TTC'2019

The MEEDUSE solution

Akram Idani[1] German Vega[1] Michael Leuschel[2]

[1]Univ. Grenoble Alpes, Grenoble INP, CNRS, LIG. F-38000 Grenoble France
{Akram.Idani, Germa.Vega}@imag.fr

[2]Universittsstrae 1n. D-40225 Dsseldorf
Michael.Leuschel@uni-duesseldorf.de

Abstract

The TTC'2019 case study deals with a realistic model transformation which is that of generating binary decision diagrams from truth tables. Among other challenges, the contest emphasizes on correctness which motivated us to apply Meeduse, a tool that we developed in order to define formal semantics with animation facilities of Domain Specific Languages (DSLs). This study allowed us to try how far we can push the abilities of a formal method to be integrated within model-driven engineering. The results were positive and concluding, and show that Meeduse can be adapted to model-transformation which brings to this field formal automated reasoning tools like AtelierB for theorem proving and ProB for model-checking. Meeduse, combined with ProB, provides three strategies: random animation, interactive animation and model-checking. The first strategy runs randomly the transformation rules until it consumes all the truth table rows and then automatically produces the binary decision diagram. The second strategy allows a step-by-step debugging of the transformation rules. And the third strategy is useful for analysing the reachability of some defined states which allows to verify whether unwanted situations may happen or not. The proposed solution and demonstration videos can be found at:

`https://github.com/meeduse/Meeduse_TTC_2019`

1 Introduction

This paper presents the application of Meeduse to the TTC'2019 case study. First we notice that the tool was conceived in order to define proved executional semantics of domain specific languages (DSLs) by integrating the formal B method [1] within EMF-based frameworks like XText, Sirius, GMF... Meeduse was recently

In: A. Editor, B. Coeditor (eds.): Proceedings of the XYZ Workshop, Location, Country, DD-MMM-YYYY, published at http://ceur-ws.org

developed (in 2018) and has had successful applications in the safety-critical domain, especially for railway systems modeling. The reader can refer to [2] for more information about the overall approach of Meeduse.

The challenge of the TTC'2019 case study for us, is to define and run model transformations as executional semantics using a well established formal technique, the B method. This works starts from the following observations:

- We are not experts in circuit design and hence the application is limited to the cases provided in the TTC'2019 call for solutions. However, we provide transformation rules written in a formal language which is assisted by automated reasoning tools; and then we believe that domain experts may be attracted by our solution. Indeed, translating a truth table into a binary decision diagram, has several applications in safety critical systems where formal methods became a strong requirement.

- Our objective is not to search for the most compact BDD, but to show how a formal method assisted by theorem proving and model-checking techniques can be applied for the particular field of model transformation. We note that we discovered too late the update of the TTC call. So, we decided to keep our work unchanged and present it as applied to the original BDD meta-model.

- We have skills in both formal methods (FM) and model-driven engineering (MDE) and we advocate for collaborations between both communities in order to take benefits of their complementarities. The Meeduse tool favors this communication since it makes possible the use of MDE and FM tools together in one unified framework.

2 Brief overview of Meeduse architecture

The goal of Meeduse[1] is to support a pragmatic approach to associate model-driven engineering with a proof-based formal approach. In practice, the tool brings together three technological spaces: EMF for model driven engineering, B Method [1] for proofs and refinements, and finally the execution of the target system.

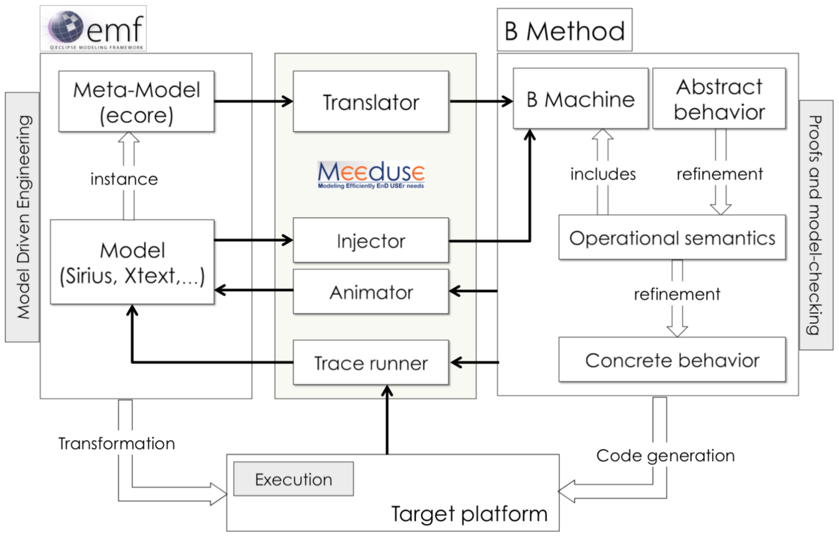


Figure 1: Overview

Figure 1 depicts the high level architecture of Meeduse, and shows the interactions of the main components of the tool: *Translator*, *Injector*, *Animator* and *Trace runner*.

(1) *Translator*: this component automatically translates an Ecore meta-model into an equivalent B specification which represents the structure of the meta-model as well as basic operations like constructors, destructors, getters and setters. The resulting B specification can be manually refined by additional invariants and concrete operational semantics, as sketched in the right hand side of figure 1. The proof of correction of the full specification can be performed with the help of an automatic prover, like the ones proposed by AtelierB.

[1]Meeduse: Modeling Efficiently EnD USEr needs.

(2) *Injector*: this component takes a model conforming to the meta-model (which can be designed using EMF-based modeling tools like Sirius, GMF, XText, etc) an translate it into a specialized B machine derived from the B specification produced from the meta-model. This translation essentially transforms abstract sets of the specification (that represent classes in the meta-model) into enumerations representing the concrete instances of the model, and hence allows valuations of the B machine variables and model checking over finite domains.

(3) *Animator*: in Meeduse, animation of B specifications is done using the ProB tool [3] which is an open-source model-checker supporting the B method. Component Animator asks ProB to animate B operations and gets the reached state by means of B variables valuations. Then, the Animator translates back these valuations to the initial EMF model resulting in automatic synchronization of the model.

(4) *Trace runner*: this component allows to play a sequence of operations issued from an execution trace by animating the corresponding B operations which leads to automatic modifications of the model. Thanks to this component, animation can be done from outside EMF by an external agent running in the execution target platform. The trace runner can be useful for conformance validation between the model and the execution, and also for some forms of run-time verification.

Our main objective for the TTC'2019 challenge is to write the model-to-model transformation rules using B specifications and then to reuse some selected components of Meeduse in order to animate these specifications given an input model. As Meeduse was not initially designed to define model transformation rules, but to define DSL execution semantics, we need to rethink the model transformation problem in terms of operational semantics of an abstract machine.

The global strategy consists in reusing the *Translator* component of Meeduse to help automate part of the writing of the B Machine formal specification of the transformation, use the ProB model checker to animate the execution of the transformation, and finally reuse the Meeduse's *Animator* synchronization capabilities to obtain the resulting EMF output model. For the TTC'2019 case study, the B specification of a model-to-model transformation will be structured in two modules:

- The "Model construction" machine (called B Machine in figure 1) is automatically generated by Meeduse from the input and output meta-models of the transformation, and defines basic modeling operations.

- The "operational semantics" machine is used to manually specify the model-to-model transformation rules (notice in the right hand part of figure 1 that Meeduse extensively use the refinement capabilities of the B method, we do not exploit this technique for this case study).

The following section will further describe these two machines and explain the approach in detail, using a simple transformation for illustration purposes. After that, we will present the complete specification of the transformation rules of the TTC'2019 case study.

3 A step-by-step overview of Meeduse approach

Presenting the full B formalization of the TTC'2019 case study requires introducing many concepts and properties, which would be inconvenient for readers from the MDE community who may not be familiar with formal methods, and particularly with the B method notation. Hence, we decided to introduce in this section our approach and its underlying formal concepts as a step by step tutorial that uses a simplistic model transformation example inspired by some basic MDE material available on-line. Application of Meeduse to the TTC'2019 case study follows similar ideas and will be presented in section 3.

Figure 2 shows the input and output meta-models for the example transformation. The input of the transformation is a model defining persons (of any gender) which may be married (represented by the person1/person2 relation) and the output is a model focused only on married wives and husbands (represented as instances of their respective classes).

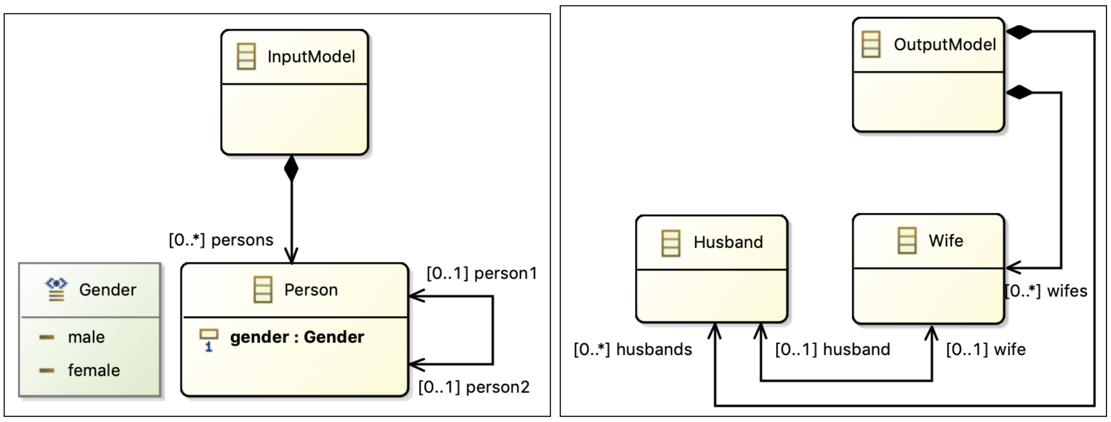


Figure 2: Input/Output meta-models

3.1 Step 1: merging meta-models

As discussed previously, the input of our tool is the meta-model of a DSL, for which we define, using the formal B method, its execution semantics. In our approach, meta-modeling elements like classes and associations, which are abstract concepts, are automatically translated into *state variables* of the corresponding B machine. Furthermore, constraints defined in the meta-model (for example, the cardinality of attributes) are translated as *invariants* of the B specification. The resulting formal specifications allow the specification of the DSL execution semantics by using B *operations*. The details of this automatic translation are given in the following section.

