td>Logical connective 'AND'</td>
</tr>
<tr>
<td>or</td>
<td>Logical connective 'OR'</td>
</tr>
<tr>
<td>not</td>
<td>Logical negation 'NOT'</td>
</tr>
<tr>
<td>:=</td>
<td>Assignment</td>
</tr>
</tbody>
</table>
A.3.3 Types

All variables are strongly typed in the TASM language. There is no type-casting and operators are defined only for operators of the same type. The type checking ensures that all operations are type safe at compile-time. Syntactically, decimal values are interpreted with a required "decimal part", which is a period ("." ) followed by a digit. This is required even from decimal numbers without a decimal part (e.g., 9.0). "9.0" and "9" are constants of different types, namely the first one is of type "Integer" while the second one is of type "Float". There is no type inference or dynamic typing of any sort as all variables are statically typed and cannot be type casted.

A.3.4 Relation to Abstract State Machines

In this section, the execution semantics of the TASM language are formally expressed using ASM. This is accomplished by using Abstract State Machines (ASM), using the syntax from the Lipari guide [113]. The aim of this section is to express the semantics of the extended language using a "desugaring" into the syntax of the Lipari guide. For the syntax, we follow the notational conventions used in both the Lipari guide and the definition of the formal semantics of SDL [92]. For a detailed list of the ASM syntax used to express formal semantics, the reader is referred to the SDL guide [92], pages 25–27. In Chapter 4, Section 4.4, a translation from TASM to timed ASM is given. The translation given in this section is similar except that the ASM version used in this section uses the Lipari guide syntax, which is closer to the classical definition of ASM.

The key extensions to the TASM language have to do with the addition of time passage and resource consumption. To illustrate time passage, the same conventions as in [72, 92] are adopted and a global dynamic and monotonic increasing function is introduced, called currentTime:

- external currentTime: \rightarrow REAL

This function is used inside of machines to query the value of the current time. The
function is modified by the environment only and returns a monotonically increasing value greater than 0.0.

A.3.5 Sugaring/Desugaring

The extensions to the TASM language have been introduced as “syntactic sugar” on top of the syntax and semantics of the ASM language as expressed in the Lipari guide [113]. In order to map a TASM specification into an ASM specification, two domains are introduced, namely $DTASM$ and $DASM$ to denote the domains of specifications expressed in the TASM language and the ASM language respectively. A function called $Desug$ is also introduced. This function maps a TASM specification into an ASM specification. The “desugaring” function is defined for all individual elements of the TASM language (specifications, variables, types, rules, etc.) and maps the TASM elements into elements of the ASM language.

- $Desug : DTASM \rightarrow DASM$

A.3.6 Resource definitions

A resource definition, $Rdef$, in the environment is desugared into a global shared dynamic function:

- $Desug([Rdef]) = \text{shared } Rdef$

The desugaring of the resource definition is a bit more complex with respect to usage, but the execution semantics of resource usage are detailed in section A.3.10.

A.3.7 Type definitions

Type definitions, $Tdef$ get desugared into static finite domains:

- $Desug([Tdef]) = \text{static domain } Tdef$
A.3.8 Variables

Controlled and monitored variables inside of machines get desugared into nullary controlled and dynamic functions, respectively.

A.3.9 Rules

The desugaring of the rules is the most complex desugaring in the TASM language, because this is where time and resource utilization play a role. To illustrate the desugaring of rules, an abstract syntax for a rule definition is defined:

- $\text{Rules} = (R_i^\uparrow)$
- $R_i = (t_i \; r_i^\uparrow \; \text{if} \; \text{cond}_i \; \text{then} \; \text{effect}_i)$

In the TASM, the set of rules for a given machine is implicitly mutually exclusive. In the ASM language, the mutual exclusion is explicit. The first desugaring of a set of rules is to generate the explicit mutual exclusion:

- $\text{Desug}[[\text{Rules}]] = \text{Desug}[[((t_0 \; r_0^\uparrow \; \text{if} \; \text{cond}_0 \; \text{then} \; \text{effect}_0) \; \ldots \; (t_n \; r_n^\uparrow \; \text{if} \; \text{cond}_n \; \text{then} \; \text{effect}_n))]]) =$

  \[
  \text{if} \; \text{cond}_0 \; \text{then} \; \text{effect}_0 \\
  \text{else if} \; \text{cond}_1 \; \text{then} \; \text{effect}_1 \\
  \ldots \\
  \text{else if} \; \text{cond}_n \; \text{then} \; \text{cond}_n
  \]

The else rule guard from the TASM language would get desugared into a simple else rule guard of the ASM language. The time annotations get desugared into an environment variable that affects each machine's execution to simulate "durative" actions. Conceptually, once a rule is triggered, a machine sets a specific variable to the duration of the rule application and will not do anything until the rule duration has elapsed. Once the rule duration has elapsed, the machine will generate the appropriate update set atomically and will be free to execute another rule. Desugaring a time
annotation for a rule introduces a new branch if the “if” conditions to denote the time. The concept of a “fresh” variable is introduced to denote a newly generated variable whose name is not previously used. The desugaring introduces two variables, one to keep the time when the rule application will finish executing and one to denote that the machine is “busy” doing work. These two variables are denoted by \( t_{complete_{fresh}} \) and \( mbusy_{fresh} \). The fresh underscore is used to indicate that the variable name is introduced by the desugaring and enforces that it does not clash with existing names. Both of these variables also desugar into controlled dynamic functions:

- \( \text{Desug}[[t_{complete_{fresh}}]] = \text{controlled } t_{complete} \text{ initially } -1 \)
- \( \text{Desug}[[mbusy_{fresh}}] = \text{controlled } mbusy \text{ initially } False \)
- \( \text{Desug}[[\text{Rule}]] = \text{Desug}[[((t_i \ r_i \ if \ condi \ then \ effect_i))] = \)

\[
\text{if/else if } condi \land mbusy_{fresh} = False \text{ then } \\
mbusy_{fresh} := True, t_{complete_{fresh}} := currentTime + getDuration(t_i) \\
\text{else if } currentTime = t_{complete_{fresh}} \land mbusy_{fresh} = True \text{ then } \\
effect_i, mbusy_{fresh} := False, t_{complete_{fresh}} := -1 \\
\ldots
\]

The function \( \text{getDuration} \) is a macro that is created using the condition and the time annotation of the rule. It returns the duration of the rule. If the time annotation is a single value, it returns that value. Otherwise, if the rule annotation is an interval, it returns a value non-deterministically selected from the interval. Using a macro will enable the desugaring to take into account possible concurrency semantics like WCET and BCET as defined in section 5.3. The introduction of the two auxiliary variables and the time conditions will guarantee that the machine will not produce any update sets and that no other rules will be enabled while the machine is executing a rule. This behavior is exactly the desired behavior to simulate “durative” actions.

Resource annotations get desugared as well, but their usage is a bit different than for the time annotations. Resources are modeled as shared dynamic functions. Their
values are set during at the beginning of a rule execution and at the end of a rule execution. Fresh variables are also introduced, for each machine, to denote resource usage:

- \(\text{Desug}[[\text{Rule}]] = \text{Desug}[[((t_i, r_i^* \text{ if } \text{cond}_i \text{ then } \text{effect}_i))]] =\)

\[
\begin{align*}
\text{if/else if } \text{cond}_i \land \text{mbusy}_{fresh} = \text{False} \text{ then } & \\
\quad \text{mbusy}_{fresh} := \text{True}, & \\
\quad t_{complete}_{fresh} := \text{currentTime} + \text{getDuration}(t_i), & \\
\quad r_{i_{fresh}} := \text{getResourceConsumption}(r_i) & \\
\text{else if } \text{currentTime} = t_{complete}_{fresh} \land \text{mbusy}_{fresh} = \text{True} \text{ then } & \\
\quad \text{effect}_i, & \\
\quad \text{mbusy}_{fresh} := \text{False}, & \\
\quad t_{complete}_{fresh} := -1, & \\
\quad r_{i_{fresh}} := 0 & \\
\end{align*}
\]

Function machines are desugared as macros and sub machines are desugared just like main machines and they are "inlined" inside the rule where they are invoked.

### A.3.10 Execution Semantics

The desugaring of the TASM language into the ASM language is an easy way to express the formal semantics of the TASM language. In the ASM world, every main machine represents an "Agent", member of the shared domain \textbf{AGENT}. The TASM language also introduces concurrency semantics that are slightly different than for the ASM language. In the TASM language, time is used to synchronize the order of execution between different agents. It is the \textit{currentTime} dynamic function that keeps all of the agents executing in a synchronized order. The time annotations create a partial order between the moves of agents. The \textit{currentTime} function increases monotonically, at a rate that is congruent with the smallest step of a given main machine. For example, if the shortest duration of a rule is 3 time units, for all agents
in \textit{AGENT}, then the \textit{currentTime} function will increment each time by 3 time units; this is denoted by this smallest value \textit{dt}, which corresponds to a \textit{static} function.

The one area that remains to be formally specified is the execution semantics of resources. For each resource that is defined in the environment, an agent is created that is used to sum up all of the resources used by existing agents. These new agents are used to ensure that resource usage falls within the specified bounds.

\begin{tabular}{l}
\textbf{Agent} \textit{RESOURCE}_i \\
controlled \textit{last\_fresh} initially 0 \\
controlled \textit{totalresource\_fresh} initially 0 \\
\end{tabular}

\begin{tabular}{l}
\textbf{if} \textit{currentTime} = \textit{last\_fresh} + \textit{dt} \textbf{then} \\
\textit{totalresource\_fresh} := \textit{sum}(r_i) \\
\textbf{else} \\
\textbf{if} \textit{totalresource\_fresh} > \textit{resource\_max} \textbf{then} \\
\textit{RESOURCE\_EXHAUSTED} \\
\end{tabular}

The role of the sum macro is to sum up all of the resource annotations from executing agents. The \textit{RESOURCE\_EXHAUSTED} macro simply halts execution to note that a given resource has been exhausted.
Appendix B

Translating TASM Models to SAT

This appendix describes how the constraints in TASM models are translated to a Boolean formula in propositional logic, also called an instance of the Boolean satisfiability problem, or SAT for short [232]. The purpose of the mapping is to verify certain properties of TASM models using a SAT solver, including completeness and consistency, as explained in Section 5.1. This appendix provides all the details of how different facets of the TASM language map to a Boolean formula.

B.1 Preliminaries

In this appendix, the canonical form of TASM models [110] is used to express the mapping algorithm. As a reminder, a TASM machine is canonical form can be expressed as a set of rules $R_i$, which are composed of rule guards $G_i$ and effect expressions $E_i$. For a TASM machine with $n$ rules, the canonical form is expressed as:

$$
\begin{align*}
R_1 &\equiv if \ G_1 \ then \ E_1 \\
R_2 &\equiv if \ G_2 \ then \ E_2 \\
&\quad \vdots \\
R_n &\equiv if \ G_n \ then \ E_n
\end{align*}
$$
B.2 Translation Algorithm

The goal of the translation algorithm is to map TASM guards to Boolean formulas. A Boolean formula is a set of Boolean variables, denoted $b_j$, connected with the logical connectives ($\wedge$, $\lor$, $\neg$). More information about SAT and Boolean formulas is provided in Section 2.7. The translation from TASM to SAT involves mapping the rule guards, $G_i$, to Boolean propositions, $b_j$, in Conjunctive Normal Form (CNF). The following sections explain how this translation is performed for the various components of the TASM language.

B.2.1 Function Machines

For a rule guard which contains a function machine call, the function machine call is replaced by the function machine definition, much like "inlining" in programming languages [239]. This substitution will create new rules, in accordance to the procedure used in the proof of Theorem 4.1. The original rule with the function machine call will give rise to $n$ new rules, where $n$ is the number of rules of the function machine. The canonical form of a function machine is given below, where the $F$ prefix denotes a function machine:

\[
FR_1 \equiv \text{if } FG_1 \text{ then out.var := out.val}_1;
FR_2 \equiv \text{if } FG_2 \text{ then out.var := out.val}_2;
\vdots
FR_n \equiv \text{if } FG_n \text{ then out.var := out.val}_n;
\]

If the rule where the function machine call is invoked is of the form "if $G_i$ then $E_i$", the following $n$ rules will be generated in the machine where the function machine is invoked:
\[ R_{i1} \equiv \text{if } G_i \land FG_1 \text{ then } E_i \]
\[ R_{i2} \equiv \text{if } G_i \land FG_2 \text{ then } E_i \]
\[ \vdots \]
\[ R_{in} \equiv \text{if } G_i \land FG_n \text{ then } E_i \]

Where, in each \( FG_i \), the values of input variables are replaced by the parameters passed to the function call and, in each original guard \( G_i \), the invocation of the function machine is replaced by the \( out\_val_i \) corresponding to the \( FG_i \) guard. Once this translation has been performed, the translations to \( SAT \) described in the following sections can be applied without special handling for function machine calls.

### B.2.2 Boolean and User-Defined Datatypes

In the TASM language, user-defined datatypes and Boolean datatypes are simple types that can take values for a finite set. Boolean variables can take one of two values (\textit{True} or \textit{False}). User-defined types can take one of multiple values, as defined by the user. In typical specifications, user-defined types rarely exceed five or six members.

The only operations defined for Boolean and user-defined datatypes are the comparison operators, = and \(!=\). No other operator is allowed for Boolean and user-defined datatypes. In the translation to \( SAT \), the equality operator (=) is assumed to mean a non-negated proposition (e.g., \( b_1 \)). The operator \(!=\) is translated to mean a negated proposition (e.g., \( \neg b_1 \)). The translation to \( SAT \) for these datatypes involves 2 steps. The first step is generating the \textit{at least one} clause and the \textit{at most one} clause for each variable of type Boolean or of type user-defined type. The second step involves formulating the property to be verified as a clause in CNF, \( S \), according to the definitions in Section 5.1. The \textit{at least one} clause ensures that the variable must take at least one value from its finite set. This clause is simply the disjunction of
equality propositions for each possible value that the variable can take. The at most one clause is a clause that ensures that each variable can take at most one value from its finite set.

To illustrate the generation of the at least one and at most one clauses, the following type is introduced: \(\text{type1} := \{\text{val}_1, \text{val}_2, \ldots, \text{val}_n\}\). A variable of type Boolean can be viewed as a variable of type \(\text{type1}\) where \(n = 2\). First, the set of propositions is generated. In SAT, a proposition is a single letter with a subscript (e.g., \(b_i\)). For a variable named \(\text{var}\) of type \(\text{type1}\), the following propositions would be generated, where the \(b_i\)'s represent the SAT atomic propositions and the right hand side represents the meaning of the proposition in the TASM context:

\[
\begin{align*}
\text{b}_1 &: \text{var} = \text{val}_1 \\
\text{b}_2 &: \text{var} = \text{val}_2 \\
\vdots \\
\text{b}_n &: \text{var} = \text{val}_n
\end{align*}
\]

The at least one clause, denoted \(C_1\) for this variable would be:

\[
C_1 \equiv \text{b}_1 \lor \text{b}_2 \ldots \lor \text{b}_n
\]

The at least one clause ensures that at least one of the \(b_i\)'s must be true for the clause to be true. The at most one clause ensures that no two \(b_i\)'s can be true at the same time. The at most one clause, denoted \(C_2\) is the conjunction of multiple clauses:
\[ C_2 \equiv (\neg b_1 \lor \neg b_2 \ldots \lor \neg b_n) \land (b_1 \lor \neg b_2 \ldots \lor \neg b_n) \land (\neg b_1 \lor b_2 \ldots \lor \neg b_n) \land \cdots \land (\neg b_1 \lor \neg b_2 \ldots \lor b_n) \]

The at most one clause generates \( n + 1 \) clauses, one for the full negations of the propositions and one for each \( n - 1 \) negations of propositions. This combination ensures that at most one of the clauses can be true. The conjunction \( C_1 \land C_2 \), which is already in conjunctive normal form, serves to enforce the “exactly one value per variable” constraint, also called type enforcement. The rule guards are made up of propositions that already exist in the proposition catalog. For each rule guard in the problem formulation \( S \), for each constraint in the guards, if the constraint is of the form \( \text{var} = \text{val}_i \), its corresponding proposition \( b_i \) is looked up in the catalog and substituted in the problem formulation \( S \). If, on the other hand, the constraint is of the form \( \text{var} \neq \text{val}_i \), the \( b_i \) corresponding to \( \text{var} = \text{val}_i \) is looked up in the proposition table and the constraint in the guard is substituted by its negation, \( \neg b_i \). Once the substitution is done in the rule guards, the formulated problem \( S \) is then converted to Conjunctive Normal Form (CNF) using the well-known algorithm in [232]. The result of this substitution and conversion to CNF yields \( S \) with only atomic Boolean propositions. The full SAT problem can then be formed by the conjunction of \( S \), \( C_1 \), and \( C_2 \):

\[ \text{Full SAT problem } \equiv S \land C_1 \land C_2 \]
B.2.3 Integer Datatypes

Similarly to Boolean datatypes and user-defined datatypes, integer datatypes take values from a finite set. However, the number of values that integers can take is much larger than for Boolean datatypes and much larger than for typical user-defined types. For example, in the TASM language, integers range from -32,768 to 32,767. While the approach suggested above for Boolean and user-defined types might also work for integer types, the enumeration of all 65,536 possible values would be intractable for a single integer variable. The adopted mapping for integer variables relies on the fact that even though integers are used in TASM specifications, they are used in such a way that they could be replaced by user-defined types. In other words, in TASM specifications, the full range of integers is typically not used.

