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Contract-Based Verification of Model Transformations: A Formally Founded Approach

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ABSTRACT
In safety-critical applications, using a Model-Driven Engineering (MDE) approach requires a high-level of trust in its underlying model transformations, i.e. the latter’s correctness should be verified formally. Yet, the applicability of formal methods to transformations correctness remains limited due to the absence of formal foundations of popular MDE languages and frameworks such as AADL and SysML. In this paper, we propose a formally founded environment to verify model transformations in MDE. First, we define a transformation in a formal way: this involves formalizing input and output models at some level of abstraction, as well as the transformation rules. Then, we build a verification environment, formalized as a transition system (TS), by extending the transformation with contracts. Finally, we formulate and verify some correctness properties which we reduce, based on the previous steps, to reachability properties over the TS. We show how our approach can be implemented in Ocarina, an open-source transformation tool for AADL, and how it applies, for example, to build correct transformations from AADL models to their Cheddar ADL counterpart.

KEYWORDS
model-driven engineering, model transformation, formal methods

1 INTRODUCTION
Designing, developing and implementing complex systems can be eased by Model-Driven Engineering (MDE) approaches in which model transformations play a prominent role [30]. A transformation operates on an input model to produce an output model. Moreover, a transformation has an intent [20], typically enabling some activity on the output model that is unfeasible on the input model (e.g. transforming an AADL [11] model into Petri nets enables model checking on the latter). In safety-critical applications, model transformation correctness is a key property.

Model transformation correctness englobes a large number of properties the relevance of which vary according to the application at hand [23, 24]. In this paper, we propose a focus on two correctness properties. First, the input model must be “transformable” w.r.t the transformation intent (prop1). As an example of prop1, if the intent of the transformation is to carry out real-time analysis, a given input model must allow to produce an output model exempt from anomalies such as a periodic task with no period specified. Second, the output model must be “equivalent” to the input model (prop2). An example of prop2 is an input model in UML and an output model in Java where the latter contains all the classes specified in the former.

Once defined, correctness properties must be verified in a rigorous manner, i.e. through integrating formal methods in MDE.

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(Section 6), compare it to related work (Section 7) and conclude with possible directions for future work in Section 8.

2 PRELIMINARIES

For illustration in this paper, we focus on AADL2Cheddar, the transformation from AADL (Section 2.1) to Cheddar ADL (Section 2.2). We consider a subset of AADL and Cheddar where we keep only the entities/mechanisms that are necessary for AADL2Cheddar.

2.1 AADL

AADL (Architecture Analysis and Design Language) is a standardized architecture description language for the modeling, analysis, and code generation of real-time, embedded and concurrent computer systems [11]. An AADL model describes the architecture of a system with components. Components can describe software or hardware entities that can be hierarchically assembled to build complex systems describing possible links between their building components. In addition, properties can be defined for components. Let us review these elements in greater detail.

Components. Software components may encapsulate components called processes, each process describing a part of the program being executed and encapsulating itself (sub)components: threads of execution and possibly data structures. Hardware components, on the other hand, include components known as memories and processor's specifying physical storage and execution resources. Physical memory components do not intervene in AADL2Cheddar and are therefore discarded. Figure 1 shows a simple AADL example of a system component s1 which is built from:

- software: with one process p1, encapsulating two threads of execution (th1, th2) and one data structure (d1),
- hardware: represented by one processor component pr1.

AADL allows to describe a system that includes several processes and processors, e.g. to represent multiprocessor systems. The composition of systems is also possible, e.g. to describe interconnected systems. However, since AADL2Cheddar applies to one system at a time, we restrict an AADL model to only one system, which can still have any number of processes and processors.

A component declaration is textual and includes features and properties, as we can see in the declaration of the thread th1 in Listing 1. Features provide the interface of a component, thus allowing to link components, while properties define the characteristics of a component. More explanation below.

Links. A link can be either a connection or a binding (both connections and bindings are optional).

Connections represent logical flows (e.g. event and/or data) between components through their features. The access feature is reserved to link threads with data. For instance, in Figure 1, both threads th1 and th2 are connected to the data structure d1 within the process p1 (solid-line links): the connection between th1 and the data d1 occurs via the feature d1_access of th1 specified in Listing 1 (line 5). A component may be involved in any number of connections. Since only access connections are relevant to AADL2Cheddar, we restrict connections in AADL to only access connections, to which we may thus refer simply as connections. Also, in the context of AADL2Cheddar, connections are intra-process only, i.e. between threads and data of the same process.

Bindings, on the other hand, link software to hardware components. For example, in Figure 1, process p1 is bound to processor pr1 which means that p1 is to be executed on pr1. AADL bindings are compatible with partitioned scheduling: a process can be bound to only one processor whereas a processor can be bound to several processes (i.e. may execute several processes).

Properties. The description of a system is completed with properties (optional). For example, the properties of th1 in Listing 1 provide timing information about the thread. A Periodic Dispatch_Protocol (line 7) means that the thread jobs occur on a regular basis, with a constant interval of time between jobs called the Period (line 9) and possibly a Dispatch_Offset (line 8) from the time origin, and a job duration is within a time interval called Compute_Execution_Time (line 10). A temporal constraint may be specified for the thread as a Deadline which is the time by which the thread must be completed (line 11). We see in Listing 1 that properties are typed: Dispatch_Protocol must be within an enumeration of Supported_Dispatch_Protocols, Period has a time value that is an aadlinieger plus a time unit (which itself may be defined from the base picosecond (ps) time unit, e.g. us => ps * 1000000), Compute_Execution_Time must be of “range of time” value, etc. Since timing constraints are – naturally – positive, we restrict the use of aadlinieger to naturals when describing time.

2.2 Cheddar ADL

Cheddar ADL is the modeling language of the Cheddar tool [31]. In the remainder of this paper, we refer to Cheddar ADL simply as Cheddar and use “Cheddar tool” to describe its underlying analysis tool. Cheddar allows to describe a “real-time task model” [6] on which schedulability analysis can be performed. A Cheddar model is “flat” (no hierarchies) and is made of entities, links and parameters, which we represent using a class diagram (Figure 2). As for AADL,
we consider in this paper a subset of Cheddar including all the elements needed for AADL2Cheddar.