In order to apply the Meeduse approach for model-to-model transformation, our idea is first to merge both input and output meta-models into a single one which is automatically translated by Meeduse into B, and then specify the transformation rules as operations of the corresponding B machine. Intuitively, the state of the transformation execution includes the input model, the partially generated output model and any additional information required by transformation rules (for instance, traceability links created by other rules).

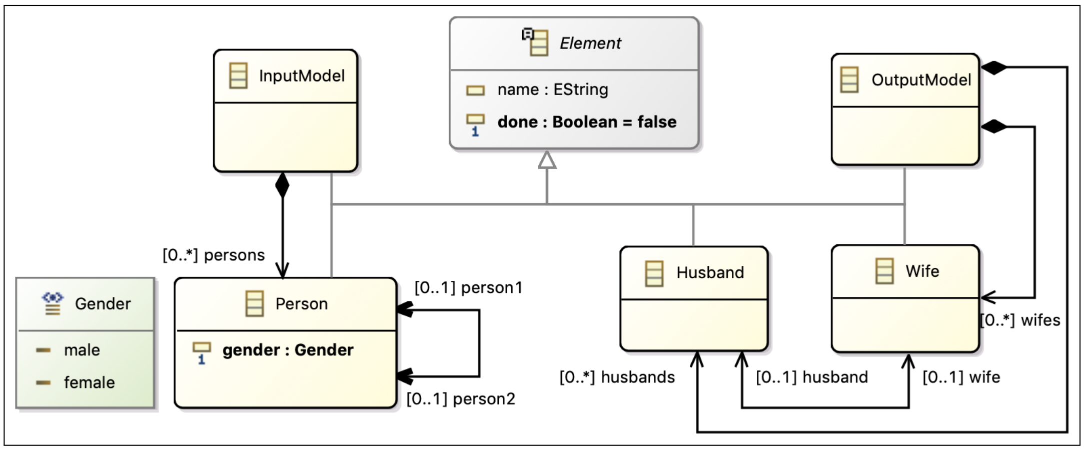


Figure 3: Merging meta-models

To concretely illustrate this idea, figure 3 shows the merging meta-model for our simple transformation. Then, we suggest that the execution semantics of the transformation follows a consumption/production technique: instances of output classes are created while consuming instances of input classes. In order to keep track of the modeling elements that have been processed by the transformation, we introduce an abstract meta-class `Element` which allows to gather modeling elements consumed by the transformation. This class introduces an attribute `name` to identify processed elements and a boolean attribute `done` which marks consumed input elements. Having defined this merging meta-model, we are ready to start thinking about the formalization of the transformation.

3.2 Step 2: generation of the *"model construction"* specification

From the merging meta-model, Meeduse automatically generates B specifications that gathers modeling operations as well as structural invariants. This technique allows to write the transformation rules in the B language. Figure 4 presents the structural part of the resulting B machine.

MACHINE
    simpleModel
SETS
    $Gender = \{male, female\}$;
    ELEMENT
ABSTRACT_VARIABLES
    Element,
    InputModel,
    Person,
    OutputModel,
    Husband,
    Wife,
    person_1_2,
    persons,
    husband_wife,
    wifes,
    husbands,
    Element_done,
    Person_gender

INVARIANT
    $Element \in \mathcal{F}\ (ELEMENT) \land$
    $InputModel \subseteq Element \land$
    $Person \subseteq Element \land$
    $OutputModel \subseteq Element \land$
    $Husband \subseteq Element \land$
    $Wife \subseteq Element \land$
    $person\_1\_2 \in Person \rightarrowtail\!\!\!\!\!+ \; Person \land$
    $persons \in Person \nrightarrow InputModel \land$
    $husband\_wife \in Husband \rightarrowtail\!\!\!\!\!+ \; Wife \land$
    $wifes \in Wife \nrightarrow OutputModel \land$
    $husbands \in Husband \nrightarrow OutputModel \land$
    $Element\_done \in Element \nrightarrow \mathbf{BOOL} \land$
    $Person\_gender \in Person \rightarrow Gender$

Figure 4: Structural part of the modeling specification

In this simple example, we can easily remark that there is a direct correspondence between entities in the meta-model and declarations in the generated specification. The Meeduse rules for translating an ecore meta-model into a B specification can be roughly summarized as following:

- Primitive types (*e.g.* integer, boolean) become B basic types ($\mathbb{Z}$, **BOOL**,...).
- Enumerations and DataTypes are translated into given abstract sets (*e.g.* $Gender = \{male, female\}$).
- For each meta-class there is a variable in the specification (named as the class) representing the set of existing instances (*e.g.* variable *Person* represents the set of existing instances of class `Person`). If a class A is a subclass of a class B then Meeduse generates an inclusion relationship between their corresponding existing instances ($A \subseteq B$). For example, we get predicate $Person \subseteq Element$ because class Person is a sub-class of class Element. The additional class Element introduced in the merging meta-model is translated into an abstract set that represents all possible instances. In this example it is designated by set *ELEMENT*.
- Each attribute leads to the definition of a variable that is typed as a function from the set of possible instances to the attribute type (*e.g.* $Person\_gender \in Person \rightarrow gender$). The function specializations depend on multiplicities and the optional/mandatory character of the attribute. For example, attribute `done` in class `Element` is an optional boolean attribute, then the corresponding variable is a partial function defined as: $Element\_done \in Element \nrightarrow \mathbf{BOOL}$.
- References are also represented as functional relations between the sets of possible instances issued from both source and target classes (*e.g.* $husband\_wife \in Husband \rightarrowtail\!\!\!\!\!+ \; Wife$). Like attributes, the relation specializations depend on the reference cardinalities (and its opposite) like for example, the *husband_wife* variable which is a partial injection.

The behavioral part of the generated B machine provides all basic operations for model manipulation: getters, setters, constructors and destructors; for this reason we often refer to this machine as the "model construction" machine. Figure 5 shows the specification of two generated operations. Operation `Husband_NEW` is a constructor that creates an instance of class `Husband`. This operation takes an element from the possible objects defined by abstract set `ELEMENT` and adds it to the set of existing instances of class `Husband`. Operation `Husband_SetWife` is a setter that straightforwardly assigns a value to the bi-directional reference husband/wife.

```
Husband_NEW (aHusband) =
PRE
    aHusband ∈ ELEMENT
THEN
    Husband:= Husband ∪ {aHusband} ||
    Element:= Element ∪ {aHusband}
END;
```

```
Husband_SetWife (aHusband,aWife) =
PRE
    aHusband ∈ Husband
    ∧ aWife ∈ Wife
THEN
    husband_wife(aHusband) := aWife
END;
```

Figure 5: Generated constructor and setter for class Husband

Notice that this step is analogous to what happens in MDE tools that generate code from meta-models. For instance, from a given meta-model definition EMF can generate Java modeling code (getters, setters, etc), that can be used to program model transformation in Java. In the same way, Meeduse generates a B machine that can in turn be used to specify model transformations in B.

The B specification issued from our simple meta-model is about 335 lines of code with 34 basic operations which are proved correct (with respect to the structural invariant) by construction. Proofs were carried out using AtelierB, for this simple specification it generated 120 proof obligations, which were all automatically proved by the theorem prover. This means that the use of these modeling operations guarantees the preservation of the structural properties (invariant) of the meta-model. They will never create an invalid instance contrary to a java based technique like that of EMF or other tools.

3.3 step 3: writing the transformation rules

A model transformation is manually written in a new B machine as a set of B operations that can reuse the modeling operations defined in the `simpleModel` machine (figures 4 and 5). Each transformation rule is defined as a B operation composed of two parts: the guard and the action. The guard gives the conditions under which the rule can be triggered, and the action specifies a sequence of calls to modeling operations (from machine `simpleModel`) whose effect is to create the output model.

```
Input2Output =
    ANY input WHERE
        input ∈ InputModel
         ∧ input ∉ OutputModel
    THEN
        OutputModel_NEW(input)
    END;
```

```
Person2HusbandWife =
    ANY output, p1, p2 WHERE
            output ∈ OutputModel
          ∧ p1 ∈ Person ∧ p2 ∈ Person
          ∧ Person_gender(p1) = male
          ∧ Person_gender(p2) = female
          ∧ ((p1 ↦ p2) ∈ person_1_2 ∨ (p2 ↦ p1) ∈ person_1_2)
          ∧ Element_done[{p1, p2}] = {FALSE}
          ∧ (husbands ∪ wifes)[{p1,p2}] = ∅
    THEN
        Husband_NEW(p1) ;
        Wife_NEW(p2) ;
        Husband_SetWife(p1, p2) ;
        OutputModel_AddHusbands(output, p1) ;
        OutputModel_AddWifes(output, p2) ;
        Element_SetDone(p1, TRUE) ;
        Element_SetDone(p2, TRUE)
    END
END
```

Figure 6: Transformation rules written in B

For our simple example, we defined the following two transformation rules (detailed in figure 6):

- Operation `Input2Output` creates an `OutputModel` for each `InputModel`. It takes any existing instance of class `InputModel` ($input \in InputModel$) which has not been yet transformed (condition $input \notin OutputModel$) and then its action creates the new instance of `OutputModel` by calling basic operation `OutputModel_NEW(input)`.
- Operation `Person2HusbandWife` takes two instances of class `Person` representing a married couple (defined by parameters $p1$ and $p2$) and translates them into instances of classes `Husband` and `Wife` in the resulting output model. The enabling conditions for this transformation rule are:
  - there exists an output model ($output \in OutputModel$)
  - the input instances satisfy a pattern, $p1$ is a male ($Person\_gender(p1) = male$), $p2$ is a female ($Person\_gender(p2) = female$) and they are married ($(p1 \mapsto p2) \in person\_1\_2 \vee (p2 \mapsto p1) \in person\_1\_2$)
  - The input instances have not been already processed by a previous execution of the transformation ($Element\_done[\{p1, p2\}] = \{\text{FALSE}\}$ and $(husbands \cup wifes)[\{p1, p2\}] = \emptyset$)

We can remark that the chosen style for specifying the transformation rules in B reminds transformation languages available in the MDE community. The specification of the rule guard (clause **ANY**) is similar to some declarative transformation languages (it looks like the *where* condition and *checkonly* patterns in QVT relational for example). Nonetheless, the action part has a more imperative style. As B is not a specialized language for model transformation, some aspects have to be taken care explicitly, for instance we have to check that a rule is not applied several times for the same input.