Nevertheless, integer datatypes are more complex than Boolean and user-defined types because more operations are defined for integer datatypes. These operations are comparison operators and arithmetic operators. The comparison operators are \( =, \neq, <, \leq, >, \) and \( \geq \). The arithmetic operators are \( +, -, *, \) and \( / \). For the suggested translation, constraints on integer variables must be of the form \( < \text{var} > < \text{compop} > < \text{expr} > \), where \( < \text{var} > \) is an integer variable \( < \text{compop} > \) is a comparison operator and \( < \text{expr} > \) is an arbitrary arithmetic expression that can contain constants, variable references, function machine calls, and operators. The restriction is that the left hand side of constraints can contain only a variable, with no arithmetic expressions allowed. The translation proposed in this section, deals only with linear constraints whose right hand sides are constants. Arbitrary symbolic right hand sides can be addressed in future research, as explained in section 9.3.

The key idea behind the translation is to convert each integer variable to a user-defined type. This is achieved by collecting all of the constraints on a given integer variable and extracting the intervals that are of interest. These intervals become the members of the user-defined types. Once the integer type has been converted to a user-defined type in this fashion, it can then be converted to a Boolean formula using the approach from Section B.2.2. The algorithm to reduce integer variable to
user-defined types consists of 4 steps. For each monitored variable of type integer:

1. Collect all constraints on the variable from \( S \)

2. Sort all constraints in ascending order of right-hand sides

3. Create unique intervals for constraints that overlap

4. In \( S \), replace original constraints by disjunction of constraints for modified constraints in overlapping intervals

The translation can be illustrated using an example. Steps 1 and 2 of the algorithm are self-explanatory. Steps 3 and 4 are illustrated using an example which contains the following set of constraints:

\[
\begin{align*}
a & \geq 2 \\
a & < 3 \\
a & \neq 5 \\
a & > 5 \\
a & = 9
\end{align*}
\]

The non-overlapping intervals for this set of constraints become the possible values for the integer variable. These intervals are shown below, with the associated Boolean propositions in the \( SAT \) problem.
Once an integer variable has been reduced to a user-defined type, the original
clauses can be replaced by the Boolean propositions or disjunction of Boolean propo-
sitions, depending on the nature of the original constraint.

\[
\begin{align*}
  a & \leq 1 : b_1 \\
  a & = 2 : b_2 \\
  3 & \leq a \leq 4 : b_3 \\
  a & = 5 : b_4 \\
  6 & \leq a \leq 8 : b_5 \\
  a & = 9 : b_6 \\
  a & \geq 10 : b_7
\end{align*}
\]

\[
\begin{align*}
  a & \geq 2 : (b_2 \lor b_3 \lor b_4 \lor b_5 \lor b_6 \lor b_7) \\
  a & < 3 : (b_1 \lor b_2) \\
  a & \neq 5 : (\neg b_4) \\
  a & > 5 : (b_5 \lor b_6 \lor b_7) \\
  a & = 9 : (b_6)
\end{align*}
\]

Once the integer variables have been reduced to user-defined types and the con-
straints in the problem formulation $S$ have been replaced with the appropriate combi-
nation of propositions, the full SAT instance can be created using the at most one and
the at least one clauses, in the same fashion as explained in Section B.2.2. For a spec-
fications where there is significant use of integer constraints, the use of Mixed Integer
Programming (MIP) solvers could be better suited for completeness and consistency
analysis. This option is investigated in [206] and is addressed in Section 9.3.
B.2.4 Constraints with Symbolic Right-Hand Sides

The translation strategy for integer variables relies on the ability to reduce integer variables to user-defined types. This strategy is straightforward for constraints of the type $<\textit{var}><\textit{comp}\_\textit{op}><\textit{constant}>$ because intervals of interest can be easily identified, as explained in Section B.2.3. However, if the right-hand side of constraints contains arbitrary arithmetic expressions containing a mix of variable references, function machine calls, operations, and constants, the reduction to a user-defined type is not trivial. This case is currently handled by reducing symbolic right-hand sides to a constant by using initial conditions combined with a configuration. In the TASM language, a configuration is a set of initial conditions which “overrides” the initial values defined in the environment. This restriction might seem potentially restrictive, but it is probable that there are more restrictions on the variables than the specification expresses. Furthermore, the reduction of symbolic right-hand sides performs constant propagation where applicable and assigns values to free variables. The ability to handle symbolic right-hand sides is considered as part of future work in Section 9.3.

B.2.5 Complete Translation Algorithm

The basic translation principles have been explained in the previous sections. The complete translation algorithm can now be given, for a single machine:

1. Create problem instance $S$ depending on the property to be checked (e.g., consistency or completeness), as explained in Section 5.1

2. Replace function machine calls with extra rules, as explained in Section B.2.1

3. Replace symbolic right-hand sides with values from the chosen configuration

4. Reduce integer variables to user-defined type variables, as explained in Section B.2.3
5. Iterate through all monitored variables and create at least one clauses and at most one clauses, as explained in section B.2.2

6. Convert problem formulation $S$ to conjunctive normal form and create the full $SAT$ instance, as explained in Section B.2.2

B.3 Analysis

In this section, the limitations of the translation algorithm, as well as the complexity of the translation algorithm are analyzed. While $SAT$ solvers have been heavily optimized and have been able to address problems of industrial size [175], it is important to understand the scalability of the translation algorithm. The scalability of the translation is crucial to ensure that relevant case studies can be analyzed using the translation to $SAT$. The preliminary results from the translation algorithm indicate that the performance of the translation algorithm might overshadow the performance of the $SAT$ solver.

B.3.1 Limitations

The translation of TASM constraints to $SAT$ rely on the TASM model being finite or on creating a finite version of the model. When a TASM model contains symbolic right-hand sides, the translation algorithm removes the symbolic values using a selected configuration. Clearly, this feature yields an underapproximation of the model, analogous to the approach explained in [110]. For many cases, as the cases studied in Chapter 8, this approximation is adequate.

If a TASM model contains variables of type float, the translation algorithm is not applied in the TASM toolset and the user is notified that the TASM specification does not meet the requirements to be analyzed using $SAT$. The reason for this limitation is that float variables are, by definition, infinite. Using other types of solvers such as an LP solver [96] or an SMT solver [97] could address these limitations. However, these types of solvers yield other limitations, as explained in Section 9.3.
B.3.2 Complexity Analysis

While the translation algorithm is fairly straightforward, there are a lot of parameters that will affect the space complexity of the translation. The evident parameters being the number of rules ($r$), the number of monitored variables ($v$), the number of function machine calls ($fc$) (with its internal properties like the number of rules inside the function machine), the number of constraints in the guards ($c$), and the number of members in user defined types ($u$). For the translation to SAT, the space complexity is characterized by the number of atomic propositions ($pr$) and the number of clauses ($cl$) which are generated by the translation. The same definitions are used from Section 2.7.2 - a proposition is an atomic Boolean variable. A clause is one disjunction block in CNF form.

Space Complexity

For the case of completeness, the number of rules, $r$, for a given machine is not the dominant factor. The number of rules will increase the number of clauses linearly ($O(r)$). For the case of consistency, since all pairs of rules are considered, the increase in the number of clauses will be quadratic ($O(r^2)$).

For function machine calls, the growth in complexity will be the generation of extra rules in the procedure to eliminate the function machine call. Every function machine call will give rise to a cross-product in the composition of rules, giving rise to exponential growth in the number of rules for each function machine call ($O(r^{(fc+1)})$). The resultant effect on the number of clauses can be inferred by the previous discussion about the clause growth in terms of number of rules for completeness and consistency.

The effect of the number of variables depends heavily on the type of the variables. For Boolean and user-defined types, the number of variables greatly affects the generation of propositions for the at least one and at most one clauses. Each variable gives rise to linear growth in the number of clauses for the type enforcement clauses ($O(v)$). Each type enforcement clause will contain a proposition for every user-defined type member, $u$, giving rise to multiplicative growth for the total number of propositions.
For integer datatypes, the nature of the constraints on the integer variables determines the growth of the reduction to a user-defined type. The number of constraints will give rise to linear growth in the number of new propositions, that is, the number of members of the user-defined type. The dominant growth in the number of total number of propositions comes from the type enforcement clauses and from the replacement of constraints by the user-defined type propositions. The worst-case scenario occurs when a constraint is replaced by approximately the entire disjunction of user-defined type propositions, as is the case for $a \geq 2$ in Section B.2.3. However, this case will occur only if there are numerous constraints and this case will be balanced out by other constraints not needing extra propositions. This is clearly illustrated in Section B.2.3 for the example given. In summary, for integer datatypes, the number of new propositions will vary linearly with the number of constraints ($O(c)$). Extra clauses will vary in the same fashion as for Boolean and user-defined types.

B.3.3 Intractability

It is well-known that the satisfiability problem is NP-Complete [232]. By formulating the completeness and consistency problem as a satisfiability problem, the performance of the verification procedure grows exponentially in the worst-case. For the case where there exists a counterexample, that is, a specification is not complete or not consistent, the average case performance can be acceptable. However, establishing completeness and consistency where there is no counterexample involves establishing that the formula is unsatisfiable. The performance of establishing this property will be highly dependent of the actual problem definition and cannot be analyzed a priori, but will require searching the complete state space.

Given the exponential growth that can result from specific problems, the translation to SAT is inadequate for large sets of rules, large sets of variables and complex rule guards. However, because the relationships between the guards are analyzed for a given machine, the number of rules is expected to be manageable from the specifier’s perspective, on the order of less than 10 rules. Furthermore, the complexity of the
guards should also be tractable from the specifier's standpoint, so it is realistic to ex-
pect moderate complexity of the individual guards. The number of function machine
calls could greatly affect the feasibility of the analysis since hierarchical structuring
of specifications is a natural mechanism in the TASM language.
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Appendix C

Translating TASM Models to UPPAAL's Timed Automata

This appendix describes how TASM models are translated to UPPAAL's timed automata. The purpose of the mapping is to verify certain properties of TASM models using the UPPAAL tool suite, such as execution time analysis, as explained in Section 5.3. Furthermore, timed automata models can be analyzed for functional correctness using temporal logic formulas [212] and model checking principles [67] using UPPAAL's tool suite [157], as explained in Section 5.2. The version of UPPAAL used in this thesis is version 4.0.6, released on March 5th, 2007, and available on the UPPAAL web site (http://www.uppaal.com). This appendix provides all the details of how different facets of the TASM language are mapped to the timed automata formalism of UPPAAL.

C.1 Preliminaries

The timed automaton formalism, also called Alur-Dill automata [5], extends finite state automata with a set of real-valued clocks to denote the passage of time. In a timed automaton, all transitions are instantaneous, but time elapses between transitions. Transition guards can contain predicates over clocks to enforce time passage before a transition is taken. State invariants can be used to enforce an upper bound
on the time passage in a state. The timed automata used in UPPAAL extend Alur-Dill automata with Integer variables, Boolean variables, committed and urgent locations, and communication channels [24]. In UPPAAL’s timed automata, locations correspond to the states of Alur-Dill automata. The states of UPPAAL’s automata are a combination of variable values, clock values, and automata locations. Urgent locations are used to denote that time should not elapse in a location. Committed locations are used to denote an atomic chain of urgent locations. In this thesis, Section 5.3.3 gives detailed description of the timed automaton formalism. For a more extensive description of the timed automaton formalism, the reader is referred to [5, 7]. For a detailed description of UPPAAL and its associated tool suite, the reader is referred to [24, 157, 211].

In the TASM language, described in Chapter 4, the general form of a timed abstract state machine is a set of rules where each rule, $R_i$, is of the form:

$$R_i \equiv (T_i, R_{R_i}, G_i, E_i)$$

Where:

- $T_i$ is the duration of the rule, which is a closed interval $[a, b]$ where $a \geq 0$, $b \geq 0$, and $a \leq b$

- $R_{R_i}$ is a set of resources consumed by the rule execution

- $G_i$ is the rule guard, which is a Boolean predicate

- $E_i$ is the rule effect, which is a series of updates to environment variables

This parameterized version of TASM rules is used to describe the translation to UPPAAL’s timed automata.
C.2 Translation Algorithm

The translation algorithm performs the translation of the environment by translating each datatype and variable in the TASM model to an equivalent datatype and variable in UPPAAL’s language, as explained in Section C.2.1. The algorithm then translates each main machine in the model to a timed automaton of UPPAAL, as explained in Section C.2.2. Before the translation of each main machine is performed, the translation algorithm uses the results of Theorem 4.1 and of Theorem 4.2 and removes the hierarchical composition from each main machine. The complete translation algorithm is provided in Section C.2.3 and a sample translation is given in Section C.3.

C.2.1 Variables and Datatypes

The TASM language contains more datatypes than the timed automata language of UPPAAL. For variable datatypes, UPPAAL contains only a bounded integer datatype, a channel datatype, and a clock datatype. Of these datatypes, only the bounded integer datatype can be used to express TASM types and variables. Nevertheless, the bounded integer datatype is generic enough to be able to express the Boolean datatype, the integer datatype, and the user-defined datatype of the TASM language. The integer datatype of the TASM language is mapped directly to the bounded integer datatype of UPPAAL. The Boolean datatype of TASM is mapped to a bounded integer with range “[0, 1]”, where “0” means “False” and “1” means “True”. The user-defined datatype of the TASM language maps to an appropriately bounded integer type. For a user-defined type that contains $m$ members, the type is translated to an integer datatype with range “[1, m]”, where “1” corresponds to the first member of the type and “$m$” corresponds to the $m^{th}$ member of the type. If a TASM model contains variables of type float, the translation to UPPAAL’s timed automata cannot be performed, and the user is notified that the given model cannot be analyzed using UPPAAL. In its current version, UPPAAL does not support datatypes from the Real domain. The summary of the datatype translations is given in Table C.2.1.
<table>
<thead>
<tr>
<th>TASM Type</th>
<th>UPPAAL Type</th>
<th>TASM Example</th>
<th>UPPAAL Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integer[a, b]</td>
<td>int[a, b]</td>
<td>Integer[-5, 5] p;</td>
<td>int[-5, 5] p;</td>
</tr>
<tr>
<td>Boolean</td>
<td>int[0, 1]</td>
<td>Boolean b;</td>
<td>int[0, 1] b;</td>
</tr>
<tr>
<td>Switch := {ON, OFF}</td>
<td>int[1, 2]</td>
<td>Switch s;</td>
<td>int[1, 2] s;</td>
</tr>
</tbody>
</table>

Table C.1: Datatype translations

C.2.2 Machines and Rules

The translation to UPPAAL’s timed automata is achieved by mapping each main machine of a TASM specification to a timed automaton. In the TASM language, a main machine is a unit of concurrency. TASM models and UPPAAL models differ in the paradigm used to model time. In UPPAAL’s timed automata, time is naturally used to express time passage between transitions. In the TASM language, time is used to denote the duration of actions, equivalent to the duration of a transition. This difference in paradigm is important conceptually, but from an expressiveness perspective, it is irrelevant since both paradigms are equally expressive [30]. For example, durative transitions can be expressed in timed automata using an extra intermediate location which is used solely to elapse time. In the intermediate location, the automaton waits for time to elapse until it can resume making transitions.