Entities and links. Entities and links form a real-time application. The latter is made of:
- a number of tasks executing on execution unit(s), and possibly sharing some resources,
- a number of address spaces for tasks and resources.

A real-time task is the basic entity of a real-time application. It represents a set of program instructions to be executed by execution unit(s). In this model, an execution unit is an abstraction of both the hardware required to execute the tasks (i.e. the central processing unit, CPU) and the software needed to build an execution order of the tasks (i.e. the scheduler). In addition, tasks can optionally share resources such as shared memories. Address spaces are virtual memory spaces allocated to tasks and resources.

Links define relations between entities, e.g. execution unit(s) to which a task is statically allocated (affinity). The cardinalities of associations in Figure 2 reflect restrictions on links, e.g. a task/resource cannot be allocated to more than one address space.

Figure 2: Elements of a real-time application in Cheddar.

Parameters. Entities of a real-time application can (optionally) have various parameters:
- task parameters: a constant interval of time between task jobs called the period according to the task type, a capacity (or worst-case execution time) for a task job, an offset that is an amount of time to the first release of the task, and a deadline to be respected,
- execution unit parameters: a scheduling policy that dynamically assigns tasks to execution units as the execution goes (within the allowed static affinity, defined by links between tasks and execution units as explained above),
- resource parameters: a sharing protocol to manage concurrent access to the shared resources between tasks.

Parameters are defined with usual types available in programming languages, e.g. unsigned integers for time-related parameters and enumerations for available task types, scheduling policies and sharing protocols.

3 AADL2CHEDDAR FORMALIZATION

The first step of our approach consists in formalizing the transformation (in this case, AADL2Cheddar). Thus, we formalize, at some level of abstraction, both the input and output model: AADL (Section 3.2) and Cheddar (Section 3.3), described informally in Section 2. Then, we present and formalize AADL2Cheddar: we define its rules and develop its formal semantics (Section 3.4). Before we get into the details, we first introduce some basic definitions and notations which we will use throughout the rest of this paper.

3.1 Basic definitions and notations

We first remind the notions of binary relations, partial functions and functions (Section 3.1.1), then provide definitions (simplified from [26]) of Transition Systems (Section 3.1.2) and Transition Diagrams (Section 3.1.3).

3.1.1 Relations and functions. A binary relation $R \subseteq X \times Y$ is a set of ordered pairs $(x, y) \in Y$. $R$ is called a partial function if it satisfies the following:

\[ \forall x \in X, \forall y \in Y : (x, y) \in R \land (x, y') \in R \implies y = y'. \]

That is, a partial function is a special type of binary relation that maps each element of $X$ to at most one element of $Y$, we may then write $R : X \Rightarrow Y$. $X$ (resp. $Y$) is the domain (resp. codomain) of $R$, and $y \in Y$ is the image of $x \in X$ iff $(x, y) \in R$. A partial function does not require that each element in $X$ has an image in $Y$. $X \subseteq X$, the domain of definition of $R$, is the largest subset of $X$ each element of which has an image in $Y$ through $R$, that is: $\forall x \in X \exists y \in Y$ s.t. $(x, y) \in R$ and $\forall x \in X \exists! y \in Y$ s.t. $(x, y) \in R$. We say that $R$ is defined over $X_0$ and undefined over $X_0$. We use the standard computer science notion $R(x) \downarrow$ (resp. $R(x) \uparrow$) to denote that $R$ is undefined (resp. defined) at $x \in X$.

A partial function $R$ is called a function iff $X_0 = X$, i.e. a function is a special type of partial function that is defined over all elements of its domain $X$. We may then write $R : X \Rightarrow Y$.

3.1.2 Transition systems.

Syntax. A transition system (TS) is a tuple $TS = (U, Q, q_0, \rightarrow)$ where $U = U_{ro} \cup U_{rw}$ is a finite set of read-only ($U_{ro}$) and read-write ($U_{rw}$) variables; $Q$ a set of states, each state $q \in Q$ provides an interpretation $q(u)$ of each $u \in U$; $q_0 \in Q$ the initial state that maps each variable $u \in U$ to its initial value $v_0$ (each read-only variable $u \in U_{ro}$ satisfies $q(u) = q_0(u) = v_0$ for all $q \in Q$); and $\rightarrow$ a set of transitions where each transition $t \in \rightarrow$ is a binary relation that maps every state $q \in Q$ to a (possibly empty) set of successors $t(q) \subseteq Q$ (we write $q \xrightarrow{t} q'$ iff $q' \in t(q)$).

Semantics. A TS evolves through taking enabled transitions. A transition $t \in \rightarrow$ is enabled iff the TS is at state $q$ and $t(q) \neq \emptyset$. After taking $t$, the TS reaches a state $q' \in t(q)$. We may thus define the set of reachable states $Q_r \subseteq Q$ s.t. state $q$ is reachable, i.e. $q \in Q_r$, iff there exists a (possibly empty) sequence of transitions $seq$ such that $q_0 \xrightarrow{seq} q$.

3.1.3 Transition Diagram.

Syntax. We define a graphical notation for a TS, called a Transition Diagram (TD). A TD is a finite directed graph with $V$ its set of vertices and $E$ its set of edges. TD operates on $X = X_{ro} \cup X_{rw}$, a finite set of variables that may be read-only (in $X_{ro}$) or read-write (in $X_{rw}$). The vertex $v_0$ in $V$ is the unique initial vertex of the TD. If $e$ connects vertex $v_a$ to vertex $v_b$, then we may write $v_a \xrightarrow{e(v_a, v_b)} v_b$.
where (i) \( g_e \) is a Boolean expression over \( X \) and (ii) \( op_e \) an atomic sequence of operations over variables in \( X \) (read-only over \( X_{in} \)).