An important aspect that is worth mentioning is that we do not specify explicitly the execution order of the rules. The semantics of a B machine is that, at any given point during the execution, the system considers all enabled operations and makes a non-deterministic choice. The choice of the parameters in the **ANY** clause is also non-deterministic, meaning that at any execution state, the system will select any objects that satisfy the condition and use them as arguments for the operation.

However, in this example we have indirectly prescribed an order of execution, because in the guard of the `Person2HusbandWife` rule we check for the existence of an object created by the `Input2Output` rule. This strategy is also similar to some declarative transformation languages that use traceability information to infer an execution order. The dynamics of a B machine execution will be further explored in the following sections.

A final point concerns the correctness of the transformation rules. As mentioned in the previous section, the individual model construction operations (constructors, setters, ...) were proved correct, then the result of executing a sequence of operations in the action part of a rule will obviously preserve the model structural properties. However, we also need to prove that the order of the sequence of calls is correct, meaning that the preconditions of every operation in the sequence are satisfied. Lets's consider for example operation `Husband_SetWife` which can be applied only on existing instances of classes Husband and Wife: $aHusband \in Husband \wedge aWife \in Wife$. As actions `Husband_NEW` and `Wife_NEW` produce these instances, then the proof of correctness associated to the call of `Husband_SetWife` in rule `Person2HusbandWife` succeeds.

For our example rules, the AtelierB generated 13 additional proof obligations, which were automatically proved. This means that we don't need to test the validity of the input models or verify the output model using the EMF validator.

3.4 step 4: animation and debugging

Proofs are mainly for a verification purposes (i.e. *"do the transformation right?"*). However, we need to validate the rules in order to be sure that they produce the results expected by a domain expert (i.e. *"do the right transformation?"*). For this purpose, Meeduse provides an interactive animation facility that uses the ProB [3] animator in background.

In Meeduse the user can load an EMF input model and injects it in the B specifications as variable valuations. Figure 7 shows an example input model open in the EMF editor, the model represents a group of 6 people. The figure also shows how to invoke this functionality in the tool: right click on the root element of a model and then, choose `Concrete behaviour view`. After loading the model, Meeduse asks ProB to animate the initialization and then gets the initial state of the machine. Given this state, ProB computes the list of operations whose guards are satisfied and which can then be animated from the initial state. Figure 8 is a screen-shot of Meeduse after loading the example input model.

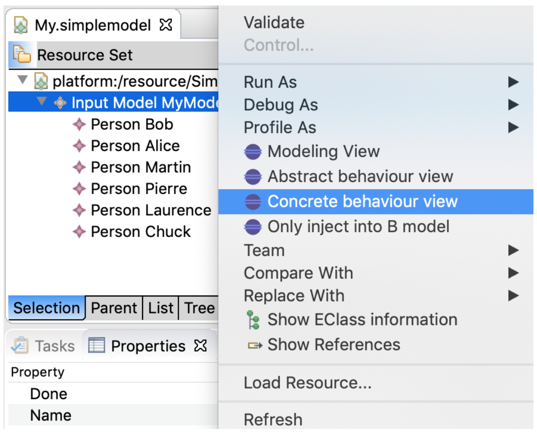


Figure 7: Loading a model in Meeduse

At this point we can make some observations for our example. From the input model (loaded in the EMF editor in view ① of figure 8) Meeduse initialized some of the variables of the machine and asked ProB to calculate the initial state of the machine. The state of the machine is displayed in View ③ of figure 8 (called `Output State View`). In particular, we can observe that the variables that represent classes of the input model (*InputModel*, *Person*) and those of the output model (*OutputModel*, *Husband* and *Wife*) were initialized as follows:

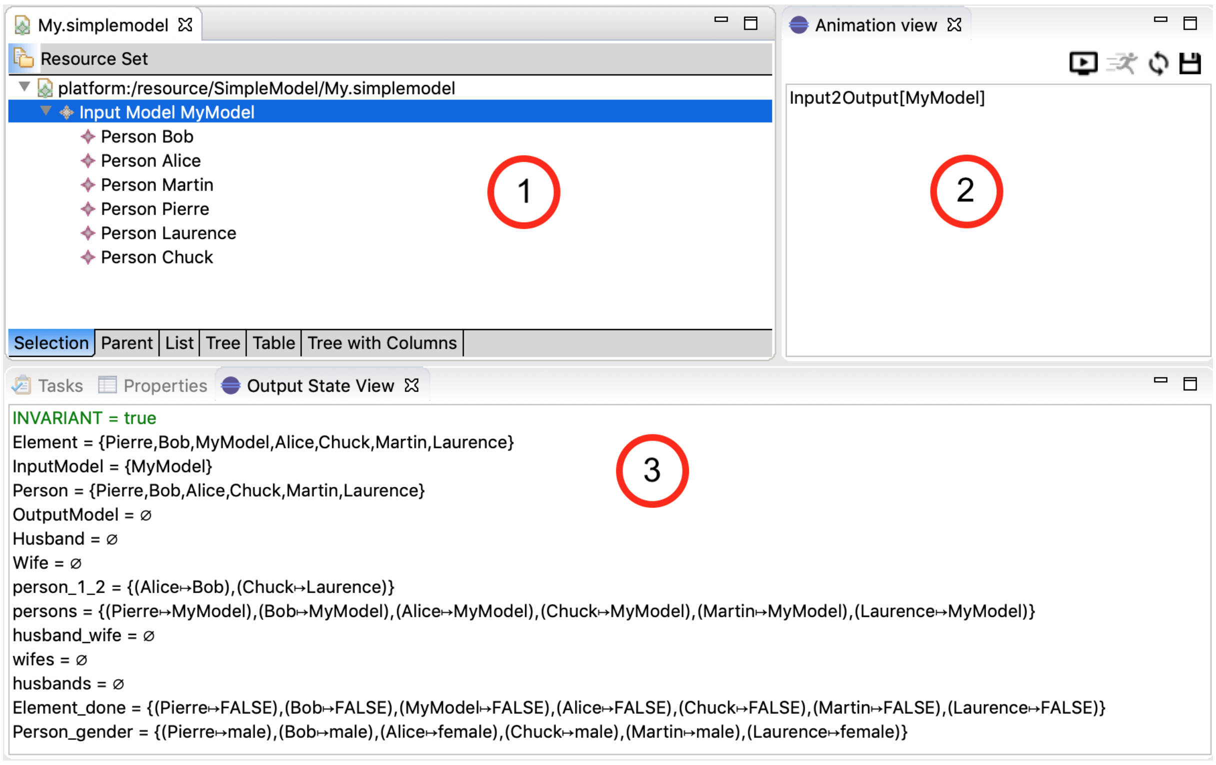
$$
\begin{aligned}
&\mathit{InputModel} := \{\mathit{MyModel}\} \mid\mid \\
&\mathit{Person} := \{\mathit{Bob}, \mathit{Alice}, \mathit{Martin}, \mathit{Pierre}, \mathit{Laurence}, \mathit{Chuck}\} \mid\mid \\
&\mathit{OutputModel} := \{\} \mid\mid \\
&\mathit{Husband} := \{\} \mid\mid \\
&\mathit{Wife} := \{\} \mid\mid
\end{aligned}
$$

Notice that the `Output State View` not only shows the valuations of the variables, but also detects invariant violations (a facility provided by ProB for a given valuation). If the input model contains errors, this view will detect them. This invariant validation acts like the EMF validator: the model is validated against its meta-model. In B, we say that the valuations satisfy the invariant.

Meeduse also asked ProB to calculate the list of operations that are enabled in the current state. This list of operations is shown in view ② of figure 8 (`the animation view`). ProB not only calculates the enabled operations, but also their arguments values when their guards are satisfied. In the case that there are several combinations of values that satisfy an operation guard, Meeduse proposes all the combinations in the `animation view`. In our case, the only enabled operation that can be animated at the initial state is *Input2Output*, and applied to parameter `MyModel`.

If the user double clicks on this operation Meeduse will ask ProB to animate it, which computes on the one hand the next reached state and on the other hand the list of operations that are enabled from this new state. Then Meeduse gets the reached state and translates it back to the EMF model. Figure 9 is a screen-shot after animation of operation `Input2Output` from which we can observe the effect of the rule execution.