To express the paradigm of durative transitions from TASM models, for each generated timed automaton during the translation, a clock $c$ is created as a local variable for the automaton. The clock is used to enforce the durative actions of the TASM language. The semantics of durative transitions are such that a rule execution lasts a finite amount of time before the effect of the rule execution is reflected in the environment. For the rule of Equation 2, the corresponding timed automaton is depicted in Figure C-1. The set of consumed resources is omitted from the UPPAAL model, because the resource model used in the TASM language does not affect timing behavior and the semantics of transitions. The behavior to be studied using the UPPAAL tool suite, namely timing behavior and functional properties, does not require the inclusion of resource consumption in the timed automata model.

In Figure C-1, the location pivot is the initial location and depicts that the corresponding machine is idle, that is, waiting to execute a rule. In UPPAAL, the pivot
location is marked as an *urgent* location, meaning that no time can elapse in this location [157]. Each TASM machine rule $R_i$ will be attached as a transition from the *pivot* location. Because the initial location is urgent, an attached transition will be taken as soon as it is enabled. A transition will be enabled when the rule guard $G_i$ of a rule $R_i$ evaluates to *true*. When this happens, the automaton will transition to a new location called $R_i$. The name of the location is used to identify the executing rule in order to map the automaton’s transitions back to the rule execution of the TASM model. During the transition, the clock $c$ is reset. The location $R_i$ is used to model the durative transitions of the TASM language. The automaton will stay in this location between $a$ and $b$ time units, by using the $c <= b$ location invariant and the $c >= a$ transition guard. Once the duration of the rule has elapsed, the automaton will transition to location *pivot* and the effect of the rule, $E_i$, will be applied to the environment.

To illustrate the translation of a timed rule, an example is provided. Listing C.1 gives a sample TASM rule. The rule has an execution time ranging between 1 time unit and 4 time units. The corresponding timed automaton is shown in Figure C-2 and contains two locations, one for the *pivot* location, and one for the rule execution.

In the TASM language, a machine can contain a special "*Else rule*" rule, which is a rule that is enabled if no other rule is enabled. The TASM language also contains a special time construct, the "$t := \text{next}$" construct. The special combination of both constructs is used to denote that a machine will wait for time to progress until one of its rules becomes enabled. For a machine with $n$ rules, the translation for the
**Listing C.1 Sample TASM rule**

R1: Sample Rule
{
    t := [1, 4];

    if x = y and y = z then
        x := 3;
        y := 5;
}

Figure C-2: Timed automaton for Listing C.1
"Else rule\(^{\text{\textquotedbl}}\) with the \(t := \text{next}\) annotation is depicted in Figure C-3. The channel \(m_{\text{else}}?\) is an urgent channel and is used to enforce that the corresponding edge is \texttt{urgent} \cite{24}. The urgent edge pattern is used to force the automaton to transition out of location \(\texttt{else}\) as soon as one of its rules becomes enabled. When no rule is enabled, the automaton will stay in location \(\texttt{else}\) and time will elapse until a rule becomes enabled. When an TASM machine contains the \(t := \text{next}\) annotation, another automaton is added to the translation. This automaton contains only one transition and emits a synchronization call along the urgent channel, \(m_{\text{else}}!\). This extra automaton is part of the urgent edge pattern \cite{24}.

![Diagram](image.png)

Figure C-3: Timed automaton for the \("\text{Else rule}\)\(^{\text{\textquotedbl}}\) and the \(t := \text{next}\) annotation

The \(t := \text{next}\) annotation and the \("\text{Else rule}\)\(^{\text{\textquotedbl}}\) can be used separately from each other. For the rule depicted in Figure C-3, if the \("\text{Else rule}\)\(^{\text{\textquotedbl}}\) did not contain the \(t := \text{next}\) annotation, the urgent channel would be replaced by a clock \(c\), a location invariant, and a clock guard along the edge out of the \(\texttt{else}\) location, in a fashion identical to the transition depicted in Figure C-1. If, on the other hand, a rule other than the \("\text{Else rule}\)\(^{\text{\textquotedbl}}\) contains the \(t := \text{next}\) annotation, the translation depicted in Figure C-1 would not have a clock \(c\), a location invariant, and an clock predicate in the edge guard. Instead, the transition would contain an urgent channel in the edge guard and the disjunction of all the other guards except for the guard of the rule being executed, similarly to the edge guard out of the \(\texttt{else}\) transition depicted in Figure C-3.

The translations expressed in Figure C-1 and in Figure C-3 can be generalized to a machine with \(n\) rules and an \("\text{Else rule}\)\(^{\text{\textquotedbl}}\). The \(i\) subscripts for the clock conditions (e.g., \(a_1, b_1\)) denote the durations of the time annotation for the \(i^{\text{th}}\) rule (e.g., \(R_i\)).
For such a machine, the resulting timed automaton would contain $n + 1$ branches, as shown in Figure C-4. In Figure C-4, the “Else rule” of the automaton contains the “t := next” time annotation.

![Timed automaton for a TASM machine with n rules](image)

Figure C-4: Timed automaton for a TASM machine with $n$ rules

### C.2.3 Complete Translation Algorithm

Given the principles explained in previous sections, the complete translation algorithm can be summarized as follows, for a given TASM model:

1. For each main machine in the TASM model, remove hierarchical composition according to the rules of Theorem 4.1 and of Theorem 4.2

2. Translate the environment:
   
   (a) Discard resource definitions
   
   (b) Translate each user-defined type to a corresponding bounded integer type of UPPAAL, as explained in Table C.2,1

430
(c) Translate each variable and corresponding datatype to the bounded integer type of UPPAAL, as explained in Table C.2.1

3. For each "flattened" main machine

(a) Create a timed automaton to represent the machine
(b) Create an initial urgent location called "pivot"
(c) For each rule $R_i$ of the machine, add a branch from the "pivot" state according to the approach explained in Section C.2.2
(d) If the machine contains an "else" rule, add an extra branch according to the approach depicted in Section C.2.2
(e) For rule that contains the "$t := \text{next}$" annotation, build an urgent edge using an extra automaton and an urgent channel

C.3 Example

The light switch example from Chapter 4 is used to illustrate the translation from TASM to UPPAAL's timed automata. In this example, version 4 of the light switch example is used, as depicted in Listing 4.6, in Listing 4.7, and in Listing 4.8. The example does not utilize hierarchical composition so the main machines can be translated directly. The first step of the translation algorithm concerns the translation of the environment. The environment, shown in Listing 4.6, contains two datatypes and four variables. The translation to UPPAAL's variables is straightforward and is shown below:

```c
int[0, 1] light = 1;
int[0, 1] light_switch = 1;
int[0, 1] fan = 1;
int[0, 1] fan_switch = 1;
```

In the translation of the `component_status` datatype, the value ON is mapped to the integer "0" and the value OFF is mapped to the integer "1". A similar translation
is performed for the `switch_status` datatype. The main machine `LIGHT_CONTROL` contains 3 rules and the corresponding timed automaton, shown in Figure C-5, contains 3 branches. Since the machine contains an “Else rule” with a “t := next” time annotation, the translation also creates an urgent edge, using an urgent channel and an extra timed automaton, shown in Figure C-6. A similar translation is performed for the `FAN_CONTROL` main machine, and the resulting automata are shown in Figure C-7 and in Figure C-8.

![Timed automaton for the LIGHT_CONTROL machine](image)

**Figure C-5**: Timed automaton for the `LIGHTCONTROL` machine

![Timed automaton to enforce the urgent channel for the else rule of machine `LIGHTCONTROL`](image)

**Figure C-6**: Timed automaton to enforce the urgent channel for the else rule of machine `LIGHTCONTROL`

The complete “Declarations” section of the resulting UPPAAL model is shown in Listing C.2. The complete “Systems declarations” section of the UPPAAL model is shown in Listing C.3. The local “Declarations” sections of the timed automata corre-
Figure C-7: Timed automaton for the FAN_CONTROL machine

Figure C-8: Timed automaton to enforce the urgent channel for the else rule of machine FAN_CONTROL
sponding to each main machine contain only the declaration of the local clock, "clock c;", used to enforce the duration of the transitions. The "Declarations" sections of the channel automata do not contain any statements.

**Listing C.2** Declarations section of the UPPAAL model

```plaintext
int[0, 1] light = 1;
int[0, 1] light_switch = 1;
int[0, 1] fan = 1;
int[0, 1] fan_switch = 1;

urgent chan LIGHT_CONTROL_else;
urgent chan FAN_CONTROL_else;
```

**Listing C.3** Systems declarations section of the UPPAAL model

```plaintext
light_c       = LIGHT_CONTROL();
light_c_chan  = LIGHT_CONTROL_chan();
fan_c         = FAN_CONTROL();
fan_c_chan    = FAN_CONTROL_chan();

system light_c, light_c_chan, fan_c, fan_c_chan;
```
Appendix D

Production Cell TASM Model

This appendix gives all of the listings for the production cell TASM model. The index of the listings is given in Table D.1. The production cell case study is described in details in [163]. In the context of the TASM language, the case study is described in Section 2.8.1. The TASM model is explained and is analyzed in details in Section 8.1. As a reminder, the logical view of the production cell model is provided in Figure D-1. The complete TASM model contains 8 main machines, one for each component in Figure D-1 and one for the controller. The model also contains 3 function machines, and 16 sub machines.

Figure D-1: Top view of the production cell
<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Purpose</th>
<th>Listing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types</td>
<td>N/A</td>
<td>List of types</td>
<td>Listing D.1</td>
</tr>
<tr>
<td>Variables</td>
<td>N/A</td>
<td>List of variables</td>
<td>Listing D.2, D.3</td>
</tr>
<tr>
<td>Loader</td>
<td>Main</td>
<td>Loads blocks onto the feed belt</td>
<td>Listing D.4</td>
</tr>
<tr>
<td>Feed</td>
<td>Main</td>
<td>Carries blocks from the loader to the robot</td>
<td>Listing D.5</td>
</tr>
<tr>
<td>Deposit</td>
<td>Main</td>
<td>Carries blocks out of the system</td>
<td>Listing D.6</td>
</tr>
<tr>
<td>Press</td>
<td>Main</td>
<td>Stamps blocks</td>
<td>Listing D.7</td>
</tr>
<tr>
<td>Robot</td>
<td>Main</td>
<td>Simulates the rotation of the robot</td>
<td>Listing D.8</td>
</tr>
<tr>
<td>ArmA</td>
<td>Main</td>
<td>Simulates arm a</td>
<td>Listing D.9</td>
</tr>
<tr>
<td>ArmB</td>
<td>Main</td>
<td>Simulates arm b</td>
<td>Listing D.10</td>
</tr>
<tr>
<td>Controller</td>
<td>Main</td>
<td>Commands the actuators</td>
<td>Listing D.11</td>
</tr>
<tr>
<td>armPosition</td>
<td>Function</td>
<td>Returns the position of an arm</td>
<td>Listing D.12</td>
</tr>
<tr>
<td>rotateClockwise</td>
<td>Function</td>
<td>Changes the robot angle by +30°</td>
<td>Listing D.13</td>
</tr>
<tr>
<td>rotateCounterClockwise</td>
<td>Function</td>
<td>Changes the robot angle by -30°</td>
<td>Listing D.14</td>
</tr>
<tr>
<td>OPERATE.FEED</td>
<td>Sub</td>
<td>Operates the feed belt</td>
<td>Listing D.15</td>
</tr>
<tr>
<td>OPERATE.DEPOSIT</td>
<td>Sub</td>
<td>Operates the deposit belt</td>
<td>Listing D.16</td>
</tr>
<tr>
<td>OPERATE.ROBOT</td>
<td>Sub</td>
<td>Rotates the robot</td>
<td>Listing D.17</td>
</tr>
<tr>
<td>OPERATE_ARM.A</td>
<td>Sub</td>
<td>Operates arm a</td>
<td>Listing D.18</td>
</tr>
<tr>
<td>OPERATE_ARM.B</td>
<td>Sub</td>
<td>Operates arm b</td>
<td>Listing D.19</td>
</tr>
<tr>
<td>OPERATE_PRESS</td>
<td>Sub</td>
<td>Operates the press</td>
<td>Listing D.20</td>
</tr>
<tr>
<td>PICK_UP_ARM.A</td>
<td>Sub</td>
<td>Picks up a block with arm a</td>
<td>Listing D.21</td>
</tr>
<tr>
<td>PICK_UP_ARM.B</td>
<td>Sub</td>
<td>Picks up a block with arm b</td>
<td>Listing D.22</td>
</tr>
<tr>
<td>DROP_ARM.A</td>
<td>Sub</td>
<td>Drop a block from arm a</td>
<td>Listing D.23</td>
</tr>
<tr>
<td>DROP_ARM.B</td>
<td>Sub</td>
<td>Drop a block from arm b</td>
<td>Listing D.24</td>
</tr>
<tr>
<td>ARM.A.FEED</td>
<td>Sub</td>
<td>Operates arm a at the feed</td>
<td>Listing D.25</td>
</tr>
<tr>
<td>ARM.A.PRESS</td>
<td>Sub</td>
<td>Operates arm a at the press</td>
<td>Listing D.26</td>
</tr>
<tr>
<td>ARM.B.DEPOSIT</td>
<td>Sub</td>
<td>Operates arm b at the deposit</td>
<td>Listing D.27</td>
</tr>
<tr>
<td>ARM.B.PRESS</td>
<td>Sub</td>
<td>Operates arm b at the press</td>
<td>Listing D.28</td>
</tr>
<tr>
<td>ROBOT_MOTION</td>
<td>Sub</td>
<td>Simulates the robot rotation</td>
<td>Listing D.29</td>
</tr>
<tr>
<td>ROTATE_ROBOT</td>
<td>Sub</td>
<td>Operates the rotation of the robot</td>
<td>Listing D.30, D.31</td>
</tr>
</tbody>
</table>

Table D.1: List of machines used in the production cell model
D.1 Environment

Listing D.1 User-defined types of the model

<table>
<thead>
<tr>
<th>Type</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>status</td>
<td>{empty, loaded}</td>
</tr>
<tr>
<td>armposition</td>
<td>{atfeed, atpress, atdeposit, intransit}</td>
</tr>
<tr>
<td>armextension</td>
<td>{retracted, extended}</td>
</tr>
<tr>
<td>Actuator</td>
<td>{on, off}</td>
</tr>
<tr>
<td>Polarity</td>
<td>{positive, negative}</td>
</tr>
<tr>
<td>Stamp</td>
<td>{notfinished, finished}</td>
</tr>
<tr>
<td>Error</td>
<td>{none, invaliddrop, invalidpickup}</td>
</tr>
</tbody>
</table>

Listing D.2 Variables of the model (part 1)

//sensors
Integer[0, 90] robot_angle := 0;
Stamp press_block := notfinished;
Boolean feed_begin := False;
armextension armaext := retracted;
armextension armbext := retracted;
Boolean feed_end := False;
Boolean deposit_begin := False;
Boolean deposit_end := False;

//redundant info, derivable from sensors
armposition armapos := atfeed;
armposition armbpos := atpress;
status arma := empty;
status armb := empty;
status feed_belt := empty;
status deposit_belt := empty;
status press := empty;