**Semantics.** Let \( q(g) \) denote the truth value of guard \( g \) at state \( q \), and \( q'_y = op(q'_y) \) denote that the valuation of each variable \( y \in Y \) at state \( q' \) agrees with the result of \( op \) over \( y \) from state \( q \). The semantics of a TD is then given by the TS \( (U, Q, q_0, \rightarrow) \) (Section 3.1.2) where:

- \( U = X \cup \{ \pi \} \) s.t. \( \pi \) holds the current vertex of the TD,
- Each state \( q \in Q \) is an interpretation of variables in \( X \cup \{ \pi \} \),
- \( q_0 \) maps \( \pi \) to \( v_0 \) and each variable in \( X \) to its initial value,
- \( \rightarrow \) results from mapping each edge \( e \in E \) to a transition \( t_e \) in

\[ q' \in t_e(q) \iff \begin{cases} (1) & (q(\pi) = v_\pi) \land (q'(\pi) = v_\pi) \land \\ (2) & (q'_x = op_x(q'_x)) \end{cases} \]

### 3.2 AADL

We define an AADL model compositionally, from the process up to the model, while formalizing the description given in Section 2.1.

**Definition 1.** Process. A process is a tuple \( p = (Th, D, C) \) where \( Th = \{th_1, \ldots, th_{|Th|}\} \) is a set of threads; \( D = \{d_1, \ldots, d_{|D|}\} \) a set of data; and \( C \subseteq Th \times D \) a binary relation representing connections from threads to data.

As explained in Section 2.1, a process is made up of two sets: threads and data. \( C \) is the set of connections within a process, defined here as a binary relation (Section 3.1.1) to make it possible for a thread to access several data and, conversely, data to be accessed by several threads, as allowed in AADL (Section 2.1). Note how process (sub)components (threads and data) features do not appear in our definition. Indeed, features are mainly introduced to define the “type” of interface through which connections are made. Since only access connections are considered (Section 2.1), features become superfluous and are consequently abstracted away.

**Definition 2.** System. A system is a tuple \( s = (P, Pr, PB) \) where \( P = \{p_1, \ldots, p_{|P|}\} \) is a set of processes (Definition 1); \( Pr = \{pr_1, \ldots, pr_{|Pr|}\} \) a set of processors; and \( PB : P \rightarrow Pr \) a partial function representing processes bindings to processors.

Thus, the system is built from processes tied to hardware elements, that is processors. Defining \( PB \) as a partial function is deliberate, as it is neither restrictive nor permissive w.r.t AADL. Indeed, since \( PB \) enjoys the properties of partial functions (Section 3.1.1), (i) a process in \( P \) may not bind to more than one processor and (ii) creating a binding for a given process is optional, which agrees with the AADL restrictions and permissions (Section 2.1). Therefore, in a given AADL system, the domain of \( PB \) is \( P \) while its domain of definition is the largest subset of \( P \) all the elements (processes) of which are bound to processors.

**Flattening a system.** In order to have a direct access to sets of components at a lower level (i.e. at the process level), we define a flat AADL system. This “raw” flat representation is only provided to ease the definition of AADL properties and AADL2Cheddar transformation rules later in this section: it does not replace our original definition (Definition 2) which reflects the real architecture of an AADL system.

To atomize the system, we adopt a generic notation following a downward propagation of indices: subscript \( i \) of each process \( p_i \) in the processes set \( P \) (Definition 2) is propagated as a superscript to each tuple element of \( p_i \) (Definition 1), e.g. \( Th^i = \{th^i_1, \ldots, th^i_{|Th|}\} \) is the set of threads in the \( i \)-th process of \( P \), the set of processes in \( s \). We obtain consequently \( T'H = \bigcup_{i \in [1..|P|]} Th^i \), the set of all threads (in all processes) in the system, \( D = \bigcup_{i \in [1..|P|]} D^i \), the set of all data (in all processes) in the system, and \( C = \bigcup_{i \in [1..|P|]} C^i \), the set of all connections between threads and data (in all processes) in the system. We may then define the flat system by redefining \( P \) (Definition 2), as the set of sets of all threads, data and connections in all processes, that is \( P = \{T'H, D, C\} \).

**Definition 3.** Model. An AADL model is a tuple \( ma = (s, Prop) \) where \( s \) is a system (Definition 2) and \( Prop \) a set of properties.

A property in \( Prop \) is a partial function with some domain \( X \) of components or subcomponents of \( s \), i.e. \( X \) can be taken directly from the flat representation of \( s \) (e.g. the domain of any thread property is \( T'H \), of any processor property is \( Pr \), etc.). The codomain \( Y \) varies depending on the property.

Let us exemplify with thread properties. To simplify notations, we assume that time values are uniformized to the smallest time unit, which permits rewriting them in \( \mathbb{N} \) (e.g. in Listing 1, all values given in period, dispatch_offset, compute_execution_time and deadline are transformed to the \( \mu s \) scale). Thus, the codomain is \( \mathbb{N} \) for the period property (that is period : \( T'H \rightarrow \mathbb{N} \)), but also for dispatch_offset and deadline. For dispatch_protocol, the codomain is the set \( DP = \{aperiodic, sporadic, periodic\} \), formalizing the Supported_Dispatch_Protocols enumeration (Section 2.1). Finally, compute_execution_time associates a thread to an interval delimited by a minimum and a maximum execution time (example in Listing 1, Section 2.1). Its codomain is thus \( \mathbb{I} \), the set of closed intervals of positive reals with natural bounds, which we may define formally: \( \mathbb{I} = \{[a, b] | a, b \in \mathbb{N} \land a \leq b\} \) with \( [a, b] = \{x \in \mathbb{R}_{\geq 0} | a \leq x \leq b\} \). We may give examples of other components properties. For instance, concurrency_protocol has \( D \) (the set of all data) as a domain and \( CP = \{Maximum_Priority, Priority_Ceiling, Spin_Lock, Priority_Inheritance, Protected_Access\} \), the enumeration of supported concurrency protocols, as a codomain.

The rationale of formalizing properties as partial functions is similar to the one used in bindings: on one hand, a component cannot have two values for the same property (e.g. a thread cannot be periodic and sporadic at the same time) and, on the other hand, AADL properties are optional (the user may choose not to define e.g. the period of a sporadic thread). Similarly to bindings, the domain of definition of a property is the largest subset of its domain for which the property is defined (e.g. for the deadline property, the largest set in \( T'H \) where a deadline is provided for each thread).

### 3.3 Cheddar

To formalize a Cheddar model, we adopt a similar strategy to the one used for AADL. The real-time application firstly describes the entities in Figure 2 (Section 2.2) and their relationships. Then, parameters are defined at the model level.