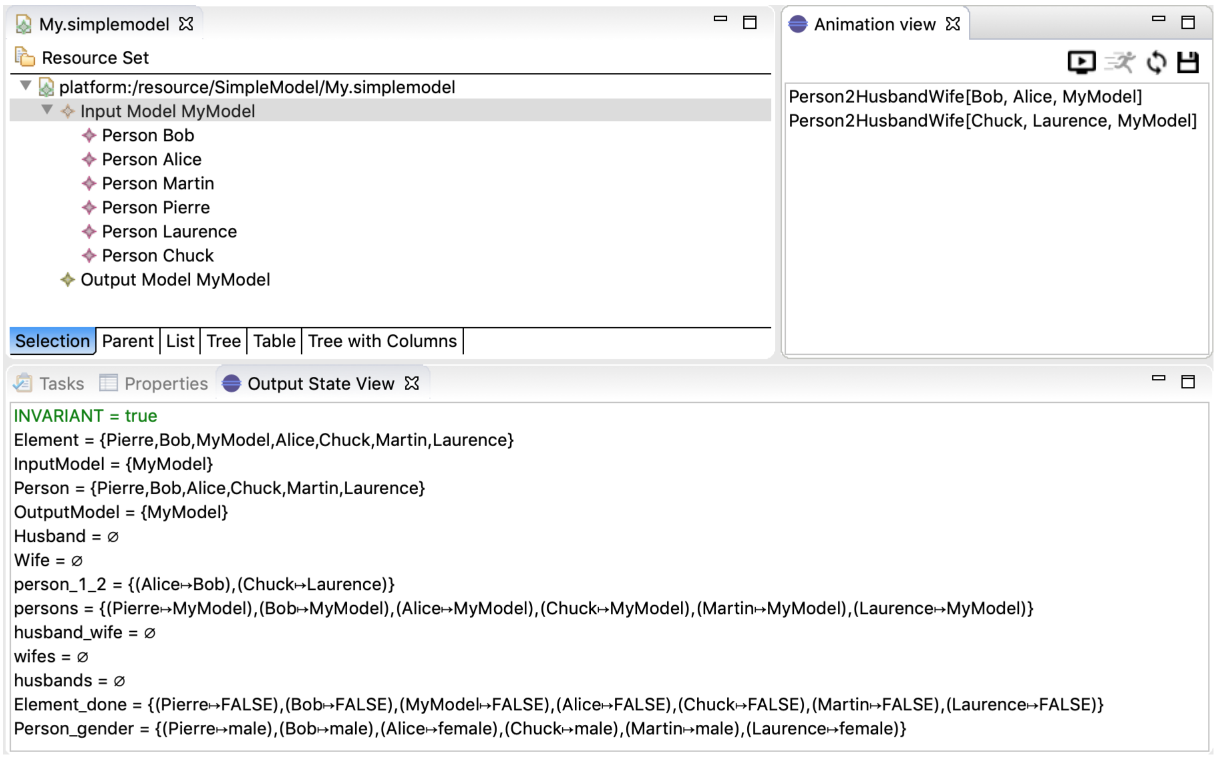
The `output state view` shows the new variable valuations computed by ProB, in particular we can observe that variable `OutputModel` contains a new element. The EMF modeling editor is automatically synchronized. An instance of class `Output`, named `MyModel` was created, which is the expected result of rule `Input2Output`. And finally, `the animation view` shows that from this new state only operation `Person2HusbandWife` can be triggered, but with two possible parameter valuations: `Bob,Alice,MyModel` and `Chuck,Laurence,MyModel`. The user can then choose which one to animate.



Input2Output[MyModel]

```
INVARIANT = true
Element = {Pierre,Bob,MyModel,Alice,Chuck,Martin,Laurence}
InputModel = {MyModel}
Person = {Pierre,Bob,Alice,Chuck,Martin,Laurence}
OutputModel = ∅
Husband = ∅
Wife = ∅
person_1_2 = {(Alice↦Bob),(Chuck↦Laurence)}
persons = {(Pierre↦MyModel),(Bob↦MyModel),(Alice↦MyModel),(Chuck↦MyModel),(Martin↦MyModel),(Laurence↦MyModel)}
husband_wife = ∅
wifes = ∅
husbands = ∅
Element_done = {(Pierre↦FALSE),(Bob↦FALSE),(MyModel↦FALSE),(Alice↦FALSE),(Chuck↦FALSE),(Martin↦FALSE),(Laurence↦FALSE)}
Person_gender = {(Pierre↦male),(Bob↦male),(Alice↦female),(Chuck↦male),(Martin↦male),(Laurence↦female)}
```

Figure 8: Meeduse screenshot: initial values

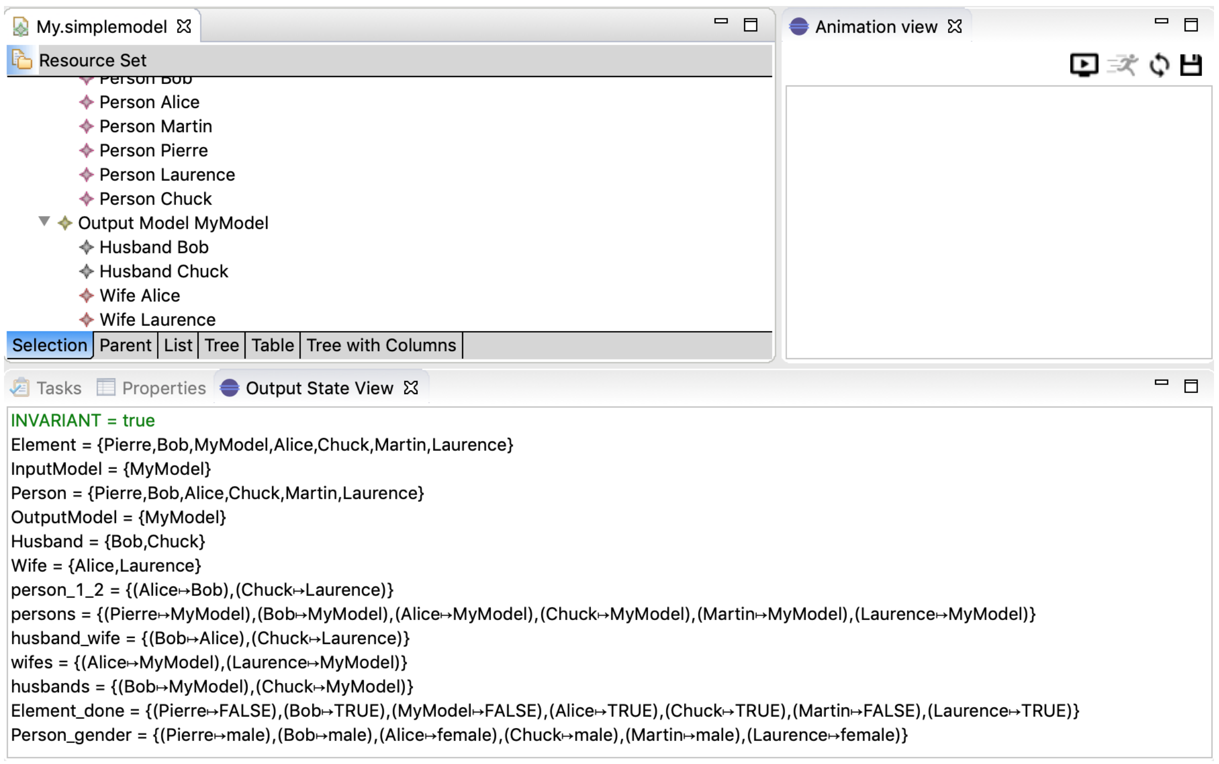


Person2HusbandWife[Bob, Alice, MyModel]
Person2HusbandWife[Chuck, Laurence, MyModel]

```
INVARIANT = true
Element = {Pierre,Bob,MyModel,Alice,Chuck,Martin,Laurence}
InputModel = {MyModel}
Person = {Pierre,Bob,Alice,Chuck,Martin,Laurence}
OutputModel = {MyModel}
Husband = ∅
Wife = ∅
person_1_2 = {(Alice↦Bob),(Chuck↦Laurence)}
persons = {(Pierre↦MyModel),(Bob↦MyModel),(Alice↦MyModel),(Chuck↦MyModel),(Martin↦MyModel),(Laurence↦MyModel)}
husband_wife = ∅
wifes = ∅
husbands = ∅
Element_done = {(Pierre↦FALSE),(Bob↦FALSE),(MyModel↦FALSE),(Alice↦FALSE),(Chuck↦FALSE),(Martin↦FALSE),(Laurence↦FALSE)}
Person_gender = {(Pierre↦male),(Bob↦male),(Alice↦female),(Chuck↦male),(Martin↦male),(Laurence↦female)}
```

Figure 9: Meeduse screenshot: after animation of rule 1

This interactive animation technique applies the transformation rules step-by-step to the input EMF model which is useful for debugging. The animation stops when the B specification reaches a deadlock: a state from which there is no other possible operation to animate. It also stops when an invariant violation is detected, which is not possible in our case as we entirely proved using AtelierB that the transformation rules preserve the invariant. Figure 10 gives the result of the animation at the final state. In the output model, two husbands (Bob and Chuck) and two wives (Alice and Laurence) were created, with the corresponding marriage relation. The valuations of the B variables showed in the `output state view` are equivalent to the EMF model since Meeduse maintains this equivalence at every animation step.



```
Person Bob
Person Alice
Person Martin
Person Pierre
Person Laurence
Person Chuck
Output Model MyModel
Husband Bob
Husband Chuck
Wife Alice
Wife Laurence
```

```
INVARIANT = true
Element = {Pierre,Bob,MyModel,Alice,Chuck,Martin,Laurence}
InputModel = {MyModel}
Person = {Pierre,Bob,Alice,Chuck,Martin,Laurence}
OutputModel = {MyModel}
Husband = {Bob,Chuck}
Wife = {Alice,Laurence}
person_1_2 = {(Alice↦Bob),(Chuck↦Laurence)}
persons = {(Pierre↦MyModel),(Bob↦MyModel),(Alice↦MyModel),(Chuck↦MyModel),(Martin↦MyModel),(Laurence↦MyModel)}
husband_wife = {(Bob↦Alice),(Chuck↦Laurence)}
wifes = {(Alice↦MyModel),(Laurence↦MyModel)}
husbands = {(Bob↦MyModel),(Chuck↦MyModel)}
Element_done = {(Pierre↦FALSE),(Bob↦TRUE),(MyModel↦FALSE),(Alice↦TRUE),(Chuck↦TRUE),(Martin↦FALSE),(Laurence↦TRUE)}
Person_gender = {(Pierre↦male),(Bob↦male),(Alice↦female),(Chuck↦male),(Martin↦male),(Laurence↦female)}
```

Figure 10: Meeduse screenshot: after animation of all rules

When the domain expert agrees with the behaviors showed by animation, transformation rules can be played without any human interaction. After loading a model (figure 7) the user can enable the automatic runner from the `animation view` by clicking on the corresponding icon. This runner executes a random animation: at every step it chooses randomly an operation from those provided by ProB and automatically animates it until reaching the ending state where a deadlock or an invariant violation is detected.