//other variables
Boolean wait := False;
Boolean robot_wait := False;
Integer[0, 50] loaded_blocks := 0;
Integer[0, 50] processed_blocks := 0;
Boolean loader_done := False;
Error error := none;
armposition robot_destination := atfeed;
### Listing D.3 Variables of the model (part 2)

```plaintext
//actuators
Actuator motor_press := off;
Actuator motor arma := off;
Actuator motor armb := off;
Actuator magnet arma := off;
Actuator magnet armb := off;
Actuator motor robot := off;
Actuator motor feed := off;
Actuator motor deposit := off;

Polarity motor_press_p := positive;
Polarity motor_arma_p := positive;
Polarity motor_armb_p := positive;
Polarity motor_robot_p := positive;
Polarity motor_feed_p := positive;
Polarity motor_deposit_p := negative;

//constants
Const Integer ROTATION_ANGLE := 30;
Const Integer ARM_B_FEED_ANGLE := 270;
Const Integer ARM_B_DEPOSIT_ANGLE := 90;
Const Integer ARM_B_PRESS_ANGLE := 0;
Const Integer ARM_A_FEED_ANGLE := 0;
Const Integer ARM_A_PRESS_ANGLE := 90;
Const Integer ARM_A_DEPOSIT_ANGLE := 180;
Const Integer ARM_B_DEPOSIT_ANGLE := 90;
```
D.2 Main Machines

Listing D.4 Rules of the Loader main machine

R1: The feed belt is empty, put a block on it {
    t := 2;
    power := 200;
    if loaded_blocks < number - 1 and feed_belt = empty then
        feed_belt := loaded;
        loaded_blocks := loaded_blocks + 1;
        feed_begin := True;
    }

R2: This is the last block... {
    t := 2;
    power := 200;
    if loaded_blocks = number - 1 and feed_belt = empty then
        feed_belt := loaded;
        loaded_blocks := loaded_blocks + 1;
        feed_begin := True;
        loader_done := True;
    }

R3: The feed belt is loaded, do nothing {
    t := next;
    if feed_belt = loaded and loaded_blocks < number then
        skip;
    }

Listing D.5 Rules of the Feed main machine

R1: Block goes to end of belt {
    t := 5;
    power := 500;
    if feed_belt = loaded and feed_begin = True and
        motor_feed = on and motor_feed_p = positive then
        feed_begin := False;
        feed_end := True;
    }

R2: Else {
    t := next;
    else then
        skip;
    }
Listing D.6 Rules of the Deposit main machine

R1: Block goes to end of belt {
    t := 7;
    power := 500;
    if deposit_belt = loaded and deposit_begin = True and
        motor_deposit = on and motor_deposit.p = negative then
        deposit_begin := False;
        deposit_end := True;
}

R2: Magically take the block out of the system {
    if deposit_end = True then
        deposit_end := False;
        deposit_belt := empty;
        processed_blocks := processed_blocks + 1;
}

R3: Else {
    t := next;
    else then
        skip;
}

Listing D.7 Rules of the Press main machine

R1: Press is loaded, motor is on {
    t := 11;
    power := 1500;
    if motor_press = on and press = loaded and press_block = notfinished then
        press_block := finished;
}

R2: Else {
    t := next;
    else then
        skip;
}
Listing D.8 Rules of the Robot main machine

R1: do {
    if robot_wait = False then
        ROBOT_MOTION();
        robot_wait := True;
}

R2: wait {
    t := next;
    if robot_wait = True then
        robot_wait := False;
}

Listing D.9 Rules of the ArmA main machine

R1: Extend arm {
    t := 3;
    power := 1200;
    if motor_arma = on and motor_arma_p = positive and armaext = retracted then
        armaext := extended;
}

R2: Retract arm {
    t := 2;
    power := 1100;
    if motor_arma = on and motor_arma_p = negative and armaext = extended then
        armaext := retracted;
}

R3: Pick up block {
    if magnet_arma = on and arma = empty then
        PICKUP_ARM_A();
}

R4: Drop block {
    if magnet_arma = off and arma = loaded then
        DROP_ARM_A();
}

R5: Else {
    t := next;
    else then
        skip;
}
Listing D.10 Rules of the ArmB main machine

R1: Extend arm {
    t := 3;
    power := 1200;
    if motor_armb = on and motor_armb_p = positive and armbext = retracted then
        armbext := extended;
}

R2: Retract arm {
    t := 2;
    power := 1100;
    if motor_armb = on and motor_armb_p = negative and armbext = extended then
        armbext := retracted;
}

R3: Pick up block {
    if magnet_armb = on and armb = empty then
        PICK_UP_ARM_B();
}

R4: Drop block {
    if magnet_armb = off and armb = loaded then
        DROP_ARM_B();
}

R5: Else {
    t := next;
    else then
        skip;
}
Listing D.11 Rules of the Controller main machine

R1: Issue Commands {
    if wait = False then
        OPERATE_FEED();
        OPERATE_DEPOSIT();
        OPERATE_ROBOT();
        OPERATE_ARM_A();
        OPERATE_ARM_B();
        OPERATE_PRESS();
        wait := True;
    }
}

R2: Wait for a step {
    t := next;
    else then
        wait := False;
    }
}
D.3 Function Machines

Listing D.12 Rules of the armPosition function machine

R1: CCW rotation will put arm at feed {
    if value = feed_angle then
        out := atfeed;
}

R2: CCW rotation will put arm at deposit {
    if value = deposit_angle then
        out := atdeposit;
}

R3: CCW rotation will put arm at press {
    if value = press_angle then
        out := atpress;
}

R4: Else, CCW rotation will put arm in transit {
    else then
        out := intransit;
}

Listing D.13 Rules of the rotateClockwise function machine

R1: Don’t go under 0... {
    if robot_angle = 0 then
        out := 360 - ROTATION_ANGLE;
}

R2: Else {
    else then
        out := robot_angle - ROTATION_ANGLE;
}

Listing D.14 Rules of the rotateCounterClockwise function machine

R1: Don’t go over 360... {
    if robot_angle = 360 then
        out := ROTATION_ANGLE;
}

R2: Else {
    else then
        out := robot_angle + ROTATION_ANGLE;
}
D.4 Sub Machines

Listing D.15 Rules of the OPERATE_FEED sub machine

R1: turn on motor {
    if motor_feed = off and feed_begin = True then
        motor_feed_p := positive;
        motor_feed := on;
}

R2: turn off motor {
    if motor_feed = on and feed_end = True then
        motor_feed := off;
}

R3: nothing to do {
    else then
        skip;
}

Listing D.16 Rules of the OPERATE_DEPOSIT sub machine

R1: turn on motor {
    if motor_deposit = off and deposit_begin = True then
        motor_deposit_p := negative;
        motor_deposit := on;
}

R2: turn off motor {
    if motor_deposit = on and deposit_end = True then
        motor_deposit := off;
}

R3: nothing to do {
    else then
        skip;
}
Listing D.17 Rules of the OPERATE_ROBOT sub machine

R1: {
    if armaext = retracted and armbext = retracted then
        ROTATE_ROBOT();
}

R2: Else {
    else then
        skip;
}

Listing D.18 Rules of the OPERATE_ARM_A sub machine

R1: At feed {
    if armapos = atfeed and motor_robot = off then
        ARM_A_FEED();
}

R2: At press {
    if armapos = atpress and motor_robot = off then
        ARM_APRESS();
}

R3: Else {
    else then
        skip;
}

Listing D.19 Rules of the OPERATE_ARM_B sub machine

R1: At press {
    if armbpos = atpress and motor_robot = off then
        ARM_BPRESS();
}

R2: At deposit {
    if armbpos = atdeposit and motor_robot = off then
        ARM_BDEPOSIT();
}

R3: Else {
    else then
        skip;
}
Listing D.20 Rules of the OPERATEPRESS sub machine

R1: Turn on press {
  if motor_press = off and press = loaded and press_block = notfinished then
    motor_press := on;
}

R2: Turn off press {
  if motor_press = on and press = loaded and press_block = finished then
    motor_press := off;
}

R3: Else {
  else then
    skip;
}

Listing D.21 Rules of the PICK_UP_ARM_A sub machine

R1: Pick up at Feed {
  t  := 3;
  power := 1000;

  if armapos = atfeed and armaext = extended and
    arma = empty and feed_end = True then
    feed_end . := False;
    feed_belt := empty;
    arma := loaded;
}

R2: Invalid pick up {

  if armapos != atfeed or arma = loaded or
    armaext != extended or feed_end = False then
    error := invalidpickup;
}
Listing D.22 Rules of the PICK_UP_ARM_B sub machine

R1: Pick up at Press {
    t := 3;
    power := 1000;

    if armbpos = atpress and armbext = extended and
        armb = empty and press_block = finished then
        press_block := notfinished;
        press := empty;
        armb := loaded;
    }

R2: Invalid pick up {

    if armbpos != atpress or press_block != finished or
        armb = loaded or armbext != extended then
        error := invalidpickup;
    }

Listing D.23 Rules of the DROP_ARM_A sub machine

R1: Drop at press {
    t := 2;
    power := 800;

    if armapos = atpress and arma = loaded and
        armaext = extended and press = empty then
        arma := empty;
        press := loaded;
        press_block := notfinished;
    }

R2: Invalid drop {

    if armapos != atpress or arma = empty or
        press = loaded or armaext != extended then
        error := invaliddrop;
    }
Listing D.24 Rules of the DROP_ARM_B sub machine

R1: Drop at deposit {
t := 2;
power := 800;

if armbpos = atdeposit and armb = loaded and
  armbext = extended and deposit_belt = empty then
  armb := empty;
deposit_begin := True;
deposit_belt := loaded;
}

R2: Invalid drop {
if armbpos = intransit or deposit_belt = loaded or armbext != extended then
  error := invaliddrop;
}

Listing D.25 Rules of the ARM_A_FEED sub machine

R1: extend arm to feed {
if motor_arma = off and arma = empty and
  armaext = retracted and feed_end = True then
  motor_arma_p := positive;
motor_arma := on;
}

R2: stop motor {
if motor_arma = on and motor_arma_p = positive and armaext = extended then
  motor_arma := off;
}

R3: pick up block {
if motor_arma = off and magnet_arma = off and
  arma = empty and armaext = extended then
  magnet_arma := on;
}

R4: retract arm {
if motor_arma = off and arma = loaded and armaext = extended then
  motor_arma_p := negative;
motor_arma := on;
}

R5: stop motor {
if motor_arma = on and arma = loaded and armaext = retracted then
  motor_arma := off;
}

R6: Else {
  else then
    skip;
}
Listing D.26 Rules of the ARM_A.PRESS sub machine

R1: extend arm to press {
    if motor_arma = off and arma = loaded and armaext = retracted then
        motor_arma_p := positive;
        motor_arma := on;
    }

R2: stop motor {
    if motor_arma = on and arma = loaded and armaext = extended then
        motor_arma := off;
    }

R3: drop block in press {
    if motor_arma = off and magnet_arma = on and
       arma = loaded and armaext = extended then
        magnet_arma := off;
    }

R4: retract arm {
    if motor_arma = off and arma = empty and armaext = extended then
        motor_arma_p := negative;
        motor_arma := on;
    }

R5: stop motor {
    if motor_arma = on and arma = empty and armaext = retracted then
        motor_arma := off;
    }

R6: Else {
    else then
        skip;
    }
Listing D.27 Rules of the ARM_B DEPOSIT sub machine

R1: extend arm to deposit {
    if motor_armb = off and armb = loaded and armbext = retracted then
        motor_armb_p := positive;
        motor_armb := on;
    }

R2: stop motor {
    if motor_armb = on and motor_armb_p = positive and
        armb = loaded and armbext = extended then
        motor_armb := off;
    }

R3: drop block {
    if motor_armb = off and magnet_armb = on and
        armb = loaded and armbext = extended then
        magnet_armb := off;
    }

R4: retract arm {
    if motor_armb = off and armb = empty and armbext = extended then
        motor_armb_p := negative;
        motor_armb := on;
    }

R5: stop motor {
    if motor_armb = on and armb = empty and
        motor_armb_p = negative and armbext = retracted then
        motor_armb := off;
    }

R6: Else {
    else then
        skip;
    }

Listing D.28 Rules of the ARM_BPRESS sub machine

R1: extend arm to press {
  if motor_armb = off and armb = empty and
      armbext = retracted and press = loaded then
    motor_armb_p := positive;
    motor_armb := on;
}

R2: stop motor {
  if motor_armb = on and motor_armb_p = positive and
      armb = empty and armbext = extended then
    motor_armb := off;
}

R3: pick up block {
  if motor_armb = off and magnet_armb = off and armb = empty and
      armbext = extended and press_block = finished then
    magnet_armb := on;
}

R4: retract arm {
  if motor_armb = off and armb = loaded and armbext = extended then
    motor_armb_p := negative;
    motor_armb := on;
}

R5: stop motor {
  if motor_armb = on and motor_armb_p = negative and
      armb = loaded and armbext = retracted then
    motor_armb := off;
}

R6: Else {
  else then
    skip;
}
Listing D.29 Rules of the ROBOT_MOTION sub machine

R1: rotate clockwise {
  t   := 2;
  power := 1000;
  if motor_robot = on and motor_robot_p = negative then
    robot_angle := rotateClockwise();
    armapos := armPosition(ARM_A_FEED_ANGLE, ARM_A_DEPOSIT_ANGLE, 
                          ARM_A_PRESS_ANGLE, rotateClockwise());
    armbpos := armPosition(ARM_B_FEED_ANGLE, ARM_B_DEPOSIT_ANGLE, 
                          ARM_B_PRESS_ANGLE, rotateClockwise());
}

R2: rotate counterclockwise {
  t   := 2;
  power := 1000;
  if motor_robot = on and motor_robot_p = positive then
    robot_angle := rotateCounterClockwise();
    armapos := armPosition(ARM_A_FEED_ANGLE, ARM_A_DEPOSIT_ANGLE, 
                          ARM_A_PRESS_ANGLE, rotateCounterClockwise());
    armbpos := armPosition(ARM_B_FEED_ANGLE, ARM_B_DEPOSIT_ANGLE, 
                          ARM_B_PRESS_ANGLE, rotateCounterClockwise());
}

R3: Else {
  else then
    skip;
}
Listing D.30 Rules of the ROTATE_ROBOT sub machine (part 1)

R1: all empty, go to feed {
    if motor_robot = off and arma = empty and
        armb = empty and armapos != atfeed then
        motor_robot_p := negative;
        motor_robot := on;
        robot_destination := atfeed;
}

R2: all empty, at feed, stop {
    if motor_robot = on and arma = empty and
        armb = empty and armapos = atfeed then
        motor_robot := off;
}

R3: both arms loaded, at feed, go to press {
    if motor_robot = off and arma = loaded and
        armb = loaded and armapos = atfeed then
        motor_robot_p := positive;
        motor_robot := on;
        robot_destination := atpress;
}

R4: both arms loaded, at press {
    if motor_robot = on and arma = loaded and
        armb = loaded and armapos = atpress then
        motor_robot := off;
}
Listing D.31 Rules of the ROTATE_ROBOT sub machine (part 2)

R5: at feed, arm a loaded, press empty, this is the first block {
    if motor_robot = off and arma = loaded and armb = empty and
    press = empty and armapos = atfeed then
    motor_robot_p := positive;
    motor_robot := on;
    robot_destination := atpress;
}

R6: at press, arm a loaded, press empty, this is the first block {
    if motor_robot = on and arma = loaded and armb = empty and
    press = empty and armapos = atpress then
    motor_robot := off;
}

R7: at feed, done loading blocks {
    if motor_robot = off and armapos = atfeed and armb = loaded and
    arma = empty and feed_belt = empty and loader_done = True then
    motor_robot_p := positive;
    motor_robot := on;
    robot_destination := atpress;
}

R8: at press, done loading blocks {
    if motor_robot = on and armapos = atpress and arma = empty and
    feed_belt = empty and loader_done = True then
    motor_robot := off;
}

R9: Else {
    else then
    skip;
}
Appendix E

Electronic Throttle Controller

TASM Model

This appendix provides the listings for the three TASM models of the Electronic Throttle Controller (ETC) case study. The ETC case study is described in details in [111]. In the context of the TASM language, the case study is described in Section 2.8.2. Section E.1.1 provides the listings for the high level model of the ETC, as explained and analyzed in Section 8.2. Section E.2.1 provides the listings for the tasking and scheduler model of the ETC, as explained and analyzed in Section 8.3. Finally, Section E.3.1 provides the listings for the low level model of the ETC, as explained and analyzed in Section 8.4. Each of the sections provides a brief summary of the model before giving the list of machines used in the model, followed by the actual listings.