**Definition 4.** Real-time application. A real-time application is a tuple \( \sigma = (T, EU, Re, AS, D) \) where \( T = \{t_1, \ldots, t_{|T|}\} \) is a set of tasks; \( EU = \{eu_1, \ldots, eu_{|EU|}\} \) a set of execution units;
Re = \{r_1, \ldots, r_{|R|}\} a set of resources; AS = \{as_1, \ldots, as_{|AS|}\} a set of address spaces; and L defined as follows. L = \{TE, TR, TA, RA\} is a set of binary relations TE \subseteq T \times EU and TR \subseteq T \times Re and partial functions TA : T \mapsto AS and RA : Re \mapsto AS for links between, respectively, tasks and execution units, tasks and resources, tasks and address spaces and resources and address spaces.

Thus, the entities of Cheddar and their links appearing in Figure 2 (Section 2.2) are described as a tuple. In the latter, L, representing all links, contains four relations to reflect the associations in Figure 2 and their cardinalities. In particular, TA and RA are defined as partial functions since no task (resp. resource) can be linked to more than one address space.

Definition 5. Cheddar model. A Cheddar model is a tuple mc = (σ, Param) were σ is a real time application (Definition 4) and Param a set of parameters.

Parameters in Param are defined as partial functions over entities of σ (codomains vary depending on the parameter). For instance, offset, period, capacity and deadline have the same domain T (the set of all tasks) and the same codomain N. As another example, parameter sharing_protocol maps resource domain Re to access protocols in the set AP = \{First_In_First_Out, Priority_Ceiling_PROTOCOL, Priority_Inheritance_PROTOCOL\}.

The rationale of using partial functions is the same as in AADL properties (Section 3.2), and the domain of definition of a parameter is the largest subset of its domain such that the parameter is defined for all elements (e.g. the domain of definition of period is the largest subset of T where a period has been provided for each task).

3.4 AADL2Cheddar

Now that we have formalized AADL and Cheddar models, we may define AADL2Cheddar formally: we develop its formal semantics involving an input AADL model, an output Cheddar model and a number of rules. We start by formally defining the latter.

3.4.1 Rules. In the following definition (and the remainder of this paper henceforth), we use the set membership symbol \(\in\) for tuple memberships as well\(^1\).

Definition 6. Rule. A transformation rule R : X \mapsto Y is a function with X \in ma its domain, an element of the AADL model and Y \in mc its codomain, an element of the Cheddar model.

A rule is defined as a function because, intuitively, describing a transformation rule implies (i) a unique mapping of input elements and (ii) an "all" quantifier, for instance "transform all threads into tasks" (see rule R₃ in Table 1). That is, a rule is defined over all its domain of which each element has exclusively one image, which coincides with the definition of a function (Section 3.1.1). To compute the image of an element, a rule R may need to read the elements of another rule R′, that is pairs \((x, R′(x))\) \in R′, which creates a rule dependency (examples in Section 3.4.2).

In total, the AADL2Cheddar transformation includes nine transformation rules, which are enumerated in Table 1 with their domains, codomains and a brief informal explanation (examples on what each rule does are given in Section 3.4.2). To ease access to lower level entities in an input AADL model ma = ⟨s, prop⟩, we rely on its flat representation (definition 3).

<table>
<thead>
<tr>
<th>Rule</th>
<th>Mapping</th>
<th>Object</th>
</tr>
</thead>
<tbody>
<tr>
<td>R₁</td>
<td>Pr \mapsto EU</td>
<td>maps every processor to an execution unit</td>
</tr>
<tr>
<td>R₂</td>
<td>P \mapsto AS</td>
<td>maps every process to an address space</td>
</tr>
<tr>
<td>R₃</td>
<td>TH \mapsto T</td>
<td>maps every thread to a task</td>
</tr>
<tr>
<td>R₄</td>
<td>D \mapsto Re</td>
<td>maps every data to a resource</td>
</tr>
<tr>
<td>R₅</td>
<td>C \mapsto TR</td>
<td>maps every connection to a task-resource link</td>
</tr>
<tr>
<td>R₆</td>
<td>PB \mapsto TE</td>
<td>maps every processor binding to a task-EU link</td>
</tr>
<tr>
<td>R₇</td>
<td>T \mapsto TA</td>
<td>maps every thread to a task-address space link</td>
</tr>
<tr>
<td>R₈</td>
<td>D \mapsto RA</td>
<td>maps every data to a resource-address space link</td>
</tr>
<tr>
<td>R₉</td>
<td>Prop \mapsto Param</td>
<td>maps every property to a parameter</td>
</tr>
</tbody>
</table>

Table 1: Rules of AADL2Cheddar transformation.

3.4.2 Transformation. Before we define AADL2Cheddar formally, let us first clarify its technical aspects: how AADL hierarchies are dealt with and how the transformation works.

Technicalities. First, we discuss architectural issues. As one may notice from the informal and formal definitions of AADL and Cheddar, the latter is flat while the former has two architectural levels (the processes level and the system level, Definition 3). To cope with this issue, we reason as follows. It is rather intuitive that the counterpart of threads in AADL is tasks in Cheddar (rule R₁) and that of data is resources (rule R₄). Now, an address space in Cheddar can be linked to many resources and many tasks, but a resource/task can be linked to only one address space (Definition 4). Dually, in AADL, the relation between a process and threads/data is a parent-child one (a process encapsulates threads/data, Definition 1). Thus, a process in AADL should be translated into an address space in Cheddar (rule R₂), and the fact that a thread/data is encapsulated in it is translated into a link between the process counterpart (address space) and the thread/data counterpart (task/resource) in Cheddar (rules R₅, R₆). The process level is thus atomized in Cheddar as the parent-child relations transform into links. Consequently, a binding between a process and a processor in AADL transforms simply into a link between the (task) Cheddar counterpart of each of the process encapsulated threads and the (execution unit) Cheddar counterpart of the processor (rule R₉).