3.5 step 5: Proving the transformation

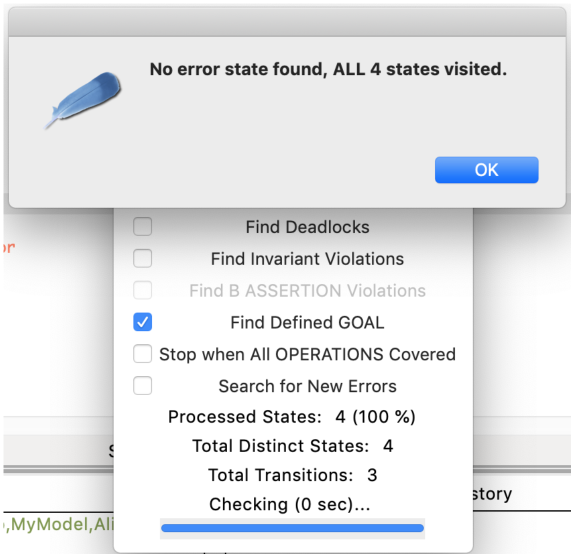
Application of a formal method to model transformation brings several benefits to this field. Indeed, since Meeduse produces a formal specification and automatically manages the traceability between EMF models and the B machine valuations, we can go a step further towards the usage of automatic reasoning tools like model-checkers.

The invariants discussed in step 2 define the properties of our meta-model, not those of the transformation. One way to analyze the transformation and have some confidence about its correctness is to define unwanted states and ask ProB to find them by model-checking. In the following we present some example goals that we defined for our simple transformation:

$$\begin{aligned}
&GOAL1 == \exists\, pp\ .\ (pp \in Husband \wedge Person\_gender(pp) = female)\ ;\\
&GOAL2 == \exists\, pp\ .\ (pp \in Wife \wedge Person\_gender(pp) = male)\ ;\\
&GOAL3 == \exists\, (p1,\, p2).((p1 \mapsto p2) \in husband\_wife \wedge \{p1,p2\} \not\subseteq \mathbf{dom}(person\_1\_2) \cup \mathbf{ran}(person\_1\_2))\ ;\\
&GOAL4 == Husband \cap Wife \neq \emptyset
\end{aligned}$$

The three first goals are linkage properties between the input and the output meta-model. Goal1 and Goal2 for example state that an instance of class Husband is created but from a Person whose gender is female and vice-versa. Goal3 means that a husband and his wife in the output model are created but without any existing marriage link between the input persons from which they originate. Goal4 represents a forbidden property of the output meta-model and means that someone is husband and wife at same time.

Given the B specification extracted from the initial model (that of figure 8), we can ask ProB, from outside Meeduse, to find by model-checking states where one of these goals are satisfied. The answer of ProB is given in figure 11. It mentions that all state space is explored without finding any of the four goals. Since the state space is entirely bounded thanks to valuations, ProB is able to compute all reachable states. This model-checking proof gives a good confidence about the correctness of the transformation. It can be applied to bigger examples in the limits of space memory and the model-checker capacities.


No error state found, ALL 4 states visited.

☐ Find Deadlocks
☐ Find Invariant Violations
☐ Find B ASSERTION Violations
☑ Find Defined GOAL
☐ Stop when All OPERATIONS Covered
☐ Search for New Errors

Processed States: 4 (100 %)
Total Distinct States: 4
Total Transitions: 3
Checking (0 sec)...

Figure 11: Result of ProB after model-checking the input model

3.6 Discussion

In this section we used together four tools:

- EMF for meta-modeling and the automatic extraction of an editor plugin in a classical MDE approach. This was the subject of step 1.
- The AtelierB prover for theorem proving in order to prove that the various B specifications (the model construction and the model transformation) preserve the meta-model structural properties. This was the subject of steps 2 and 3.
- ProB for one of its numerous model-checking capabilities (step 5).
- Meeduse was involved in step 2 in order to translate an ecore meta-model into a B specification, and also in steps 3 and 4 for debugging and executing the transformation given an instance of the input model.

In this work, we are not advising that the MDE expert learns the B method and its associated tooling, or conversely that the FM expert learns meta-modeling with its tools. We believe that skills in both domains are required, and we suggest a way to make people collaborate. Meeduse provides practical solutions for that, as shown by this simplistic example. Furthermore, we didn't exploit neither the whole MDE capabilities nor the whole FM capabilities, but we limited our proposal there to a subset of what can be done for the particular case of model-to-model transformations. Some interesting research directions would be:

- MDE: Apply a model-to-text transformation in order to translate the proved B operations into a well-known MDE language for model-to-model transformation, like ATL. Indeed, once the rules are proved (using a theorem proving technique, or a bounded model-checking approach), we can think about their translation into the ATL language (for example) then apply the ATL tool for running the transformation.
- FM: Apply refinement in order to produce a correct implementation from the B specifications. In B, the refinement technique is well mastered and assisted by automated reasoning tools. It starts from abstract specifications and incrementally introduces properties with additional data until reaching an implementation of the transformation rules.

4 Application to the TTC'2019 case study

4.1 Provided artifacts and some technical details

Meeduse is an eclipse plugin, distributed as an update site of the Eclipse Modeling Platform. We developed and tested it on the Oxygen distribution of Eclipse, with various operating systems: MacOS, Windows and Linux. Its application to the TTC'2019 case study followed exactly the same principles than those presented in the previous section and led to several artifacts provided at:

`https://github.com/meeduse/Meeduse_TTC_2019`

- Meta-modeling artifacts: provided in folder Meeduse_TTC_2019/eclipse_wksp/Meeduse_tt2bdd/model/
  - The merging meta-model (named `meeduse_tt2bdd.ecore`) follows the main principles of the merging step described in section 3.1. This meta-model was done in EMF Ecore-Tools.
  - The model construction B specification (named `meeduse_tt2bdd.mch`) was first automatically generated by Meeduse from the ecore file of the merging meta-model. Then, it was manually enhanced by few additional utility operations which were useful for the transformation but not yet integrated to Meeduse. This B specification is about 1162 lines of code. Refer to section 3.2 for an overview of its main principles.
  - Files with extensions `.bmethod`, `.trace` and `.uml` can be exploited by a Meeduse developer. Note that the tool applies a UML-to-B transformation technique that's why it first generates a UML model from the ecore file. It also integrates a meta-model of the B method which is instantiated during the transformation. The textual file `.mch` is produced from this instance.
  - The model transformation specification (named `meeduse_tt2bddref.ref`). This file will be explained in the following since it gives our solution rules to the TTC'2019 call. The proposed transformation is based on five rules: `TruthTable2BDD`, `SelectPort`, `setLinks`, `Transform` and `Continue`.
- Merging models driver: provided in folder Meeduse_TTC_2019/eclipse_wksp/MeeduseRepo/. On the one hand, this driver produces an instance of the merging meta-model (`meeduse_tt2bdd.ecore`) from a truth table conforming to `TT.ecore`. The generated instance contains exactly the same input truth table. On the other hand, it extracts a binary decision diagram from the merging model which produces an instance of meta-model `BDD.ecore`. The generated instance contains exactly the same output BDD than that computed by Meeduse when executing the transformation rules. This driver is implemented as generic as possible in order to be reused further for other kinds of meta-models. Figure 12 shows how to use the driver on an input truth table. Simply right click on your `.ttmodel` file and then choose `Transform to/from Meeduse -> Transform TruthTable model`. It will create a `.meeduse_tt2bdd` file. After running the transformation right click on the `.meeduse_tt2bdd` file and choose `Transform to/from Meeduse -> Transform meeduse model to BDD`. The resulting file is a `.bddmodel` on which the validator, given by the TTC'2019 organizers, can be executed.
- Modeling artifacts: provided in folder Meeduse_TTC_2019/runtime_wksp/
  - meeduse.tt2bdd.design: this is a sirius project allowing to have a nice representation of the truth table and of the BDD. When executed on a given root element of an EMF resource, Meeduse is synchronised with the resource and then every eclipse tool also synchronised with the same resource is expected to be compatible with Meeduse. We tested it with: Sirius, XText, Ecore Reflective Editor and also