E.1 High Level Model

The high level TASM model of the ETC describes the mode switching logic and the logic used to decide on the law for the controller output. The controller output is the desired current, which is calculated based on the controller logic. This version describes a high level model because it does not have any tasks or any calculation of the desired current. The desired current is abstracted using a user-defined type.
The index of the listings is given in Table E.1. The complete TASM model contains 3 main machines, one for the controller, one for the driver behavior, and one for the behavior of the vehicle. The model also contains 13 function machines, and 9 sub machines.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Purpose</th>
<th>Listing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types</td>
<td>N/A</td>
<td>List of types</td>
<td>Listing E.1</td>
</tr>
<tr>
<td>Variables</td>
<td>N/A</td>
<td>List of variables</td>
<td>Listing E.2</td>
</tr>
<tr>
<td>CONTROLLER</td>
<td>Main</td>
<td>Performs the controller functions</td>
<td>Listing E.3</td>
</tr>
<tr>
<td>DRIVER</td>
<td>Main</td>
<td>Simulates driver behavior</td>
<td>Listing E.4, E.5</td>
</tr>
<tr>
<td>VEHICLE</td>
<td>Main</td>
<td>Simulates vehicle behavior</td>
<td>Listing E.6, E.7</td>
</tr>
<tr>
<td>Cruise</td>
<td>Function</td>
<td>Determines the cruise control mode</td>
<td>Listing E.8</td>
</tr>
<tr>
<td>Cruise_Mode</td>
<td>Function</td>
<td>Sets the cruise mode</td>
<td>Listing E.9</td>
</tr>
<tr>
<td>Cruise.Throttle.C</td>
<td>Function</td>
<td>Calculates the cruise mode current</td>
<td>Listing E.10</td>
</tr>
<tr>
<td>Driver.Throttle.C</td>
<td>Function</td>
<td>Calculates the human mode current</td>
<td>Listing E.11</td>
</tr>
<tr>
<td>Driving.Throttle.C</td>
<td>Function</td>
<td>Calculates the driving mode current</td>
<td>Listing E.12</td>
</tr>
<tr>
<td>Fault</td>
<td>Function</td>
<td>Detects if a fault is present</td>
<td>Listing E.13</td>
</tr>
<tr>
<td>Limiting.Throttle.C</td>
<td>Function</td>
<td>Calculates the limiting mode current</td>
<td>Listing E.14</td>
</tr>
<tr>
<td>Over_Rev</td>
<td>Function</td>
<td>Determines whether the engine revolution is too high</td>
<td>Listing E.15</td>
</tr>
<tr>
<td>Over_Rev_Mode</td>
<td>Function</td>
<td>Sets the revolution limiting mode</td>
<td>Listing E.16</td>
</tr>
<tr>
<td>Over_Rev.Throttle.C</td>
<td>Function</td>
<td>Calculates the revolution limiting mode current</td>
<td>Listing E.17</td>
</tr>
<tr>
<td>Over_Torque</td>
<td>Function</td>
<td>Determines whether the vehicle torque is too high</td>
<td>Listing E.18</td>
</tr>
<tr>
<td>Over_Torque_Mode</td>
<td>Function</td>
<td>Sets the traction limiting mode</td>
<td>Listing E.19</td>
</tr>
<tr>
<td>Over_Torque.Throttle.C</td>
<td>Function</td>
<td>Calculates the traction limiting mode current</td>
<td>Listing E.20</td>
</tr>
<tr>
<td>CALCULATE_OUTPUT</td>
<td>Sub</td>
<td>Wrapper machine to calculate the desired current</td>
<td>Listing E.21</td>
</tr>
<tr>
<td>DO_SHUTDOWN</td>
<td>Sub</td>
<td>Performs the shut down functions</td>
<td>Listing E.22</td>
</tr>
<tr>
<td>DO_STARTUP</td>
<td>Sub</td>
<td>Performs the start up functions</td>
<td>Listing E.23</td>
</tr>
<tr>
<td>HANDLE_FAULT</td>
<td>Sub</td>
<td>Performs the fault tolerance functions</td>
<td>Listing E.24</td>
</tr>
<tr>
<td>MONITOR_HEALTH</td>
<td>Sub</td>
<td>Detects the presence of faults</td>
<td>Listing E.25</td>
</tr>
<tr>
<td>SAMPLE_STATE</td>
<td>Sub</td>
<td>Reads the state through sensors for the controller</td>
<td>Listing E.26</td>
</tr>
<tr>
<td>SET_MAJOR_MODE</td>
<td>Sub</td>
<td>Wrapper machine to set the major controller mode</td>
<td>Listing E.27</td>
</tr>
<tr>
<td>SET_MAJOR_MODE_WORK</td>
<td>Sub</td>
<td>Sets the controller major mode</td>
<td>Listing E.28</td>
</tr>
<tr>
<td>SET_MINOR_MODE</td>
<td>Sub</td>
<td>Wrapper machine to set the minor controller mode</td>
<td>Listing E.29</td>
</tr>
<tr>
<td>SET_MINOR_MODE_WORK</td>
<td>Sub</td>
<td>Sets the controller minor mode</td>
<td>Listing E.30</td>
</tr>
</tbody>
</table>

Table E.1: List of machines used in the high level ETC model
E.1.1 Environment

<table>
<thead>
<tr>
<th>Listing E.1 User-defined types of the model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary_Mode := {active, inactive};</td>
</tr>
<tr>
<td>Binary_Status := {on, off};</td>
</tr>
<tr>
<td>Health_Status := {nominal, fault_detected};</td>
</tr>
<tr>
<td>Mode := {off, startup, shutdown, driving, limiting, faulty};</td>
</tr>
<tr>
<td>Gear_Status := {park, drive};</td>
</tr>
<tr>
<td>Control_Mode := {sample, mode_set_major, mode_set_minor, output, health};</td>
</tr>
<tr>
<td>Desired_Current := {none_c, human_c, cruise_c, traction_c, rev_c, min_limiting_c, max_driving_c, fault_c, error_c};</td>
</tr>
<tr>
<td>Simulation_Mode := {begin_s, drive_s, random_s, stop_s};</td>
</tr>
</tbody>
</table>
### Listing E.2 Variables of the model

//internal controller modes

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary_Mode rev_limiting_mode</td>
<td>inactive;</td>
</tr>
<tr>
<td>Binary_Mode traction_mode</td>
<td>inactive;</td>
</tr>
<tr>
<td>Binary_Mode cruise_mode</td>
<td>inactive;</td>
</tr>
<tr>
<td>Mode controller_mode</td>
<td>off;</td>
</tr>
<tr>
<td>Control_Mode control_mode</td>
<td>sample;</td>
</tr>
<tr>
<td>Health_Status system_health</td>
<td>nominal;</td>
</tr>
<tr>
<td>Boolean startup_done</td>
<td>False;</td>
</tr>
<tr>
<td>Boolean shutdown_done</td>
<td>False;</td>
</tr>
</tbody>
</table>

//powertrain sensors

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integer[0, 120] vehicle_speed</td>
<td>0; //mph</td>
</tr>
<tr>
<td>Integer[0, 8000] engine_speed</td>
<td>0; //rpm</td>
</tr>
<tr>
<td>Integer[0, 250] vehicle_torque</td>
<td>0; //kPa</td>
</tr>
<tr>
<td>Boolean fault</td>
<td>False; //is there a fault?</td>
</tr>
</tbody>
</table>

//driver inputs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary_Status ignition</td>
<td>off;</td>
</tr>
<tr>
<td>Binary_Status cruise_switch</td>
<td>off;</td>
</tr>
<tr>
<td>Integer[0, 45] pedal_angle</td>
<td>0; //degrees</td>
</tr>
<tr>
<td>Gear_Status gear</td>
<td>park;</td>
</tr>
<tr>
<td>Binary_Mode break_pedal</td>
<td>inactive;</td>
</tr>
</tbody>
</table>

//constants

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Const Integer MAX_ENGINE_SPEED</td>
<td>6000; //rpm</td>
</tr>
<tr>
<td>Const Integer MAX TORQUE</td>
<td>110; //kPa</td>
</tr>
<tr>
<td>Const Integer MIN CRUISE_SPEED</td>
<td>30; //mph</td>
</tr>
</tbody>
</table>

//controller inputs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integer[0, 120] c_vehicle_speed</td>
<td>0;</td>
</tr>
<tr>
<td>Integer[0, 8000] c_engine_speed</td>
<td>0; //rpm</td>
</tr>
<tr>
<td>Integer[0, 250] c_vehicle_torque</td>
<td>0; //kPa</td>
</tr>
<tr>
<td>Boolean c_fault</td>
<td>False;</td>
</tr>
<tr>
<td>Binary_Status c_ignition</td>
<td>off;</td>
</tr>
<tr>
<td>Binary_Status c_cruise_switch</td>
<td>off;</td>
</tr>
<tr>
<td>Integer[0, 45] c_pedal_angle</td>
<td>0; //degrees</td>
</tr>
<tr>
<td>Gear_Status c_gear</td>
<td>park;</td>
</tr>
<tr>
<td>Binary_Mode c_break_pedal</td>
<td>inactive;</td>
</tr>
</tbody>
</table>

//controller output

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired_Current desired_current</td>
<td>none_c;</td>
</tr>
</tbody>
</table>

//simulation mode

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation_Mode driver_s</td>
<td>start_s;</td>
</tr>
<tr>
<td>Boolean vehicle_over_rev_s</td>
<td>False;</td>
</tr>
<tr>
<td>Boolean vehicle_over_tor_s</td>
<td>False;</td>
</tr>
</tbody>
</table>
E.1.2 Main Machines

Listing E.3 CONTROLLER main machine

R1: Controller loop when nominal
{  
  if control_mode = sample then  
    SAMPLE_STATE();  
    control_mode := mode_set;  
}

R2: Controller loop to set major mode
{  
  if control_mode = mode_set_major then  
    SET_MAJOR_MODE();  
    control_mode := mode_set_minor;  
}

R3: Controller loop to set minor mode
{  
  if control_mode = mode_set_minor then  
    SET_MINOR_MODE();  
    control_mode := output;  
}

R4: Controller loop to output current
{  
  if control_mode = output then  
    CALCULATE_OUTPUT();  
    control_mode := health;  
}

R5: Controller loop to find failure
{  
  if control_mode = health then  
    MONITOR_HEALTH();  
    control_mode := sample;  
}
Listing E.4 DRIVER main machine (part 1)

R1: Turn on the car
{
    if driver_s = begin_s and controller_mode = off and
        ignition = off then
        ignition := on;
    driver_s := drive_s;
}

R2: Start driving
{
    if driver_s = drive_s and controller_mode = driving and
        vehicle_speed = 0 and gear = park then
        gear := drive;
        pedal_angle := 22;
        vehicle_speed := 30;
    driver_s := random_s;
}

R3: Turn on cruise, slow speed
{
    if driver_s = random_s and cruise_switch = off then
        cruise_switch := on;
        vehicle_speed := 10;
}

R4: Turn on cruise, normal speed
{
    if driver_s = random_s and cruise_switch = off then
        cruise_switch := on;
        vehicle_speed := 30;
}

R5: Turn off cruise
{
    if driver_s = random_s and cruise_switch = on then
        cruise_switch := off;
}

R6: Press break pedal
{
    if driver_s = random_s and break_pedal = inactive then
        break_pedal := active;
}

R7: Depress break pedal
{
    if driver_s = random_s and break_pedal = active then
        break_pedal := inactive;
}
Listing E.5 DRIVER main machine (part 2)

R8: Stop
{  
  if driver_s = random_s then  
    gear := park;  
    vehicle_speed := 0;  
    ignition := off;  
    driver_s := stop_s;  
}

R9: Do nothing
{  
  if driver_s = random_s then  
    skip;  
}

R10: Stopped
{  
  if driver_s = stop_s then  
    skip;  
}

R11: Else
{  
  else then  
    skip;  
}
Listing E.6 VEHICLE main machine (part 1)

R1: Randomly change, do nothing
{
    if driver_s = random_s and vehicle_over_rev_s = False and
        vehicle_over_tor_s = False then
        skip;
}

R2: Randomly change RPM
{
    if driver_s = random_s and vehicle_over_rev_s = False and
        vehicle_over_tor_s = False then
        engine_speed := MAX_ENGINE_SPEED + 1;
        vehicle_over_rev_s := True;
}

R3: Randomly change Traction
{
    if driver_s = random_s and vehicle_over_rev_s = False and
        vehicle_over_tor_s = False then
        vehicle_torque := MAX_TORQUE + 1;
        vehicle_over_tor_s := True;
}

R4: Randomly change Both
{
    if driver_s = random_s and vehicle_over_rev_s = False and
        vehicle_over_tor_s = False then
        engine_speed := MAX_ENGINE_SPEED + 1;
        vehicle_over_rev_s := True;
        vehicle_torque := MAX_TORQUE + 1;
        vehicle_over_tor_s := True;
}

R5: Randomly change RPM, correct
{
    if driver_s = random_s and vehicle_over_rev_s = True and
        vehicle_over_tor_s = False and desired_current = rev_c then
        engine_speed := MAX_ENGINE_SPEED;
        vehicle_over_rev_s := False;
}
Listing E.7 VEHICLE main machine (part 2)

R6: Randomly change traction, correct
{
    if driver_s = random_s and vehicle_over_rev_s = False and
        vehicle_over_tor_s = True and desired_current = traction_c then
        vehicle_torque := MAX_TORQUE;
        vehicle_over_tor_s := False;

R7: Randomly change both, correct
{
    if driver_s = random_s and vehicle_over_rev_s = True and
        vehicle_over_tor_s = True and desired_current = min_limiting_c then
        vehicle_torque := MAX_TORQUE;
        vehicle_over_tor_s := False;
        engine_speed := MAX_ENGINE_SPEED;
        vehicle_over_rev_s := False;

R8: Randomly put in a fault
{
    if driver_s = random_s and fault = False then
        fault := True;

R9: Else
{
    else then
    skip;
}
E.1.3 Function Machines

Listing E.8 Cruise function machine
R1: Cruise condition
{
    if c_vehicle_speed >= MIN_CRUISE_SPEED
        and c_gear = drive
        and c_break_pedal = inactive
        and c_cruise_switch = on then
        outb := True;
    }
R2: Else
{
    else then
    outb := False;
}

Listing E.9 Cruise_Mode function machine
R1: Cruise Active
{
    if Cruise() then
    out := active;
}
R2: Else
{
    else then
    out := inactive;
}

Listing E.10 Cruise_Throttle_C function machine
R1: Always
{
    if True then
    out := cruise_c;
}
Listing E.11 Driver_Throttle_C function machine
R1: Always
{
    if True then
        out := human_c;
}

Listing E.12 Driving_Throttle_C function machine
R1: Cruise enabled, driver input
{
    if cruise_mode = active and c_pedal_angle != 0 then
        out := max_driving_c;
}
R2: Cruise enabled, no driver input
{
    if cruise_mode = active and c_pedal_angle = 0 then
        out := Cruise_Throttle_C();
}
R3: Else
{
    else then
        out := Driver_Throttle_C();
}