Second, we explain how AADL2Cheddar works. The transformation applies to an input AADL model ma to generate an output Cheddar model mc. The latter, initially empty, is constructed by executing the rules in Table 1 sequentially. Executing a rule boils down to the application of the function formalizing it, e.g. the execution of R₁ (Table 1) is equivalent to computing for each pr \in Pr from ma its image R₁(th), which results in a set of execution units that are then written to mc. We explain more formally some of AADL2Cheddar rules, mainly those that translate bindings, connections and properties, which need to read the elements of other rules. R₅ translates connections into task-resource links: for each connection between a thread and a data in ma, a link between their task and resource counterpart, already written to mc (after executing, respectively, R₃ and R₄) is created. More formally, for each C ∈ C such that \((th ∈ TH, d ∈ D) ∈ C\), a link is created between th ∈ T, the image of th through R₅ (\(th, r ∈ R₅\)) and r ∈ Re, the image of d through R₅ (\((d, r) ∈ R₅\). In a similar way, the execution of R₆ generates links between tasks and execution units. Finally, through executing R₉,
the Cheddar counterpart parameters of the properties in ma are generated and written to mc (e.g. the dispatch_protocol property is translated into the scheduling_protocol parameter). The need of a rule to read the (pairs) elements of another rule creates a rule dependency, which makes the order of execution of rules important (e.g. R₅ may be executed only after R₃ and R₄). To simplify the presentation, AADL2Cheddar rules (Table 1) are executed sequentially following the increasing order of their indices².

Let us now define formal syntax and semantics of AADL2Cheddar in line with the explanations above.

Syntax. AADL2Cheddar is a tuple (ma, mc, R) where ma is the input AADL model (Definition 3), mc the (initially empty) output Cheddar model (Definition 5) and R = {R₁, ..., R₉} a set of rules (Definition 6, Table 1).

Semantics. We can represent AADL2Cheddar with a TD that defines its semantics (Section 3.1.3), where:
- Variables the set X₉₀, i.e. read-only (resp. X₉₁, i.e. read-write) is the input (resp. output) model ma (resp. mc).
- Vertices V = {v₀, ..., v₉} (the transformation steps).
- Edges E = {e₁, ..., e₉} s.t. each eᵢ in E connects vertex vᵢ₋₁ to vertex vᵢ (i ∈ 1..9), i.e. vᵢ₋₁ → vᵢ where g₉₀ is a tautology and op₈ = UP; the operation of updating the output model by applying rule R₈ over all its domain (from ma) and writing the result of such application to mc.

Figure 3 shows a part of the TD that gives the AADL2Cheddar transformation semantics (the dashed edge denotes missing edges and vertices). Operations are in blue and guards are not represented (always true here). Taking an edge eᵢ moves the underlying TS (Section 3.1.3) from state q (with q(π) = vᵢ₋₁) to q’ (with q’(π) = vᵢ) such that the set (element of mc) corresponding to the codomain of rule Rᵢ is empty at q and “filled” at q’; from q to q’, the operation UPᵢ executes Rᵢ and “fills” the corresponding element of mc with the result of such execution. And so, by reaching v₉₀ all entities in ma are translated and the corresponding mc is fully constructed. The transformation is thus terminated.

Figure 3: An example of transformation TD.

## 4 VERIFICATION ENVIRONMENT

Our objective is to verify properties prop₁ and prop₂ of correctness (Section 1): respectively, the transformability of the input model w.r.t transformation intent and the correctness of the transformation rules themselves. To make that possible, we build, by extending the transformation with contracts, a lightweight verification environment with formal semantics.

### 4.1 Contracts

A contract extends a transformation rule with an assumption on the input model ma to apply the rule and a guarantee provided on the output model mc after executing the rule.

**Definition 7. Contract.** A contract is a triple γ = (A, R, G) with A and G are logical formulae called, respectively, an assumption and a guarantee; and R a transformation rule (Definition 6). The domain of discourse for any A (resp. G) is ma (resp. ma ∪ mc).

Thus, a contract provides a means to reason on two types of anomalies: either in the input model (an assumption does not hold) or at the rule level (a guarantee fails). Notice how the domain of discourse of G is ma ∪ mc rather than just mc. This is because, oftentimes, a guarantee on the output model is given w.r.t the input model (see example below).

**Examples.** We give below two examples of contracts. The first example relates only to reasoning on the correctness of a transformation rule using a guarantee (prop₂). For rule R₁, we may propose a contract γ₁ = (A₁, R₁, G₁) where A₁ is a tautology and G₁ = (|E|P = |Pr|). This means that R₁ may execute without a prior condition (A₁) and, after it executes, we have a “weak” equivalence guarantee between the input (AADL processors) and the output (Cheddar execution units) stating that the number of execution units written to mc is equal to the number of processors in ma (which can be strengthened according to the engineer needs).

In the second example, both prop₁ and prop₂ are considered. For rule R₅, we may propose contract γ₅ = (A₅, R₅, G₅) where A₅ = ∀p ∈ P : PB(p) ⊑ and G₅ = ∀r ∈ T : TE(r) ⊑. Here, the assumption conditions the execution of R₅ to the fact that bindings are defined for all processes in the input AADL model. This is a typical example of prop₁ of correctness (Section 1), where correctness depends on the intent of the transformation: we require all processes to be bound to processors because the transformation to Cheddar is for real-time analysis purposes, and such analysis would not be possible if there is a process that is not allocated to any processor. G₅, on the other hand, is a guarantee on the correct implementation of R₅, ensuring that, after executing R₅, all tasks in the output model are bound to execution units, which gives a form of equivalence between input bindings and output links (prop₂)³. We emphasize the importance of both assumptions and guarantees even if they look similar. For instance, A₅ may seem redundant because anyway G₅ will check a posteriori whether all tasks in the generated Cheddar model are linked to execution units. However, if we remove A₅ and G₅ does not hold, it will be impossible to know whether the error comes from the input AADL model or the implementation of R₅, whereas both A₅ and G₅ localizing the source of the error is straightforward using a transition system (see below).

### 4.2 Building the Environment

We extend AADL2Cheddar with contracts (once all contracts are defined) to obtain a formal environment in which assumptions and guarantees can be verified. The transformation thus succeeds if all contracts are validated, i.e. all assumptions and guarantees evaluate to true as the transformation goes.