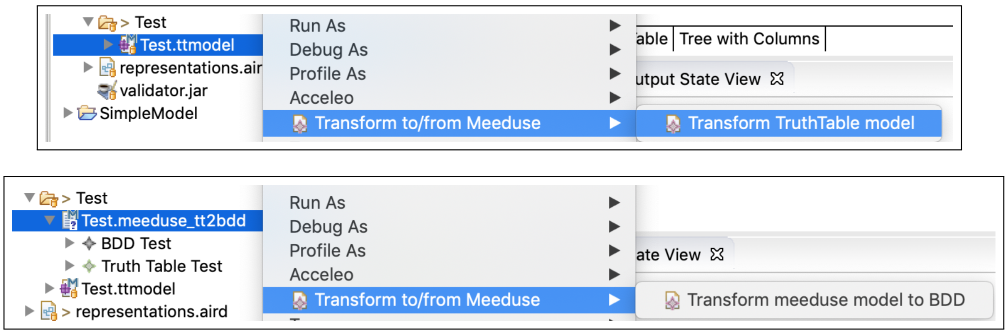
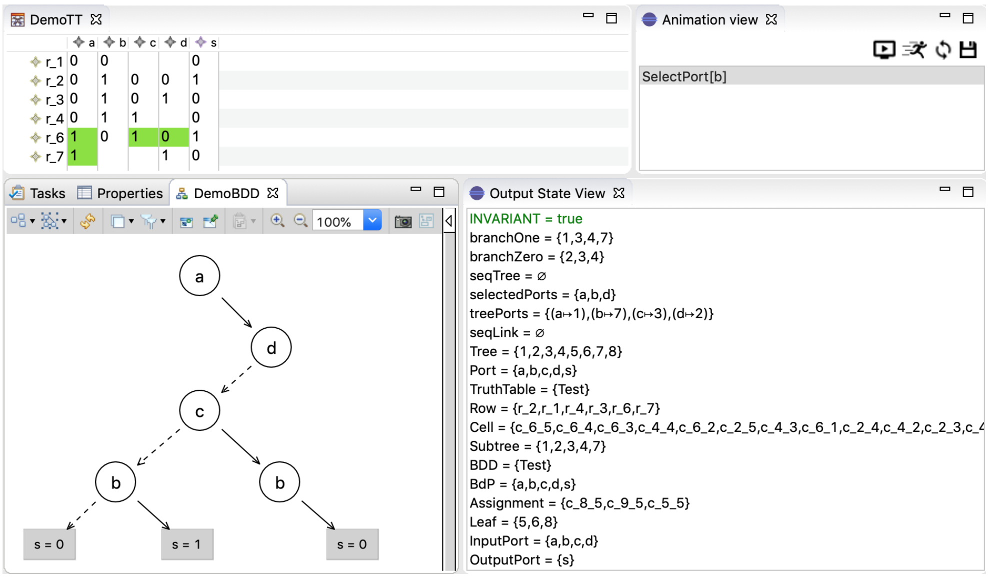


Figure 12: Using the merging driver

automatically generated outline editor plugins from `.genmodel` files. In this solution, one can use our Sirius artifacts for visualizing the models (the TT and the BDD) issued from the merging meta-model. Sirius has two benefits: (1) it favours graphical animation because when executed the model changes (input elements are consumed and output elements are produced) and Sirius automatically updates its rendering at every modification of the model, and (2) it is an easy-way to define conditional styles which changes the visual representation depending on some OCL-like conditions. For this example, when a cell is selected it becomes green which allows the user to know which rows are being transformed. Figure 13 shows the sirius views of a truth table under transformation and the current state of the corresponding BDD. In this snapshot some cells of rows `r_6` and `r_7` are currently selected (for ports `a, c, d`), and a sub-part of the BDD is produced from rows already consumed (`r_5` and `r_8`). In our transformation a consumed row is simply removed from the truth table.



	a	b	c	d	s
r_1	0	0			0
r_2	0	1	0	0	1
r_3	0	1	0	1	0
r_4	0	1	1		0
r_6	1	0	1	0	1
r_7	1			1	0

```
INVARIANT = true
branchOne = {1,3,4,7}
branchZero = {2,3,4}
seqTree = ∅
selectedPorts = {a,b,d}
treePorts = {(a↦1),(b↦7),(c↦3),(d↦2)}
seqLink = ∅
Tree = {1,2,3,4,5,6,7,8}
Port = {a,b,c,d,s}
TruthTable = {Test}
Row = {r_2,r_1,r_4,r_3,r_6,r_7}
Cell = {c_6_5,c_6_4,c_6_3,c_4_4,c_6_2,c_2_5,c_4_3,c_6_1,c_2_4,c_4_2,c_2_3,c_4
Subtree = {1,2,3,4,7}
BDD = {Test}
BdP = {a,b,c,d,s}
Assignment = {c_8_5,c_9_5,c_5_5}
Leaf = {5,6,8}
InputPort = {a,b,c,d}
OutputPort = {s}
```

Figure 13: A Truth Table under transformation

– meeduse.tt2bdd.sample: in this folder we provide models with the resulting BDD. Every model is ranged in a sub-folder with the same name as the model. Folder `Test` contains the illustration model used in the TTC'2019 call for solutions. The demo videos are also done based on this model. Each of these folders contains the three files: `.ttmodel`, `.bddmodel` and `.meeduse_tt2bdd`. Note that our (bad) result is that the biggest model that Meeduse was able to deal with is in folder `GeneratedI1202Seed7634`. For the two remaining models (`GeneratedI1404Seed7634` and `GeneratedI1505Seed282316`) ProB produced a memory overhead. We are currently trying to enhance our tools in order to load such huge models. However, for the other models, our results were satisfactory since our major interest in the TTC'2019 challenge is not to load the most explosive model but to provide a correct transformation on which proof of correctness is done thanks to formal automated reasoning tools: we guarantee the preservation of the meta-model structural properties and also the transformation properties that we identified.

4.2 Transformation rules

The transformation rules are specified in file `meeduse_tt2bddref.ref` where the rules are written in ASCII encoding. In appendix the whole specification (which is about 150 lines of code) is presented using the B language. In this subsection we describe the general idea of the transformation.

First, the definition clause allows to define some kinds of helpers (we reuse the ATL term) that calculate some formula based on the set theory and the first order logic predicates:

$$zeroCells(pp) == (cellPort^{-1}[\{pp\}] \cap cells^{-1}[selectedRows]) \cap Cell\_value^{-1}[\{\mathbf{FALSE}\}]\ ;$$

$$oneCells(pp) == (cellPort^{-1}[\{pp\}] \cap cells^{-1}[selectedRows]) \cap Cell\_value^{-1}[\{\mathbf{TRUE}\}]\ ;$$

$$selectedCells == \mathbf{dom}(Cell\_selected \rhd \{\mathbf{TRUE}\})\ ;$$

$$outputCells(rr) == cells^{-1}[\{rr\}] \cap cellPort^{-1}[OutputPort]\ ;$$

$$inputCells(rr) == cells^{-1}[\{rr\}] \cap cellPort^{-1}[InputPort]$$

- *zeroCells* applied to a port *pp* gives all cells with value 0 that belong to the selected rows. The row selection mechanism will be discussed while presenting the transformation rules. Definition *oneCells* is similar but gives cells with value 1.
- *outputCells* and *inputCells* applied to a row *rr* gives the cells that are concerned by an output or an input port.
- *selectedCells* gives the set of cells that are consumed during the transformation.

The algorithm proposed in the TTC'2019 call for solutions suggests to find an input port which is (ideally) defined in all the Rows, and turn it into an inner node. We somehow applied this technique but introduced a maximality criterion. In fact our algorithm chooses the port whose set of cells is the biggest one, with respect to the selected rows. This maximality is computed by the following definition called *maxPort* . Definition *maxRow* simply gives the ports of a given row *rr*.

$$portRow(rr) == (cellPort^{-1}\ ;\ cells) \rhd rr\ ;$$

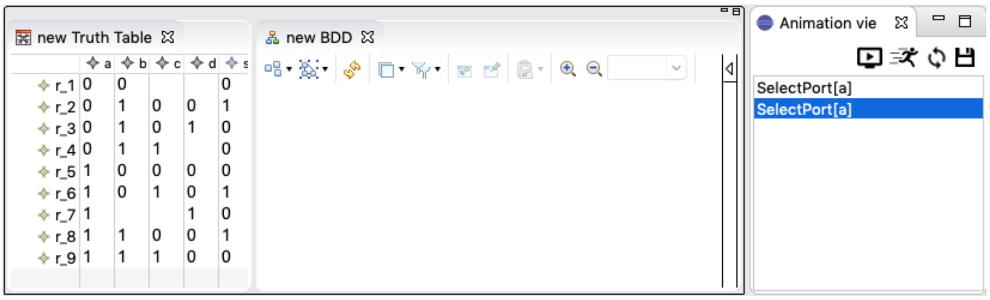
$$\begin{array}{l} maxPort(pp,rr) == pp \in InputPort \wedge rr \subseteq Row \wedge \\ \quad \neg\ (\ \exists\ ss\ .\ (ss \in InputPort \wedge ss \neq pp \wedge ss \in \mathbf{dom}(portRow(rr)) \\ \quad\quad \wedge\ \mathbf{card}(portRow(rr)[\{ss\}]) > \mathbf{card}(portRow(rr)[\{pp\}])))\ ; \end{array}$$

4.3 A step-by-by step execution

The screen-shot of figure 14 shows that at the beginning of the transformation the only port that can be selected is port `a`. This is the expected result since port `a` establishes the maximality criterion. Note that in the initial state all rows are selected and then `a` has the biggest set of cells in comparison with the other ports.

The `Animation view` provides two possibilities for `selectPort(a)` because one can select the zero value or the one value. The animation of the second occurrence of `selectPort(a)` leads to figure 15 where cells of value one of port `a` are selected and a node is created in the BDD model. In fact, every time a port is selected, a node in the BDD is created. For this state, formula *maxPort* identifies port `d` as the one satisfying the maximality criterion and then the animation view gives two possible executions of `selectPort(d)` (for value zero and for value one).