Listing E.13 Fault function machine
R1: Main loop
{
    if fault then
        outb := True;
}
R2: Else
{
    else then
        outb := False;
}
Listing E.14 Limiting_Throttle_C function machine

R1: Both  //if both over rev and over torque are active
{   
  if rev_limiting_mode = active and traction_mode = active then
    out := min_limiting_C;
}

R2: Over_Rev  //if only over rev is active
{   
  if rev_limiting_mode = active and traction_mode = inactive then
    out := Over_Rev_Throttle_C();
}

R3: Over_Torque //if only over torque is active
{   
  if rev_limiting_mode = inactive and traction_mode = active then
    out := Over_Torque_Throttle_C();
}

R4: Else  //both are inactive. This should never happen!
{   
  else then
    out := error_c;
}

Listing E.15 Over_Rev function machine

R1: Over Rev Condition
{   
  if c_engine_speed > MAX_ENGINE_SPEED then
    outb := True;
}

R2: No Over Rev
{   
  else then
    outb := False;
}

Listing E.16 Over_Rev_Mode function machine

R1: Over Rev Mode
{   
  if Over_Rev() then
    out := active;
}

R2: Else {
  else then
    out := inactive;
}
Listing E.17 Over_Rev_Throttle_C function machine
R1: Always
{
    if True then
        out := rev_c;
}

Listing E.18 Over_Torque function machine
R1: Over Torque Condition
{
    if c_vehicle_torque > MAX_TORQUE then
        outb := True;
}
R2: No Over Torque
{
    else then
        outb := False;
}

Listing E.19 Over_Torque_Mode function machine
R1: Over Torque Mode
{
    if Over_Torque() then
        out := active;
}
R2: Else
{
    else then
        out := inactive;
}

Listing E.20 Over_Torque_Throttle_C function machine
R1: Always
{
    if True then
        out := traction_c;
}
E.1.4 Sub Machines

Listing E.21 CALCULATE_OUTPUT sub machine

R1: Driving Mode
{
  if controller_mode = driving then
    desired_current := Driving_Throttle_C();
}

R2: Limiting Mode
{
  if controller_mode = limiting then
    desired_current := Limiting_Throttle_C();
}

R3: Fault Mode
{
  if controller_mode = faulty then
    HANDLE_FAULT();
}

R4: Startup Mode
{
  if controller_mode = startup then
    DO_STARTUP();
}

R5: Shutdown Mode
{
  if controller_mode = shutdown then
    DO_SHUTDOWN();
}

R6: Fault Mode
{
  if controller_mode = off then
    desired_current := none_c;
}
Listing E.22 DO_SHUTDOWN sub machine

R1: Do shutdown only when vehicle is stationary
{       
  if c_vehicle_speed = 0 
    and c_gear = park 
    and ignition = off then 
  desired_current := none_c; 
  shutdown_done := True; 
}

R2: No shutdown
{       
  else then
  desired_current := none_c; 
  shutdown_done := False; 
}

Listing E.23 DO_STARTUP sub machine

R1: Do startup only when vehicle is stationary
{       
  if c_vehicle_speed = 0 and c_gear = park and 
    c_break_pedal = active and c_cruise_switch = off then 
  desired_current := none_c; 
  startup_done := True; 
}

R2: No startup
{       
  else then
  desired_current := none_c; 
  startup_done := False; 
}

Listing E.24 HANDLE_FAULT sub machine

R1: Handle the fault
{       
  if c_vehicle_speed = 0 and c_gear = park then
  desired_current := none_c;
  controller_mode := shutdown;
  fault := False;
  c_fault := False;
}

R2: Else
{       
  else then
  desired_current := fault_c;
}  

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Listing E.25 MONITOR.HEALTH sub machine

R1: Find Fault
{
    if Fault() then
        system_health := fault_detected;
}

R2: Else do nothing
{
    else then
        system_health := nominal;
}

Listing E.26 SAMPLE.STATE sub machine

R1: Cache the state
{
    if True then
        c_vehicle_speed := vehicle_speed;
        c_engine_speed := engine_speed;
        c_vehicle_torque := vehicle_torque;
        c_ignition := ignition;
        c_cruise_switch := cruise_switch;
        c_pedal_angle := pedal_angle;
        c_gear := gear;
        c_break_pedal := break_pedal;
}

Listing E.27 SET_MAJOR.MODE sub machine

R1: No fault
{
    if system_health = nominal then
        SET_MAJOR_MODE_WORK();
}

R2: Else there are faults
{
    if system_health = fault_detected and controller_mode != shutdown then
        controller_mode = faulty;
}

R3: Else
{
    else then
        skip;
}
Listing E.28 SET MAJOR MODE WORK sub machine

R1: Off -> Startup
{  
if controller_mode = off and ignition = on then
   controller_mode := startup;
}

R2: Startup -> Driving
{  
if controller_mode = startup and startup_done = True then
   controller_mode := driving;
}

R3: Driving -> Limiting
{  
if controller_mode = driving and (Over_Rev() or Over_Torque()) and ignition = on then
   controller_mode := limiting;
}

R4: Limiting -> Driving
{  
if controller_mode = limiting and not (Over_Rev() or Over_Torque()) and ignition = on then
   controller_mode := driving;
}

R5: Driving, Limiting, Faulty -> Shutdown
{  
if (controller_mode = limiting or controller_mode = driving or controller_mode = faulty) and ignition = off then
   controller_mode := shutdown;
}

R6: Shutdown -> Off
{  
if controller_mode = shutdown and shutdown_done = True then
   controller_mode := off;
}

R7: Any other case, do nothing
{  
else then
   skip;
}
Listing E.29 SET_MINOR_MODE sub machine

R1: No fault
{
    if system_health = nominal then
        SET_MINOR_MODE_WORK();
}

R2: Else
{
    else then
        skip;
}

Listing E.30 SET.MINOR.MODE_WORK sub machine

R1: Else
{
    if True then
        cruise_mode := Cruise_Mode();
        rev_limiting_mode := Over_Rev_Mode();
        traction_mode := Over_Torque_Mode();
}
E.2 Tasking Model

The tasking model describes the tasking structure and scheduler used to implement the electronic throttle controller functionality. The implementation is achieved through 3 tasks, a scheduler, and a 1 ms clock. The index of the listings is given in Table E.2. The complete TASM model contains 3 main machines, 1 function machine, and 10 sub machines.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Purpose</th>
<th>Listing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types</td>
<td>N/A</td>
<td>List of types</td>
<td>Listing E.31</td>
</tr>
<tr>
<td>Variables</td>
<td>N/A</td>
<td>List of variables</td>
<td>Listing E.32</td>
</tr>
<tr>
<td>CLOCK</td>
<td>Main</td>
<td>Ticks at 1 ms intervals</td>
<td>Listing E.33</td>
</tr>
<tr>
<td>SCHEDULER</td>
<td>Main</td>
<td>Assigns tasks to the processor</td>
<td>Listing E.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>based on fixed priority and period</td>
<td></td>
</tr>
<tr>
<td>TASKS</td>
<td>Main</td>
<td>Simulates the behavior of the 3 tasks</td>
<td>Listing E.35</td>
</tr>
<tr>
<td>finished_to_waiting</td>
<td>Function</td>
<td>Resets completed tasks</td>
<td>Listing E.36</td>
</tr>
<tr>
<td>MANAGER.TICK</td>
<td>Sub</td>
<td>Keeps track of manager task period</td>
<td>Listing E.37</td>
</tr>
<tr>
<td>MONITOR.TICK</td>
<td>Sub</td>
<td>Keeps track of monitor task period</td>
<td>Listing E.38</td>
</tr>
<tr>
<td>SERVO.TICK</td>
<td>Sub</td>
<td>Keeps track of servo task period</td>
<td>Listing E.39</td>
</tr>
<tr>
<td>SET_EXECUTING_TASK</td>
<td>Sub</td>
<td>Assigns execution of a task</td>
<td>Listing E.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>if the processor is free</td>
<td></td>
</tr>
<tr>
<td>SET_EXECUTION_PRIORITY</td>
<td>Sub</td>
<td>Decides on the next task to execute based on priority ordering</td>
<td>Listing E.41, E.42</td>
</tr>
<tr>
<td>UPDATE_TASK_STATUSES</td>
<td>Sub</td>
<td>Resets finished tasks to waiting</td>
<td>Listing E.43</td>
</tr>
<tr>
<td>WAKE_UP_MANAGER</td>
<td>Sub</td>
<td>Releases manager task on the period</td>
<td>Listing E.44</td>
</tr>
<tr>
<td>WAKE_UP_MONITOR</td>
<td>Sub</td>
<td>Releases monitor task on the period</td>
<td>Listing E.45</td>
</tr>
<tr>
<td>WAKE_UP_SERVO</td>
<td>Sub</td>
<td>Releases servo task on the period</td>
<td>Listing E.46</td>
</tr>
<tr>
<td>WAKE_UP_TASKS</td>
<td>Sub</td>
<td>Wrapper machine to release tasks</td>
<td>Listing E.47</td>
</tr>
</tbody>
</table>

Table E.2: List of machines used in the tasking model of the ETC
E.2.1 Environment

Listing E.31 User-defined types of the model
Task_Status := \{waiting, released, executing, finished\};
Execution := \{done, not_done\};
Scheduler := \{wakeup, update, execute, wait\};

Listing E.32 Variables of the model
//Task properties
Task_Status manager_s := released;
Task_Status monitor_s := released;
Task_Status servo_s := released;

//Constants
Const Integer MANAGER_PERIOD := 10; //in ms
Const Integer MONITOR_PERIOD := 30; //in ms
Const Integer SERVO_PERIOD := 3; //in ms
Const Integer MAJOR_CYCLE := 30; //in ms

//Scheduler
Scheduler scheduler_s := wakeup;
Integer tick := 0;
Integer oldtick := 0;
Integer managertick := 0;
Integer monitor tick := 0;
Integer servotick := 0;
E.2.2 Main Machines

Listing E.33 CLOCK main machine

R1: Tick, no reset
{
    t := 1000;

    if tick != MAJOR_CYCLE then
        tick := tick + 1;
        MANAGER_TICK();
        MONITOR_TICK();
        SERVO_TICK();
    }

R2: Tick, with reset
{
    t := 1000;

    if tick = MAJOR_CYCLE then
        tick := 1;
        MANAGER_TICK();
        MONITOR_TICK();
        SERVO_TICK();
    }
Listing E.34 SCHEDULER main machine

R1: Step 1, set status

{ if scheduler_s = update then
    UPDATE_TASK_STATUSES();
    scheduler_s := wakeup;
}

R2: Step 2, wake up tasks

{ if scheduler_s = wakeup then
    WAKE_UP_TASKS();
    scheduler_s := execute;
}

R3: Step 3, set executing

{ if scheduler_s = execute then
    SET_EXECUTING_TASK();
    scheduler_s := wait;
}

R4: Wait for a tick

{ t := 1000;
    if scheduler_s = wait then
        scheduler_s := update;
}
Listing E.35 TASKS main machine

R1: Execute manager
{
    \( t := [0, 5] \);
    if manager_s = executing then
        manager_s := finished;
}

R2: Execute monitor
{
    \( t := [100, 200] \);
    if monitor_s = executing then
        monitor_s := finished;
}

R3: Execute servo
{
    \( t := [70, 100] \);
    if servo_s = executing then
        servo_s := finished;
}

R4: Else, do nothing, wait for event
{
    \( t := \text{next} \);
    else then
        \text{skip};
}
E.2.3 Function Machines

Listing E.36 finished_to_waiting function machine

R1:
{
  if in = finished then
    out := waiting;
}

R2:
{
  else then
    out := in;
}
E.2.4 Sub Machines

Listing E.37 MANAGER_TICK sub machine
R1: tick
{
    if managertick = MANAGER_PERIOD then
        managertick := 1;
}

R2: reset
{
    else then
        managertick := managertick + 1;
}

Listing E.38 MONITOR_TICK sub machine
R1: tick
{
    if monitortick = MONITOR_PERIOD then
        monitortick := 1;
}

R2: reset
{
    else then
        monitotick := monitotick + 1;
}

Listing E.39 SERVO_TICK sub machine
R1: tick
{
    if servotick = SERVO_PERIOD then
        servotick := 1;
}

R2: reset
{
    else then
        servotick := servotick + 1;
}
Listing E.40 SET_EXEcuting_TasK sub machine
R1: Someone is still executing, do nothing
{ if manager_s = executing or monitor_s = executing or
servo_s = executing then
    skip;
}

R2: Processor is free, assign a task
{ else then
    SET_EXECUTION_PRIORITY();
}

Listing E.41 SET_EXECUTION_PRIORITY sub machine (part 1)
R1: All released
{ if manager_s = released and monitor_s = released and
    servo_s = released then
    manager_s := executing;
}

R2: manager, monitor released
{ if manager_s = released and monitor_s = released and
    servo_s != released then
    manager_s := executing;
}

R3: manager, servo released
{ if manager_s = released and servo_s = released and
    monitor_s != released then
    manager_s := executing;
}

R4: monitor, servo released
{ if monitor_s = released and servo_s = released and
    manager_s != released then
    monitor_s := executing;
}
Listing E.42 SET_EXECUTION_PRIORITY sub machine (part 2)

R5: only manager
{
    if manager_s = released and monitor_s != released and
        servo_s != released then
        managers := executing;
}

R6: only monitor
{
    if monitor_s = released and manager_s != released and
        servo_s != released then
        monitors := executing;
}

R7: only servo
{
    if servo_s = released and manager_s != released and
        monitor_s != released then
        servos := executing;
}

R8: no one released
{
    if manager_s != released and monitor_s != released and
        servo_s != released then
        skip;
}

Listing E.43 UPDATE_TASK_STATUSES sub machine

R1: We are at a tick
{
    if tick != oldtick then
        manager_s := finished_to_waiting(manager_s);
        monitor_s := finished_to_waiting(monitor_s);
        servos := finished_to_waiting(servos);
}

R2: Not at a tick
{
    else then
        skip;
}
Listing E.44  WAKE_UP_MANAGER sub machine

R1:  wakeup
{   
    if manager_s = waiting and managertick = MANAGER_PERIOD then
        manager_s := released;
    }

R2:  otherwise
{   
    else then
        skip;
    }

Listing E.45  WAKE_UP_MONITOR sub machine

R1:  wakeup
{   
    if monitor_s = waiting and monitortick = MONITOR_PERIOD then
        monitor_s := released;
    }

R2:  otherwise
{   
    else then
        skip;
    }

Listing E.46  WAKE_UP_SERVO sub machine

R1:  wakeup
{   
    if servo_s = waiting and servotick = SERVO_PERIOD then
        servo_s := released;
    }

R2:  otherwise
{   
    else then
        skip;
    }

Listing E.47 WAKE_UP_TASKS sub machine

R1: wakeup
{
    if oldtick != tick then
        WAKE_UP_MANAGER();
        WAKE_UP_MONITOR();
        WAKE_UP_SERVO();
        oldtick := tick;
}

R2: Else
{
    else then
        skip;
}
E.3 Low Level Model

The low level TASM model of the ETC describes the implementation of the mode switching logic and the logic used to decide on the law for the controller output, as implemented through a tasking model. This version combines the functional model from Section E.1 with the tasking model from Section E.2. The index of the listings is given in Table E.3 and in Table E.4. The complete TASM model contains 5 main machines, 14 function machines, and 20 sub machines. In this section, only the modified and new machines are listed. Unchanged machines from previous sections are not repeated and the relevant table entries refer to the listings given in previous sections. The new and changed machines are shown in bold font. The changed machines where only resource consumptions are added are shown in bold and italic font.