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²Actually, since there are rules that do not depend on each other, other orders of execution are allowed, e.g. permuting R₅ and R₆ in Table 1. It can be easily shown that choosing any allowed order accordingly has no effect on the verification results, but this is omitted for the lack of space.

³Note that since the elements of each pair in R₅ come from, respectively, ma and mc, all the literals of G₅ fall within the domain of discourse of a guarantee given in Definition 7, that is ma ∪ mc.
4.2.1 Syntax. The syntax of the verification environment is extended from that of AADL2Cheddar (Section 3.4.2): each rule in $\mathcal{R}$ is incorporated within a contract. Thus, the environment is a triple $E = (\langle ma, mc, I \rangle, \{ v_0, m_0 \}$ and $mc$ are the input and output models of the transformation (Section 3.4.2) and $T = \{ y_1, \ldots, y_9 \}$ is the set of contracts each incorporating the rule having the same index from $\mathcal{R}$, that is $y_i = \{ A_i, R_i, G_i \}$ for each $i \in 1..9$.

4.2.2 Semantics. The semantics of the verification environment is obtained by extending the semantics (TD) of AADL2Cheddar (Section 3.4.2) so that for each rule $R_i$, assumption $A_i$ (resp. guarantee $G_i$) is verified before (resp. after) its execution. This gives a new TD with a set of vertices $V'$, a set of edges $E'$ and a set of variables $X'$ derived from the AADL2Cheddar TD (vertices $V$, edges $E$ and variables $X$) following the rules below:

- **Variables**: $X' = X$ (with $X_0' = X_0$ and $X_{mc}' = X_{mc}$).
- **Vertices**: $V' = V \cup \{ v_{i-1} \}$. Each additional vertex $v_{i-1}$ denotes an intermediate step between vertices $v_i$ and $v_{i-1}$ in $V$.
- **Edges**: Each edge $v_{i-1} \rightarrow v_i \in E$ is replaced with two edges $v_{i-1} \rightarrow v_{i-1}^\prime$ and $v_{i-1}^\prime \rightarrow v_i$ where $null$ denotes any side-effect-free operation.

Thus, the resulting TD has the same input and output variables, and augments the original transformation TD with additional vertices, edges and guards to verify assumptions and guarantees. Figure 4 shows a part of the TD resulting from the extension of the TD in Figure 3, following the rules given in the semantics above (the dashed edge denotes missing edges and vertices, null operations and edges names are removed). Additional vertices are in red. Thus, rule $R_1$, for instance, will not be executed unless $A_1$ is true (guard in green), in which case the result of executing $R_1$ is written to $mc$ (operation $UP_1$ in blue) and vertex $v_{0.1}$ is reached. Afterwards, $v_1$ may not be reached unless the guarantee following the execution of $R_1$ is satisfied (guard $G_1$ in green). Then the same behavior is repeated for all remaining rules until $v_9$ is reached.

![Figure 4: Example of verification environment TD.](image-url)

4.2.3 Correctness verification. Using the verification environment semantics, we can reason on the transformation correctness w.r.t. the transformability of the input model (assumptions) and the correctness of the execution rules implementation (guarantees) at “runtime” (i.e. on the fly when executing the transformation on an input model instance). For example, if $G_0$ is false, any state $q$ in the underlying TS such that $q(\pi) = v_0$ (we recall that $\pi$ is the variable, in the underlying TS, denoting the current vertex of the TD, Section 3.1.3) is unreachable, that is $q \not\in Q_0$. Dually, if $A_0$ does not hold, states $q$ s.t. $q(\pi) = v_{0.9}$ are also unreachable. And so, we can define from the set of reachable states exactly at which state the transformation failed and conclude on the error source, i.e. input model or rule implementation, and in the former case, more precisely from which part of the input model (e.g. threads, bindings, etc.). If any reachable state $q \in Q_0$ satisfies $q(\pi) = v_i$, this means that rule $R_i$ is successfully executed with both $A_i$ and $G_i$ evaluating to true, in which case we say contract $y_i$ is validated.

Since the system is sequential, concluding on reachability of states is rather straightforward: if $q$ is unreachable with $q(\pi) = v_{1..j}$ (resp. $q(\pi) = v_j$) then any other state $q'$ with $q'(\pi) = v_{j..l}$ or $q'(\pi) = v_j$ is also unreachable for any $j \geq i$ (resp. $j > i$). Also, if there exists a reachable state $q$ such that $q(\pi) = v_i$ where $i$ is the largest index (9 for AADL2Cheddar), then the transformation is correct (all contracts are validated).

5 APPLICATION TO OCARINA

In this section, we propose an implementation of our formal environment (Section 4) within the transformation tool called Ocarina (Section 5.1), then illustrate with verifying AADL2Cheddar correctness on a case study (Section 5.2). All the implementation and case study elements presented in this section are publicly available at https://github.com/artxy/sac2021 with a notice to reproduce the experimentation results.

5.1 Implementation

We briefly introduce Ocarina and review the key elements of our implementation. Then, we explain how the abstract verification of reachability, explained in Section 4.2.3, can be achieved at the implementation level.

**Ocarina.** Ocarina is a “processor” of AADL models, written in Ada. It allows to generate, from AADL, various kinds of codes for embedded platforms and models for analysis/verification purposes such as real-time task models (e.g. for Cheddar) and Petri nets (e.g. for TINA [5]).

Ocarina is designed as a compiler. Figure 5 gives an overview of a typical process flow in Ocarina, that transforms an AADL model into a Cheddar model. Models are represented as Abstract Syntax Trees (AST) and transformation rules as AST-to-AST mappings, encoded as Ada functions. The transformation itself is then a set of organized visitor routines that process the AST and execute on-the-fly transformation rules.

![Figure 5: Process flow to transform an AADL model.](image-url)
are temporarily saved in a data structure which $R'$ can access. Such structures are destroyed at the end of the transformation.

Now, in order to incorporate contracts, we extend their implementation, that is Ada functions, using Ada 2012 contracts: for each Ada function implementing rule $R_k$, we add a precondition (resp. postcondition) that maps $A_i$ (resp. $G_i$), the assumption (resp. guarantee) of contract $\gamma_i$ incorporating $R_i$ (Section 4.2.1). This implementation coincides with the semantics of our environment in Section 4.2.2 (see below).