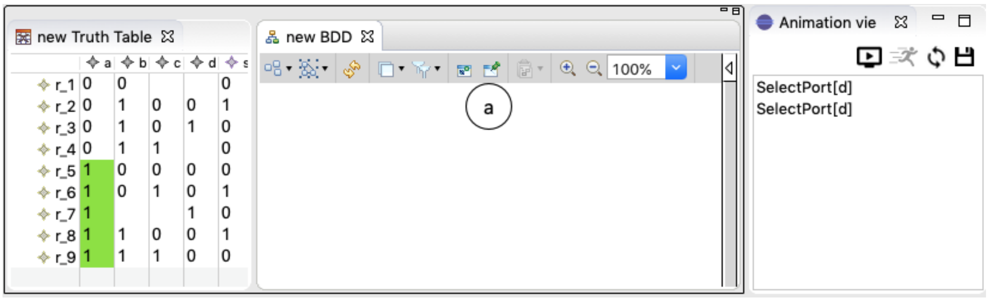
The animation of the first occurrence of `selectPort(d)` leads to the model of figure 16 where zero cells of port `d` are selected and an other node is created in the BDD model. In this new state four possible rules can be triggered because ports `b` and `c` are equivalent regarding the maximality criterion. Meeduse suggests then two possibilities for each of `selectPort(b)` and `selectPort(c)`. Running the second occurrence of `selectPort(b)`



	a	b	c	d	s
r_1	0	0			0
r_2	0	1	0	0	1
r_3	0	1	0	1	0
r_4	0	1	1		0
r_5	1	0	0	0	0
r_6	1	0	1	0	1
r_7	1			1	0
r_8	1	1	0	0	1
r_9	1	1	1	0	0

SelectPort[a]
SelectPort[a]

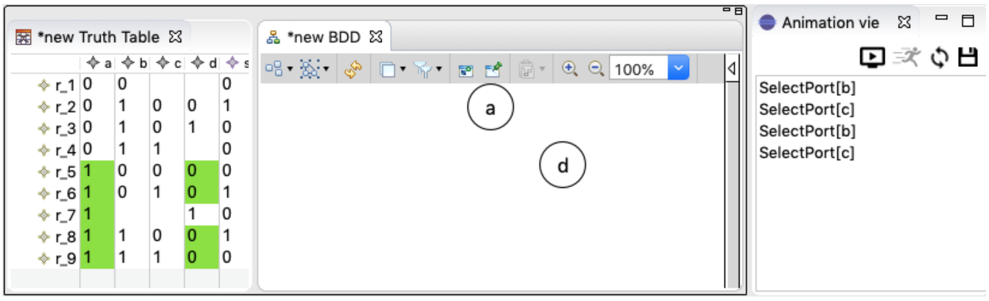
Figure 14: First execution



	a	b	c	d	s
r_1	0	0			0
r_2	0	1	0	0	1
r_3	0	1	0	1	0
r_4	0	1	1		0
r_5	1	0	0	0	0
r_6	1	0	1	0	1
r_7	1			1	0
r_8	1	1	0	0	1
r_9	1	1	1	0	0

SelectPort[d]
SelectPort[d]

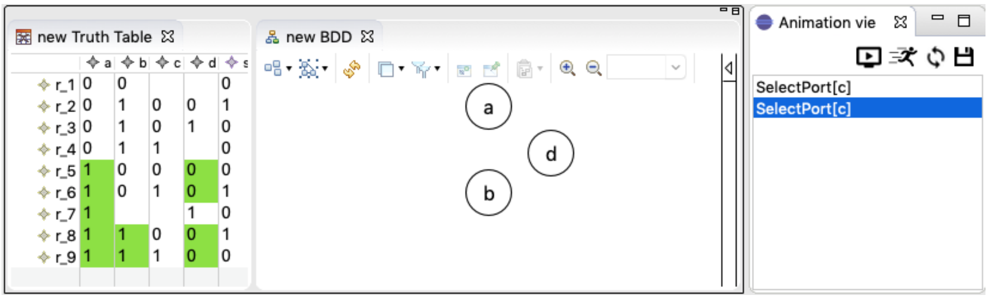
Figure 15: Second execution



	a	b	c	d	s
r_1	0	0			0
r_2	0	1	0	0	1
r_3	0	1	0	1	0
r_4	0	1	1		0
r_5	1	0	0	0	0
r_6	1	0	1	0	1
r_7	1			1	0
r_8	1	1	0	0	1
r_9	1	1	1	0	0

SelectPort[b]
SelectPort[c]
SelectPort[b]
SelectPort[c]

Figure 16: Third execution



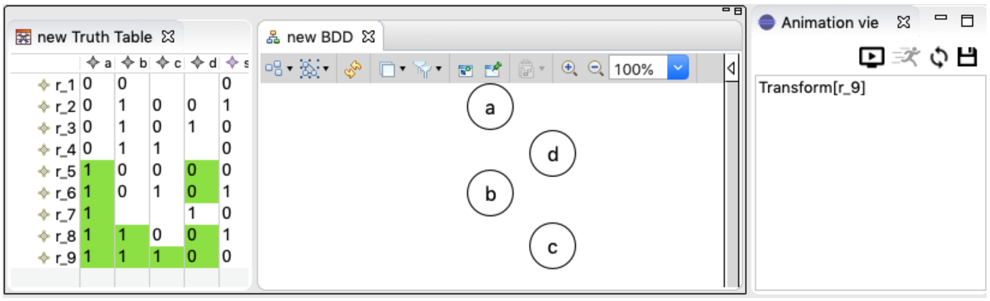
	a	b	c	d	s
r_1	0	0			0
r_2	0	1	0	0	1
r_3	0	1	0	1	0
r_4	0	1	1		0
r_5	1	0	0	0	0
r_6	1	0	1	0	1
r_7	1			1	0
r_8	1	1	0	0	1
r_9	1	1	1	0	0

SelectPort[c]
SelectPort[c]

Figure 17: Fourth execution

produces figure 17 from which it is possible to trigger finally rule `selectPort(c)` and hence reach the end of the selection step with nodes extraction.

From step of figure 17 the execution of the second occurrence of `selectPort(c)` leads to figure 18 where only one row `r_9` has all its cells selected. Now, only rule `Transform(r_9)` is proposed. When applied this rule iterates several times on row `r_9` until it transforms it entirely. The first calls transform non-deterministically the row output cells into assignments with the same values (figure 19). After consuming all output cells (in this case we have only one output cell), this rule creates a Leaf and then removes the row from the model together with its cells. By this way row `r_9` and its cells will not be considered for the next calculus of the enabledness conditions of the transformation rules.

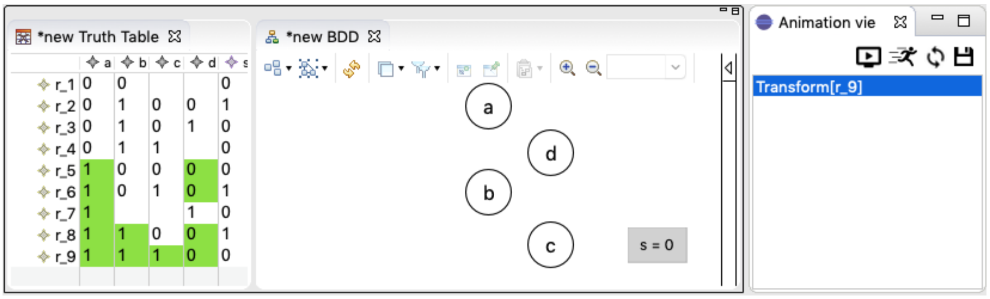


new Truth Table

	a	b	c	d	s
r_1	0	0			0
r_2	0	1	0	0	1
r_3	0	1	0	1	0
r_4	0	1	1		0
r_5	1	0	0	0	0
r_6	1	0	1	0	1
r_7	1			1	0
r_8	1	1	0	0	1
r_9	1	1	1	0	0

Transform[r_9]

Figure 18: Fifth execution



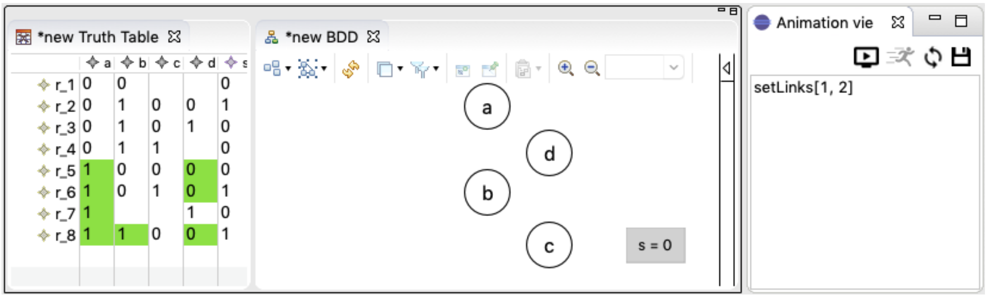
*new Truth Table

	a	b	c	d	s
r_1	0	0			0
r_2	0	1	0	0	1
r_3	0	1	0	1	0
r_4	0	1	1		0
r_5	1	0	0	0	0
r_6	1	0	1	0	1
r_7	1			1	0
r_8	1	1	0	0	1
r_9	1	1	1	0	0

Transform[r_9]

Figure 19: Sixth execution

In figure 20, after removing row `r_9`, the enabled rules are those that create links between nodes, assignments and leafs. These are successive occurrences of operation `setLinks`: `setLinks(1,2)`, `setLinks(2,3)`, `setLinks(3,4)`, `setLinks(4,5)`. The valuations correspond to tree identifiers managed by the internal state of the B specification every time an instance of class tree is produced.