<table>
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<tr>
<th>Name</th>
<th>Type</th>
<th>Purpose</th>
<th>Listing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types</td>
<td>N/A</td>
<td>List of types</td>
<td>Listing E.48</td>
</tr>
<tr>
<td>Variables</td>
<td>N/A</td>
<td>List of variables</td>
<td>Listing E.50, E.51</td>
</tr>
<tr>
<td>Resources</td>
<td>N/A</td>
<td>List of resources</td>
<td>Listing E.49</td>
</tr>
<tr>
<td>CLOCK</td>
<td>Main</td>
<td>Ticks at 1 ms intervals</td>
<td>Listing E.33</td>
</tr>
<tr>
<td>DRIVER</td>
<td>Main</td>
<td>Simulates the behavior of the driver</td>
<td>Listing E.52, E.53</td>
</tr>
<tr>
<td>SCHEDULER</td>
<td>Main</td>
<td>Assigns tasks to the processor based on fixed priority and period</td>
<td>Listing E.54</td>
</tr>
<tr>
<td>TASKS</td>
<td>Main</td>
<td>Performs the controller functions</td>
<td>Listing E.55</td>
</tr>
<tr>
<td>VEHICLE</td>
<td>Main</td>
<td>Simulates the environment</td>
<td>Listing E.56, E.57</td>
</tr>
<tr>
<td>Cruise</td>
<td>Function</td>
<td>Determines the cruise control mode</td>
<td>Listing E.8</td>
</tr>
<tr>
<td>Cruise_Mode</td>
<td>Function</td>
<td>Sets the cruise mode</td>
<td>Listing E.9</td>
</tr>
<tr>
<td>Cruise_Throttle_C</td>
<td>Function</td>
<td>Calculates the cruise mode current</td>
<td>Listing E.58</td>
</tr>
<tr>
<td>Driver_Throttle_C</td>
<td>Function</td>
<td>Calculates the human mode current</td>
<td>Listing E.59</td>
</tr>
<tr>
<td>Driving_Throttle_C</td>
<td>Function</td>
<td>Calculates the driving mode current</td>
<td>Listing E.60</td>
</tr>
<tr>
<td>Fault</td>
<td>Function</td>
<td>Detects if a fault is present</td>
<td>Listing E.13</td>
</tr>
<tr>
<td>Limiting_Throttle_C</td>
<td>Function</td>
<td>Calculates the limiting mode current</td>
<td>Listing E.61</td>
</tr>
<tr>
<td>Over_Rev</td>
<td>Function</td>
<td>Determines whether the engine revolution is too high</td>
<td>Listing E.15</td>
</tr>
<tr>
<td>Over_Rev_Mode</td>
<td>Function</td>
<td>Sets the revolution limiting mode</td>
<td>Listing E.16</td>
</tr>
<tr>
<td>Over_Rev_Throttle_C</td>
<td>Function</td>
<td>Calculates the revolution limiting mode current</td>
<td>Listing E.62</td>
</tr>
<tr>
<td>Over_Torque</td>
<td>Function</td>
<td>Determines whether the vehicle torque is too high</td>
<td>Listing E.18</td>
</tr>
</tbody>
</table>

Table E.3: List of machines used in the low level ETC model (part 1)
<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Purpose</th>
<th>Listing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over_Torque_Mode</td>
<td>Function</td>
<td>Sets the traction limiting mode</td>
<td>Listing E.19</td>
</tr>
<tr>
<td>Over_Torque_Throttle_C</td>
<td>Function</td>
<td>Calculates the traction limiting mode current</td>
<td>Listing E.63</td>
</tr>
<tr>
<td>finished_to_waiting</td>
<td>Function</td>
<td>Resets completed tasks</td>
<td>Listing E.36</td>
</tr>
<tr>
<td>CALCULATE_OUTPUT</td>
<td>Sub</td>
<td>Wrapper machine to calculate the desired current</td>
<td>Listing E.21</td>
</tr>
<tr>
<td>DO_SHUTDOWN</td>
<td>Sub</td>
<td>Performs the shut down functions</td>
<td>Listing E.64</td>
</tr>
<tr>
<td>DO_STARTUP</td>
<td>Sub</td>
<td>Performs the start up functions</td>
<td>Listing E.65</td>
</tr>
<tr>
<td>HANDLE_FAULT</td>
<td>Sub</td>
<td>Performs the fault tolerance functions</td>
<td>Listing E.66</td>
</tr>
<tr>
<td>MANAGER_TICK</td>
<td>Sub</td>
<td>Keeps track of manager task period</td>
<td>Listing E.37</td>
</tr>
<tr>
<td>MONITOR_HEALTH</td>
<td>Sub</td>
<td>Detects the presence of faults</td>
<td>Listing E.67</td>
</tr>
<tr>
<td>MONITOR_TICK</td>
<td>Sub</td>
<td>Keeps track of monitor task period</td>
<td>Listing E.38</td>
</tr>
<tr>
<td>SAMPLE_STATE</td>
<td>Sub</td>
<td>Reads the state through sensors for the controller</td>
<td>Listing E.26</td>
</tr>
<tr>
<td>SERVO_TICK</td>
<td>Sub</td>
<td>Keeps track of servo task period</td>
<td>Listing E.39</td>
</tr>
<tr>
<td>SET_EXECUTING_TASK</td>
<td>Sub</td>
<td>Assigns execution of a task if the processor is free</td>
<td>Listing E.40</td>
</tr>
<tr>
<td>SET_EXECUTION_PRIORITY</td>
<td>Sub</td>
<td>Decides on the next task to execute based on priority ordering</td>
<td>Listing E.41, E.42</td>
</tr>
<tr>
<td>SET_MAJOR_MODE</td>
<td>Sub</td>
<td>Wrapper machine to set the major controller mode</td>
<td>Listing E.27</td>
</tr>
<tr>
<td>SET_MAJOR_MODE_WORK</td>
<td>Sub</td>
<td>Sets the controller major mode</td>
<td>Listing E.28</td>
</tr>
<tr>
<td>SET_MINOR_MODE</td>
<td>Sub</td>
<td>Wrapper machine to set the minor controller mode</td>
<td>Listing E.29</td>
</tr>
<tr>
<td>SET_MINOR_MODE_WORK</td>
<td>Sub</td>
<td>Sets the controller minor mode</td>
<td>Listing E.30</td>
</tr>
<tr>
<td>UPDATE_TASK_STATUSES</td>
<td>Sub</td>
<td>Resets finished tasks to waiting</td>
<td>Listing E.43</td>
</tr>
<tr>
<td>WAKE_UP_MANAGER</td>
<td>Sub</td>
<td>Releases manager task on the period</td>
<td>Listing E.44</td>
</tr>
<tr>
<td>WAKE_UP_MONITOR</td>
<td>Sub</td>
<td>Releases monitor task on the period</td>
<td>Listing E.45</td>
</tr>
<tr>
<td>WAKE_UP_SERVO</td>
<td>Sub</td>
<td>Releases servo task on the period</td>
<td>Listing E.46</td>
</tr>
<tr>
<td>WAKE_UP_TASKS</td>
<td>Sub</td>
<td>Wrapper machine to release tasks</td>
<td>Listing E.47</td>
</tr>
</tbody>
</table>

Table E.4: List of machines used in the low level ETC model (part 2)
E.3.1 Environment

Listing E.48 User-defined types of the model

```
Binary_Mode := {active, inactive};
Binary_Status := {on, off};
Health_Status := {nominal, fault_detected};
Mode := {off, startup, shutdown, driving, limiting, faulty};
Gear_Status := {park, drive};
Desired_Current := {none_c, human_c, cruise_c, traction_c, rev_c, min_limiting_c,
                   max_driving_c, fault_c, error_c};
Simulation_Mode := {begin_s, drive_s, random_s, stop_s, done_s};
Task_Status := {waiting, released, executing, finished};
Scheduler := {wakeup, update, execute, wait, update_state};
Manager_Step := {major_mode, minor_mode};
```

Listing E.49 Resources of the model

```
memory := [0, 2048000];  //in bytes
power := [0, 1000000];   //in milliWatts
```
Listing E.50 Variables of the model (part 1)

//internal controller modes
Binary_Mode rev_limiting_mode := inactive;
Binary_Mode traction_mode := inactive;
Binary_Mode cruise_mode := inactive;
Mode controller_mode := off;
Control_Mode control_mode := sample;
Health_Status system_health := nominal;
Boolean startup_done := False;
Boolean shutdown_done := False;

//powertrain sensors
Integer[0, 120] vehicle_speed := 0; //mph
Integer[0, 8000] engine_speed := 0; //rpm
Integer[0, 250] vehicle_torque := 0; //kPa
Boolean fault := False; //is there a fault?

//driver inputs
Binary_Status ignition := off;
Binary_Status cruise_switch := off;
Integer[0, 45] pedal_angle := 0; //degrees
Gear_Status gear := park;
Binary_Mode break_pedal := inactive;

//constants
Const Integer MAX_ENGINE_SPEED := 6000; //rpm
Const Integer MAX_TORQUE := 110; //kPa
Const Integer MIN_CRUISE_SPEED := 30; //mph
Listing E.51 Variables of the model (part 2)

//controller inputs
Integer[0, 120] c_vehicle_speed := 0;  //rpm
Integer[0, 8000] c_engine_speed := 0;  //kPa
Integer[0, 250] c_vehicle_torque := 0;
Boolean c_fault := False;
Binary_Status c_ignition := off;
Binary_Status c_cruise_switch := off;
Integer[0, 45] c_pedal_angle := 0;  //degrees
Gear_Status c_gear := park;
Binary_Mode c_break_pedal := inactive;

//controller output
Desired_Current desired_current := none_c;

//simulation mode
Simulation_Mode driver_s := start_s;
Boolean vehicle_over_rev_s := False;
Boolean vehicle_over_tor_s := False;

//Task properties
Task_Status manager_s := released;
Task_Status monitor_s := released;
Task_Status servo_s := released;

//Constants
Const Integer MANAGER_PERIOD := 10;  //in ms
Const Integer MONITOR_PERIOD := 30;  //in ms
Const Integer SERVO_PERIOD := 3;  //in ms
Const Integer MAJOR_CYCLE := 30;  //in ms

//Scheduler
Scheduler scheduler_s := update_state;
Integer tick := 0;
Integer oldtick := 0;
Integer managertick := 0;
Integer monitor_tick := 0;
Integer servotick := 0;

//Extra variables for refinement
Manager_Step manager_s_step := major_mode;
E.3.2 Main Machines

Listing E.52 DRIVER main machine (part 1)

R1: Turn on the car
{
    if driver_s = begin_s and controller_mode = off and
        ignition = off then
        ignition := on;
        driver_s := drive_s;
}

R2: Start driving
{
    if driver_s = drive_s and controller_mode = driving and
        vehicle_speed = 0 and gear = park then
        gear := drive;
        pedal_angle := 22;
        vehicle_speed := 30;
        driver_s := random_s;
}

R3: Turn on cruise, slow speed
{
    if driver_s = random_s and cruise_switch = off then
        cruise_switch := on;
        vehicle_speed := 10;
}

R4: Turn on cruise, normal speed
{
    if driver_s = random_s and cruise_switch = off then
        cruise_switch := on;
        vehicle_speed := 30;
}

R5: Turn off cruise
{
    if driver_s = random_s and cruise_switch = on then
        cruise_switch := off;
}

R6: Press break pedal
{
    if driver_s = random_s and break_pedal = inactive then
        break_pedal := active;
Listing E.53 DRIVER main machine (part 2)

R7: Depress break pedal
{
    if driver_s = random_s and break_pedal = active then
        break_pedal := inactive;
}

R8: Stop
{
    if driver_s = random_s then
        gear := park;
        vehicle_speed := 0;
        ignition := off;
        driver_s := stop_s;
}

R9: Do nothing
{
    if driver_s = random_s then
        skip;
}

R10: Stopped
{
    if driver_s = stop_s then
        skip;
}

R11: Else
{
    else then
        skip;
}
Listing E.54 SCHEDULER main machine

R0: Step 0, update state
{}
    if scheduler_s = update_state then
        SAMPLE_STATE();
        scheduler_s := update_tasks;
    }

R1: Step 1, set status
{}
    if scheduler_s = update_tasks then
        UPDATE_TASK_STATUSES();
        scheduler_s := wakeup;
    }

R2: Step 2, wake up tasks
{}
    if scheduler_s = wakeup then
        WAKE_UP_TASKS();
        scheduler_s := execute;
    }

R3: Step 3, set executing
{}
    if scheduler_s = execute then
        SET_EXECUTING_TASK();
        scheduler_s := wait;
    }

R4: Wait for a tick
{}
    t := 1000;
    else then
        scheduler_s := update_state;
    }

493
Listing E.55 TASKS main machine

R11: Execute manager
{
    t := [0, 3];

    if manager_s = executing and manager_s_step = major_mode then
        SET_MAJOR_MODE();
        manager_s_step := minor_mode;
    }

R12: Execute manager
{
    t := [0, 2];

    if manager_s = executing and manager_s_step = minor_mode then
        SET_MINOR_MODE();
        manager_s_step := major_mode;
        manager_s := finished;
    }

R2: Execute monitor
{
    t := [100, 200];

    if monitor_s = executing then
        MONITOR_HEALTH();
        monitor_s := finished;
    }

R3: Execute servo
{
    t := [70, 100];

    if servo_s = executing then
        CALCULATE_OUTPUT();
        servo_s := finished;
    }

R4: Else, do nothing, wait for event
{
    t := next;

    else then
        skip;
}
Listing E.56 VEHICLE main machine (part 1)

R1: Randomly change, do nothing
{
    if driver_s = random_s and vehicle_over_rev_s = False and
        vehicle_over_tor_s = False then
        skip;
}

R2: Randomly change RPM
{
    if driver_s = random_s and vehicle_over_rev_s = False and
        vehicle_over_tor_s = False then
        engine_speed := MAX_ENGINESPEED + 1;
        vehicle_over_rev_s := True;
}

R3: Randomly change Traction
{
    if driver_s = random_s and vehicle_over_rev_s = False and
        vehicle_over_tor_s = False then
        vehicle_torque := MAX_TORQUE + 1;
        vehicle_over_tor_s := True;
}

R4: Randomly change Both
{
    if driver_s = random_s and vehicle_over_rev_s = False and
        vehicle_over_tor_s = False then
        engine_speed := MAX_ENGINESPEED + 1;
        vehicle_over_rev_s := True;
        vehicle_torque := MAX_TORQUE + 1;
        vehicle_over_tor_s := True;
}

R5: Randomly change RPM, correct
{
    if driver_s = random_s and vehicle_over_rev_s = True and
        vehicle_over_tor_s = False and desired_current = rev_c then
        engine_speed := MAX_ENGINESPEED;
        vehicle_over_rev_s := False;
}
Listing E.57 VEHICLE main machine (part 2)

R6: Randomly change traction, correct
{
    if driver_s = random_s and vehicle_over_rev_s = False and
        vehicle_over_tor_s = True and desired_current = traction_c then
        vehicle_torque := MAX_TORQUE;
        vehicle_over_tor_s := False;
}

R7: Randomly change both, correct
{
    if driver_s = random_s and vehicle_over_rev_s = True and
        vehicle_over_tor_s = True and desired_current = min_limiting_c then
        vehicle_torque := MAX_TORQUE;
        vehicle_over_tor_s := False;
        engine_speed := MAX_ENGINE_SPEED;
        vehicle_over_rev_s := False;
}

R8: Randomly put in a fault
{
    if driver_s = random_s and fault = False then
        fault := True;
}

R9: Else
{
    else then
        skip;
}
E.3.3 Function Machines

Listing E.58 Cruise_Throttle_C function machine
R1: Always
{
    memory := 128;
    power := 800;
    if True then
        out := cruise_c;
}

Listing E.59 Driver_Throttle_C function machine
R1: Always
{
    memory := [196, 360];
    power := [769, 895];
    if True then
        out := human_c;
}

Listing E.60 Driving_Throttle_C function machine
R1: Cruise enabled, driver input
{
    memory := [324, 826];
    power := [864, 1695];
    if cruise_mode = active and c_pedal_angle != 0 then
        out := max_driving_c;
}

R2: Cruise enabled, no driver input
{
    if cruise_mode = active and c_pedal_angle = 0 then
        out := Cruise_Throttle_C();
}