We have thus a full equivalent implementation to our environment in Ocarina the elements of which are further detailed below.

**Models = AST.** In Figure 5, an instance of model (either an AADL model in input or a Cheddar in output) is described with a tree structure, namely the AST, that is a collection of nodes (each one is identified by a node_Id that forms a tree structure via child-parent links descending from the root node. A node in the tree denotes an entity in the related model (e.g. a component, a connection, a property, ...), thus representing the structure of an AADL or Cheddar model, hierarchical in the case of AADL (Definition 3, Definition 5). In Figure 5, the AST of the input AADL model is an Instance Tree (on the top left), whereas the XML Tree (at the bottom right) is the AST of the output Cheddar model.

**Rules = functions.** Transformation rules are mapped to functions defined over AST nodes, thereby implementing the definition of rules (Definition 6, Section 3.4). For instance, rule $R_k$, that translates every thread (in an AADL model) into a task (in a Cheddar model), is implemented in a function called Map_Thread. A rule is "atomic" in a function: the function takes a node_Id in the input AST and returns the node_Id of the created node in the output AST. The application of a rule over its whole domain is ensured by a visitor (see below). For each rule $R_k$ that depends on the result of executing rule $R, R'$ reads, besides the node_Id in the AST, the temporary data structure holding all pairs $(x, y) \in R$ as explained above.

**(Ada) contracts.** The function declaration is extended with preconditions and postconditions. According to the Ada 2012 Rationale [2], "a precondition is an obligation on the caller to ensure that it is true before the subprogram is called", whereas "a postcondition is an obligation on the implementer of the body to ensure that it is true on return from the subprogram". Thus, this implementation complies with the semantics of our environment (Section 4.2.2).

Let us see how this is done for e.g. assumption $A_0$ in contract $\gamma_0$, incorporating rule $R_0$ (transform all properties in Prop to parameters in Param, Table 1). Similarly to $A_5$ on bindings (see example in Section 4.1), $A_0$ stipulates that each property in Prop must be defined over all its domain, that is $\phi(x) \in D$ is satisfied for each $x$ in $X$ for each property $\phi : X \rightarrow Y$ in Prop. For e.g. the compute_execution_time property, that is the literal of $A_0$: $\forall y \in T^H : compute_execution_time(th) \in D$, the precondition in Ada checks, for each thread node $th$, whether the function Get_Execution_Time, giving the image of $th$ via the property compute_execution_time in an array, returns a valid value (i.e. different from Empty_Time_Array, denoting that such property is not defined for $th$):

\[(Get_Execution_Time(th) \neq Empty_Time_Array)\]

**Transformation flow = visitors.** Finally, a main procedure ensures the transformation flow by reading all the input AST nodes and invoking transformation rules sequentially as the visiting goes (which results in nodes creation in the output AST). Contracts are validated (or not) on the fly through preconditions and postconditions.

**Verification = condition checks.** If a precondition or postcondition fails, an execution error is raised as the flow is interrupted. Locating the function at which the error occurred allows to find the error source: a rule implementation or the input model. In the latter case, we may further locate at which element of the input model (threads, data, etc.) the transformation failed. This "error location" mirrors the state reached last in the underlying TS (Section 4.2.2) and enables thus an implementation-level verification of the reachability property explained in Section 4.2.3 (an example is given in Section 5.2). A transformation is then correct iff the flow terminates without errors, thus generating a complete Cheddar model.

### 5.2 Case Study

Let us illustrate our approach on a real AADL model describing the well-known Mars Pathfinder system\(^4\), with model transformation from AADL to Cheddar performed using our implementation within Ocarina (Section 5.1). We shortly present the AADL model of the system before we perform transformation verification.

#### 5.2.1 Overview of the AADL model.\(^5\) The Mars Pathfinder system consists of a stationary lander and a rover named Sojourner. All the system elements are described with the usual AADL components (see Section 2). In particular, the overall system mars_pathfinder includes a main process (prs_PSC) describing the lander application and a processor (rs_6000) specifying the RS 6000 processor. The main (lander) process includes seven (periodic) threads, four of which may access a critical resource, described by a data (data_rw), in mutual exclusion (for read/write). The AADL model is completed with the description of connections/bindings and properties.

#### 5.2.2 Verification.\(^5\) We apply our environment, implemented in Ocarina, to the AADL model of the case study as an input. We recall that our environment includes the AADL2Cheddar transformation extended with 9 contracts (Section 4) and implemented within Ocarina using ASTs and Ada functions and contracts (Section 5.1).

We run our environment on an initial AADL model mars_pathfinder.init. From the execution log (Figure 6), we see that an error is raised during the transformation of the AADL model: a precondition given at line 102 within the flow specification (cheddar-mapping.ads) fails. This precondition is found in the declaration of the function which implements rule $R_5$ and the error occurs at the line corresponding to the literal of $A_0$ requesting concurrency_protocol to be defined for all data in the input model, that is $\forall d \in D : concurrency_protocol(d) \in D$. Indeed, by investigating the AADL model, we find that such a property is not specified for data_rw which is shared between four threads in the main process prs_PSC of the system mars_pathfinder.init.

Once we locate the error source, we correct it by adding the missing property. Listing 2 shows an excerpt of the corrected AADL model mars_pathfinder.correct which extends the initial model mars_pathfinder.init and specifies a concurrency_protocol

\(^4\)From the Mars Pathfinder mission by the NASA, https://mars.nasa.gov/mars-exploration/missions/pathfinder/(last accessed October 2020)
The error found in this example is at the input model level w.r.t the transformation intent, i.e. since the transformation to Cheddar is for real-time analysis purposes, the input model must define a concurrency protocol over data. Verifying the transformation allows to detect such anomaly at an early stage of the transformation and thus prevents using analysis techniques on an unreliable output model. In this case, if we run the transformation blindly (without contracts), the Cheddar tool still runs analysis on the output model on which no shared protocols are defined for resources and gives thus non exploitable results w.r.t the input model: in a real-time system with shared resources, the definition of a shared protocol is necessary in order to ensure that the system does not exhibit undesirable phenomena such as priority inversion [6].

6 GENERALIZABILITY

In this section, we explain how our approach can be generalized to other transformations and customized according to the engineer needs w.r.t to both prop1 and prop2 of correctness (Section 1).

Other input/output models. Reusing our approach for other input/output models requires formalizing such models like we did for AADL and Cheddar (Section 3). Though it might seem disabling, such formalization is rather achievable with a reasonable cost. Indeed, first, as we have seen in Section 3, our formalization is done at some abstraction level that is the highest necessary for the transformation: e.g. we did not need to formalize AADL memories since they play no role in AADL2Cheddar. Second, the cost of formalization may be further reduced on a property-driven basis: e.g. we did not need to formalize the internal behavior of AADL threads because the “equivalence” between AADL and Cheddar models here (prop2 of correctness) relates to entities (AADL threads, Cheddar tasks, etc.), their relations (AADL bindings, Cheddar links, etc.) and properties/parameters rather than low-level behavioral models.

Other transformations. Though presented for AADL2Cheddar, our formal environment is rather generic. For instance, if the number of any transformation rules is parametrized with the natural \( n \), it is sufficient to replace the upper bound of \( i \in 1 \ldots 9 \) (and consequently the indices of \( e_9, e_9, \gamma_9 \) and \( R_9 \)) with \( n \) to make the transformation and environment syntax and semantics (Section 3.4.2, Section 4.2.1, Section 4.2.2) fully generic. Therefore, besides defining their input model, output model, transformation rules and contracts according to their needs, engineers may reuse our formal environment without any further effort.

Other “levels” of prop2. Engineers may need to verify prop2 of correctness at different “levels”, e.g. one may content, in some context, with only syntactic correctness, whereas semantic correctness is necessary in a different context. This may be achievable following our approach without any change made to the underlying definitions of rules, contracts, and the formal environment. Indeed, since contracts guarantees can be any logical formula (including quantifiers), they may be written to express most syntactic and semantic checks (and anything in between). For instance, our guarantee \( \gamma_9 \) (Section 4.1) may be viewed as something between syntactic and semantic equivalence, which may be replaced with a weaker or a stronger variant according to the level of prop2 to achieve. This “flexibility” strengthens the rationale of using contracts, especially that in the case where only simple guarantees are needed, the cost of formalizing the input and output model may be drastically reduced (since such cost depends on the properties to verify, see §“Other input/output models” above). Yet, using our approach for heavy semantical checks (e.g. bisimulation) will need further reflection (Section 8).

Discarding prop1/prop2. Finally, if the engineer needs to verify only prop1 or prop2, they may do so easily by simply encoding their assumptions (resp. guarantees) as tautologies. This aspect, stemming from the flexibility aspect described in the previous paragraph, gives the practitioner a full control over which aspect of correctness they are interested in.

7 RELATED WORK

There is a large corpus of works on model transformation verification (see e.g. reviews in [7, 25]). In this section, we focus on contract-based works. Contracts, having their roots in the Floyd-Hoare logic [12, 18], have been proposed to support the design and analysis of software in various domains [10, 22, 27, 28]. Due to their assumption/guarantee structure, contracts have naturally been integrated within transformation frameworks. In particular, Cariou et al. [8, 9] studied model transformation contracts written in OCL, where transformation operations are associated with contracts. Part of these contracts can be implemented as OCL invariants and then checked using a standard OCL evaluator. The other part requires to use a set of OCL utility functions. Thus, the approach enables to ensure that a model transformation conforms to a set of contracts with no need to execute the transformation. In a quite different scope, Guerra et al. [17] proposed a language called PaMoMo to specify visual transformation contracts and a process to compile and verify them. At first, contracts enable to specify requirements on a model transformation through preconditions, postconditions and invariants. Then, the model transformation is compiled with its contract(s) into the QVT-R executable language for checking whether it fulfills the requirements or not (providing the user with information on which part of contract failed and why). In general, besides applicability limitations (e.g. contracts in [8, 9] are only
applicable to endogenous model transformation, i.e. models with the same input and output metamodels), contract-based verification efforts presented above lack formal environments that define correctness properties and explain how they are verified.

The closest approach to ours is DSLTrans [3, 29], a transformation language featuring a formal contract-based prover. The spirit of DSLTrans is similar to that of our approach as contracts are verified in a formal way. However, whereas our approach relies on verifying the correctness of a transformation at runtime given an input model instance, DSLTrans is more generic as it targets proving correctness of a given transformation for any input model. Yet, since in DSLTrans the existence of a transformation (on which the prover runs) is assumed, such transformation (i) is not executed, which makes it impossible to verify prop1 and (ii) must be encoded beforehand into DSLTrans (e.g. GM-2-AUTOSAR in [29]), which raises concerns on the correctness of such encoding.

8 CONCLUSION AND PERSPECTIVES

Reasoning on model transformations correctness in MDE is a challenging task. Formal methods may be employed to rigorously verify such correctness, but are out of software engineers expertise. In this paper, we proposed a formal, engineer-friendly and flexible approach to verify both prop1 and prop2 (Section 1) of transformation correctness. Flexibility refers to the possibility to tailor such verification to the engineer needs by e.g. increasing the level of prop2 or discarding prop1. The “formal” aspect enables rigorous verification of correctness on a formal model. Finally, engineer friendliness is achieved through contracts, supported with a well-known programming language. Our approach is applied to the AADL to Cheddar model transformation and validated on a real case study.

We give two examples of future work directions. First, we will investigate extending our approach to other model-based frameworks, other application domains and other levels of correctness (Section 6). We believe that our approach may be suitable for e.g. component-based robotic frameworks (e.g. MAUVE [16]), where systematic mapping to verification frameworks through model transformation is of high importance. A major challenge will be to account for heavy yet necessary semantical guarantees knowing that the underlying robotic models feature rich behavioral models, hard real-time constraints and complex interaction mechanisms. Second, locating the source of errors (in case an assumption or a guarantee fails) based on errors raised by Ada may be inconvenient for large applications or transformations with a significant number of contracts. In future work, we will investigate implementing our framework in BIP [4]. Being both based on transition systems and able to embed blackbox functions, the BIP model will allow to find at which “state” the transformation failed without the need to worry about the Ada code or read the runtime errors.

REFERENCES