R3: Else
{
    else then
        out := Driver_Throttle_C();
}
Listing E.61 Limiting.Throttle_C function machine

R1: Both //if both over rev and over torque are active
{
    memory := 648;
    power := 1425;

    if rev_limiting_mode = active and traction_mode = active then
        out := min_limiting_c;
}

R2: Over_Rev //if only over rev is active
{
    if rev_limiting_mode = active and traction_mode = inactive then
        out := Over_Rev_Throttle_C();
}

R3: Over_Torque //if only over torque is active
{
    if rev_limiting_mode = inactive and traction_mode = active then
        out := Over_Torque_Throttle_C();
}

R4: Else //both are inactive. This should never happen!
{
    else then
        out := error_c;
}

Listing E.62 Over_Rev.Throttle_C function machine

R1: Always
{
    memory := 256;
    power := 1200;

    if True then
        out := rev_c;
}

Listing E.63 Over_Torque.Throttle_C function machine

R1: Always
{
    memory := 256;
    power := 1200;

    if True then
        out := traction_c;
}
Listing E.64 DO_SHUTDOWN sub machine

R1: Do shutdown only when vehicle is stationary
{
    memory := 256;
    power := 900;

    if c_vehicle_speed = 0
        and c_gear = park
        and ignition = off then
        desired_current := none_c;
        shutdown_done := True;
}

R2: No shutdown
{
    else then
        desired_current := none_c;
        shutdown_done := False;
}

Listing E.65 DO_STARTUP sub machine

R1: Do startup only when vehicle is stationary
{
    memory := 128;
    power := 900;

    if c_vehicle_speed = 0 and c_gear = park and
        c_break_pedal = active and c_cruise_switch = off then
        desired_current := none_c;
        startup_done := True;
}

R2: No startup
{
    else then
        desired_current := none_c;
        startup_done := False;
}
Listing E.66 HANDLE_FAULT sub machine

R1: Handle the fault
{
    memory := 512;
    power := 895;

    if c_vehicle_speed = 0 and c_gear = park then
        desired_current := none_c;
        controller_mode := shutdown;
        fault := False;
        c_fault := False;
    }

R2: Else
{
    memory := 512;
    power := 895;

    else then
        desired_current := fault_c;
    }

Listing E.67 MONITOR_HEALTH sub machine

R1: Find Fault
{
    memory := [512, 1024];
    power := [1530, 1624];

    if Fault() then
        system_health := fault_detected;
    }

R2: Else do nothing
{
    memory := [512, 1024];
    power := [1530, 1624];

    else then
        system_health := nominal;
    }
Appendix F

Timeliner Plant Control System

TASM Model

This appendix gives all of the listings for the Timeliner plant control system TASM model. The plant control system case study is described in details in [238]. In the context of the TASM language, the case study is described in Section 2.8.3. The TASM models are explained and are analyzed in details in Section 8.5. The complete TASM model contains 5 main machines, no function machines, and 7 sub machines. The machines are listed in Table F.1.
<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Purpose</th>
<th>Listing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types</td>
<td>N/A</td>
<td>List of types</td>
<td>Listing F.1</td>
</tr>
<tr>
<td>Variables</td>
<td>N/A</td>
<td>List of variables</td>
<td>Listing F.2</td>
</tr>
<tr>
<td>Control_Task</td>
<td>Main</td>
<td>Shares the processor with Timeliner</td>
<td>Listing F.3</td>
</tr>
<tr>
<td>Scheduler</td>
<td>Main</td>
<td>Switches processor between the control task and Timeliner</td>
<td>Listing F.4</td>
</tr>
<tr>
<td>Timeliner</td>
<td>Main</td>
<td>Executes plant control sequences</td>
<td>Listing F.5</td>
</tr>
<tr>
<td>Temperature</td>
<td>Main</td>
<td>Simulates the behavior of the cabin temperature</td>
<td>Listing F.6</td>
</tr>
<tr>
<td>Humidity</td>
<td>Main</td>
<td>Simulates the behavior of the cabin humidity</td>
<td>Listing F.7</td>
</tr>
<tr>
<td>EXECUTE_BUNDLES</td>
<td>Sub</td>
<td>Executes all active bundles</td>
<td>Listing F.8</td>
</tr>
<tr>
<td>PLANTSIM_BUNDLE</td>
<td>Sub</td>
<td>Execute the plantsim bundle</td>
<td>Listing F.9</td>
</tr>
<tr>
<td>EXECUTE_PLANTSIM</td>
<td>Sub</td>
<td>Execute the sequences in the plantsim bundle</td>
<td>Listing F.10</td>
</tr>
<tr>
<td><em>SEQUENCES</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEQUENCE_TEMP</td>
<td>Sub</td>
<td>Execute the temperature monitor sequence</td>
<td>Listing F.11</td>
</tr>
<tr>
<td><em>MONITOR</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEQUENCE_TEMP</td>
<td>Sub</td>
<td>Maintains the temperature between 19 and 26 Celsius degrees</td>
<td>Listing F.12, F.13</td>
</tr>
<tr>
<td><em>MONITOR_WORK</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEQUENCE_HUMIDITY</td>
<td>Sub</td>
<td>Execute the humidity monitor sequence</td>
<td>Listing F.14</td>
</tr>
<tr>
<td><em>MONITOR</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEQUENCE_HUMIDITY</td>
<td>Sub</td>
<td>Maintains the humidity between 40 and 60 percent</td>
<td>Listing F.15, F.16</td>
</tr>
<tr>
<td><em>MONITOR_WORK</em></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table F.1: List of machines used in the Timeliner plant control system model
### F.1 Environment

Listing F.1 User-defined types of the model

<table>
<thead>
<tr>
<th>Type</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status</td>
<td>:= {active, inactive};</td>
</tr>
<tr>
<td>Device</td>
<td>:= {on, off};</td>
</tr>
<tr>
<td>Temp_Sequence_Block</td>
<td>:= {b0, b1, b2, b3, b4};</td>
</tr>
<tr>
<td>Humid_Sequence_Block</td>
<td>:= {c0, c1, c2, c3, c4, c5};</td>
</tr>
<tr>
<td>Processor_Status</td>
<td>:= {timeliner, controltask};</td>
</tr>
<tr>
<td>Execution_Status</td>
<td>:= {done, not_done};</td>
</tr>
<tr>
<td>Bundle</td>
<td>:= {plantsim};</td>
</tr>
<tr>
<td>Sequence</td>
<td>:= {temp_monitor, humid_monitor};</td>
</tr>
</tbody>
</table>
Listing F.2 Variables of the model

//Bundle Status
Status plantsim_bundle_status := active;

//Sequence Statuses
Status temp_seq_status := active;
Status humid_seq_status := active;

//Sequence Blocks
Temp_Sequence_Block temp_seq_b := b0;
Humid_Sequence_Block humid_seq_b := c0;

//Bundle Execution Status
Execution_Status plantsim_s := not_done;

//Sequence Execution Statuses
Execution_Status temp_seq_s := not_done;
Execution_Status humid_seq_s := not_done;

//Sequences
Bundle exec_bundle := plantsim;
Sequence exec_seq := temp_monitor;

//Plant Variables
Boolean trying_to_cool_system := False;
Integer temperature := 24;
Integer humidity := 50;

//Devices
Device cooling := off;
Device heating := off;
Device humidifier := off;

//Control Variables
Processor_Status processor := controltask;
Execution_Status execution := not_done;

//Fault control
Boolean fault := False;
F.2 Main Machines

Listing F.3 Rules of the Control_Task main machine
R1: Control Task
{
    t := [3500, 5000];

    if processor = controltask and execution = not_done then
        execution := done;
}

R2: Else
{
    t := next;

    else then
        skip;
}

Listing F.4 Rules of the Scheduler main machine
R1: Controller
{
    t := 1000;

    if processor = controltask and execution = done then
        processor := timeliner;
        execution := not_done;
}

R2: Timeliner
{
    t := 1000;

    if processor = timeliner and execution = done then
        processor := controltask;
        execution := not_done;
}

R3: Else
{
    t := next;

    else then
        skip;
}
Listing F.5 Rules of the Timeliner main machine

R1: Execute bundles
{
    if processor = timeliner and execution = not_done then
        EXECUTE_BUNDLES();
}

R2: Else
{
    t := next;
    else then
        skip;
}
Listing F.6 Rules of the Temperature main machine

R1:
{  
t := 685;
  if temperature > 19 and temperature < 26 and
    cooling = off and heating = off and humidifier = off then
    skip;
}

R2:
{  
t := 685;
  if temperature > 19 and temperature < 26 and
    cooling = off and heating = off and humidifier = off then
    temperature := 18;
}

R3:
{  
t := 685;
  if temperature > 19 and temperature < 26 and
    cooling = off and heating = off and humidifier = off then
    temperature := 27;
}

R4: Cooling on
{  
t := [0, 1500];
  if temperature > 25 cooling = on and heating = off then
    temperature := 24;
}

R5: Heating on
{  
t := [0, 1500];
  if temperature < 20 and heating = on and cooling = off then
    temperature := 24;
}

R6: Else
{  
t := next;
  else then
    skip;
}
Listing F.7 Rules of the Humidity main machine

R1:
{ 
  t := 685;

  if humidity > 39 and humidity < 61 and
    cooling = off and heating = off and humidifier = off then
    skip;
}

R2:
{ 
  t := 685;

  if humidity > 39 and humidity < 61 and
    cooling = off and heating = off and humidifier = off then
    temperature := 35;
}

R3:
{ 
  t := 685;

  if humidity > 39 and humidity < 61 and
    cooling = off and heating = off and humidifier = off then
    temperature := 65;
}

R4: Cooling on
{ 
  t := [0, 1500];

  if humidity > 60 and cooling = on and humidifier = off then
    humidity := 50;
}

R5: Humidifier on
{ 
  t := [0, 1500];

  if humidity < 40 and humidifier = on and cooling = off then
    humidity := 50;
}

R6: Else
{ 
  t := next;

  else then
    skip;
}
F.3 Function Machines

The plant control system does not contain function machines

F.4 Sub Machines

Listing F.8 Rules of the EXECUTE_BUNDLES sub machine

R1: Execute plantsim
{
    if exec_bundle = plantsim and plantsim_s != done then
        PLANTSIM_BUNDLE();
}

R2: Pass is done
{
    if exec_bundle = plantsim and plantsim_s = done then
        plantsim_s := not_done;
        exec_bundle := plantsim;
        execution := done;
}

Listing F.9 Rules of the PLANTSIM_BUNDLE sub machine

R1: Bundle Active
{
    if plantsim_bundle_status = active then
        EXECUTE_PLANTSIM_SEQUENCES();
}

R2: Bundle Inactive
{
    if plantsim_bundle_status = inactive then
        plantsim_s := done;
}
Listing F.10 Rules of the EXECUTE_PLANTSIM_SEQUENCES sub machine

R1: Exec Temp Seq
{ if exec_seq = temp_monitor and temp_seq_s = not_done then
   SEQUENCE_TEMP_MONITOR();
}

R2: Switch Seq
{ if exec_seq = temp_monitor and temp_seq_s = done then
   exec_seq := humid_monitor;
   humid_seq_s := not_done;
}

R3: Exec Humid Seq
{ if exec_seq = humid_monitor and humid_seq_s = not_done then
   SEQUENCE_HUMIDITY_MONITOR();
}

R4: Bundle finished
{ if exec_seq = humid_monitor and humid_seq_s = done then
   plantsim_s := done;
   exec_seq := temp_monitor;
   temp_seq_s := not_done;
}

Listing F.11 Rules of the SEQUENCE_TEMP_MONITOR sub machine

R1: Sequence Active
{ if temp_seq_status = active then
   SEQUENCE_TEMP_MONITOR_WORK();
}

R2: Sequence Inactive
{ if temp_seq_status = inactive then
   temp_seq_s := done;
}
Listing F.12  Rules of the SEQUENCE_TEMP_MONITOR_WORK sub machine
(part 1)

R1: b0 -> b1
{ t := 685;

  if temp_seq_b = b0 then
  temp_seq_b := b1;
}

R2: b1 -> b2
{ t := 2285;

  if temp_seq_b = b1 and temperature >= 26 then
  temp_seq_b := b2;
  trying_to_cool_system := True;
  cooling := on;
}

R3: b1 -> b3
{ t := 1730;

  if temp_seq_b = b1 and temperature < 26 then
  temp_seq_b := b3;
}

R4: b2 -> b2
{ t := 1625;

  if temp_seq_b = b2 and temperature > 22 then
  temp_seq_b := b2;
  temp_seq_s := done;
}
Listing F.13 Rules of the SEQUENCE_TEMP_MONITOR_WORK sub machine (part 2)

R5: b2 -> b3
{
    t := 1730;
    if temp_seq_b = b2 and temperature <= 22 then
        temp_seq_b := b3;
        trying_to_cool_system := False;
        cooling := off;
}

R6: b3 -> b0
{
    t := 1950;
    if temp_seq_b = b3 and temperature > 19 then
        temp_seq_b := b0;
        temp_seq_s := done;
}

R7: b3 -> b4
{
    t := 2390;
    if temp_seq_b = b3 and temperature <= 19 then
        temp_seq_b := b4;
        heating := on;
}

R8: b4 -> b4
{
    t := 1630;
    if temp_seq_b = b4 and temperature < 22 then
        temp_seq_b := b4;
        temp_seq_s := done;
}

R9: b4 -> b0
{
    t := 3195;
    if temp_seq_b = b4 and temperature >= 22 then
        temp_seq_b := b0;
        heating := off;
        temp_seq_s := done;
}
Listing F.14 Rules of the SEQUENCE_HUMIDITY_MONITOR sub machine

R1: Sequence Active
{
    if humid_seq_status = active then
        SEQUENCE_HUMIDITY_MONITOR_WORK();
}

R2: Sequence Inactive
{
    if humid_seq_status = inactive then
        humid_seq_s := done;
}
Listing F.15 Rules of the SEQUENCE_HUMIDITY_MONITOR_WORK sub machine (part 1)

R1: c0 -> c1
{ t := 685;
    if humid_seq_b = c0 then
        humid_seq_b := c1;
}

R2: c1 -> c2
{ t := 2395;
    if humid_seq_b = c1 and humidity >= 61 then
        humid_seq_b := c2;
        cooling := on;
}

R3: c1 -> c4
{ t := 1730;
    if humid_seq_b = c1 and humidity < 61 then
        humid_seq_b := c4;
}

R4: c2 -> c2
{ t := 1625;
    if humid_seq_b = c2 and humidity > 50 then
        humid_seq_b := c2;
        humid_seq_s := done;
}

R5: c2 -> c3
{ t := 1625;
    if humid_seq_b = c2 and humidity <= 50 then
        humid_seq_b := c3;
}

R6: c3 -> c4
{ t := 2160;
    if humid_seq_b = c3 and trying_to_cool_system = False then
        humid_seq_b := c4;
        cooling := off;
}
Listing F.16 Rules of the SEQUENCE_HUMIDITY_MONITOR_WORK sub machine (part 2)

R7: c3 -> c4
{ t := 1265;
  if humid_seq_b = c3 and trying_to_cool_system = True then
    humid_seq_b := c4;
}

R8: c4 -> c5
{ t := 2390;
  if humid_seq_b = c4 and humidity <= 39 then
    humidifier := on;
    humid_seq_b := c5;
}

R9: c4 -> c0
{ t := 1950;
  if humid_seq_b = c4 and humidity > 39 then
    humid_seq_b := c0;
    humid_seq_s := done;
}

R10: c5 -> c5
{ t := 1630;
  if humid_seq_b = c5 and humidity < 50 then
    humid_seq_b := c5;
    humid_seq_s := done;
}

R11: c5 -> c0
{ t := 3195;
  if humid_seq_b = c5 and humidity >= 50 then
    humid_seq_b := c0;
    humid_seq_s := done;
    humidifier := off;
}
Bibliography


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