*new Truth Table

	a	b	c	d	s
r_1	0	0			0
r_2	0	1	0	0	1
r_3	0	1	0	1	0
r_4	0	1	1		0
r_5	1	0	0	0	0
r_6	1	0	1	0	1
r_7	1			1	0
r_8	1	1	0	0	1

setLinks[1, 2]

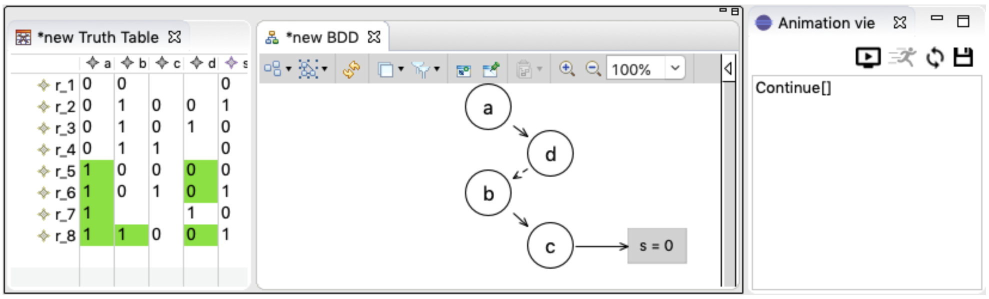
Figure 20: Seventh execution

Figure 21 gives the resulting model after a row is entirely consumed and the corresponding path in the BDD is produced. Rule `continue` then updates the internal state of the B machine and makes possible the port selection process for the remaining rows. From the model of figure 21 only port `c` with value zero can be selected. Indeed, given the set of selected rows and cells, only port `c` satisfies the maximality criterion.

4.4 Checking the transformation rules

The transformation sequence that is executed by Meeduse based on our transformation rules (refer to annexes for the formal details), can be summarized by:

- `TruthTable2BDD`: this rule creates a BDD from a truth table under the condition that the BDD was not previously created. It also creates the BDD input and output ports, and then adds all generated ports to the BDD. It calls sequentially modeling operations `BDD_NEW`, `BddInput_NEW`, `BddOutput_NEW` and `BDD_Addports` which were generated from the meta-model.



	a	b	c	d	s
r_1	0	0			0
r_2	0	1	0	0	1
r_3	0	1	0	1	0
r_4	0	1	1		0
r_5	1	0	0	0	0
r_6	1	0	1	0	1
r_7	1			1	0
r_8	1	1	0	0	1

```
Continue[]
```

Figure 21: A successive animation of setLink

- `SelectPort`: this rule selects an input port satisfying the maximality condition and depending on the current state of the transformation and then decides whether it creates a new tree or reuses a tree already created. When it creates a tree it calls the modeling operation `Subtree_NEW`. For the first tree only it calls `Tree_SetOwnerBDD` which marks this first tree as a root tree. These are the first actions that the operation makes and which are defined by the first SELECT clause. The next actions defined in the second SELECT clause of this operation select non-deterministically cells of value zero or those of value one. This explains the two possible instances of operation `SelectPort` that can be applied to the same selected port.

- `Transform`: this operation can be triggered only when there is no more one selected row, and allows to consume the row and its cells. It has two deterministic behaviours defined by clause IF: creates an assignment for output cells if there exists an output cell not yet consumed, or creates a leaf if all output cells are consumed.

- `Continue`: it is not really a transformation rule because it is mainly used as a checkpoint for the model-checker. The model-checking proof technique applied to this case study, verifies the transformation properties not for all the state space (like for the tutorial example), but before every call to operation `Continue`.

The ProB model-checker computes exhaustively all the execution possibilities. Note that we added some preference to the DEFINITION clause:

```
SET_PREF_SHOW_EVENTB_ANY_VALUES == TRUE
SET_PREF_MAX_OPERATIONS == 4
```

The first preference allows the tool to explicitly show parameters when running the transformation. The second preference allows to configure the maximum number of enabled operations. In fact, at every step ProB computes operations whose guard is evaluated to true and will limits its analysis of every operation to the maximum preferred size. In the example above, number 4 is sufficient but the user can choose to modify it for his convenience. ProB allows to check the reachability of unwanted states using goals and based on the maximum number of computed operations:

- For every consumed row, one distinct leaf is created.

- For every output cell of a consumed row, one assignment is created with the same value.

- When there is no row to deal with then all tree links are produced.

- Values of trees in a computed BDD path (before running operation `Continue`) are equivalent to the selected cells values in the consumed row.

Our exhaustive model-checking validation technique was done on input models of reasonable sizes: until 5 input ports, 2 output ports, and 32 rows. We believe that the model-checking proofs done given these models are sufficient to have some confidence about our rules because most of the provided models are generated by a combinatorial technique. We think that since the proof succeeded for a restricted number of port combinations, then it can be generalized for bigger combinations. Not only the algorithm applies redundantly the same principles to the consumed rows but also the properties of these rows (by means of cell values and connexion with ports) are similar and they don't change during the transformation.

Further study may be required in order to show the existence of a least fixed point, from which one can generalize the proof and stop building input models for the exhaustive model-checking. For bigger examples we simply apply Meeduse as a runner of the transformation in order to get the output BDD. For these examples we set property `SET_PREF_MAX_OPERATIONS` to one, which forces ProB to compute only one instance of each operation which is immediately animated by Meeduse in the automatic execution mode. Finally, we note that all our output models successfully passed the validator provided by the TTC'2019 organizers which was somehow expected since we spent a lot of time on checking the B specifications using automated reasoning tools. Meeduse was also helpful for debugging the formal specifications thanks to the visualization designed in Sirius.

5 Conclusion

First, from a methodological point of view we were able to define how formal DSL execution semantics can be applied to define model transformations. Merging meta-models required the implementation of an additional driver, but we believe that Meeduse can be adapted to deal with two or several heterogeneous meta-models. This issue is now considered as a possible evolution of the tool. In general, we are satisfied by the application of Meeduse to the model-to-model transformation problem because as far as we know none of the existing works combine theorem proving and model-checking in a publicly available tool and which is well integrated within EMF-based platforms.

For performance, it mainly depends on the performance of ProB. Execution times spent by the tool to generate the output models are given in table 1. The number of model elements grow exponentially. For 14 input ports and 2 output ports, Meeduse reached an out of memory. For bigger examples, it should be useful to try the experiments on a machine with higher performances than that on which we have done these measures.

Input Model	rows	input ports	output ports	Cells	Exec. Time
`GeneratedI4O2Seed42`	16	4	2	96	3s
`GeneratedI5O2Seed5`	32	5	2	224	5s
`GeneratedI8O2Seed68`	256	8	2	2560	1mn3s
`GeneratedI8O4Seed68`	256	8	4	3072	2mn1s
`GeneratedI10O2Seed68`	1024	10	2	20480	18mn8s
`GeneratedI12O2Seed7634`	4096	12	2	57344	6h40mn

Table 1: Some performance measures

For readability, we believe that the verbose notation of the B method is accessible because it recalls some programmatic styles. It is often said to be less difficult than other formal notations. Our transformation file is about 150 lines which remains reasonable. However, we don't believe that an MDE expert must become expert in the B method in order to apply Meeduse. We think that model transformation interests the safety-critical community whose main intention is to develop systems which are bug-free because a failure can lead to human loss. This study gives solutions to this problem with the support of a tool. In this sense we advocate for a collaboration between MDE and FM experts. The B specification that we provide is expected to be readable for a FM expert, may be more readable than an ATL or a QVT transformation. But this intuition needs some empirical studies in order to be confirmed.

References

[1] J.-R. Abrial. *The B-book: Assigning Programs to Meanings.* Cambridge University Press, New York, NY, USA, 1996.

[2] Akram Idani, Yves Ledru, Abderrahim Ait Wakrime, Rahma Ben Ayed, and Philippe Bon. Towards a tool-based domain specific approach for railway systems modeling and validation. In *Third International Conference, RSSRail 2019, Lille, France, June 4-6, 2019, Proceedings*, volume 11495 of *LNCS*, pages 23–40. Springer, 2019.

[3] Michael Leuschel and Michael Butler. Prob: an automated analysis toolset for the b method. *International Journal on Software Tools for Technology Transfer*, 10(2):185–203, Mar 2008.

Appendix

```
REFINEMENT
  $meeduse\_tt2bddref$
REFINES
  $meeduse\_tt2bddmain$
INCLUDES
  $meeduse\_tt2bdd$
DEFINITIONS
  $selectedRows$ ==
          LET $cr$ BE $cr = \{cc,rr \mid rr \in Row \wedge cc = \mathbf{card}(cells^{-1}[\{rr\}] \cap selectedCells)\}$ IN
            LET $mx$ BE $mx = \mathbf{max}(\mathbf{dom}(cr))$ IN
              $\mathbf{cr}[\{mx\}]$
            END
          END;

  $portRow(rr) == (cellPort^{-1} ; cells) \rhd rr$ ;

  $maxPort(pp,rr) == pp \in InputPort \wedge rr \subseteq Row \wedge$
      $\neg\ (\exists\ ss\ .\ (ss \in InputPort \wedge ss \neq pp \wedge ss \in \mathbf{dom}(portRow(rr))$
         $\wedge\ \mathbf{card}(portRow(rr)[\{ss\}]) > \mathbf{card}(portRow(rr)[\{pp\}])))$ ;

  $zeroCells(pp) == (cellPort^{-1}[\{pp\}] \cap cells^{-1}[selectedRows]) \cap Cell\_value^{-1}[\{\mathbf{FALSE}\}]$ ;

  $oneCells(pp) == (cellPort^{-1}[\{pp\}] \cap cells^{-1}[selectedRows]) \cap Cell\_value^{-1}[\{\mathbf{TRUE}\}]$ ;

  $selectedCells == \mathbf{dom}(Cell\_selected \rhd \{\mathbf{TRUE}\})$ ;

  $outputCells(rr) == cells^{-1}[\{rr\}] \cap cellPort^{-1}[OutputPort]$ ;

  $inputCells(rr) == cells^{-1}[\{rr\}] \cap cellPort^{-1}[InputPort]$


VARIABLES
  $branchOne$, $branchZero$,
  $seqTree$, $selectedPorts$, $treePorts$, $seqLink$
INVARIANT
  $branchOne \subseteq Tree \wedge$
  $branchZero \subseteq Tree \wedge$
  $selectedPorts \subseteq Port \wedge$
  $treePorts \in InputPort \leftrightarrow Tree \wedge$
  $seqTree \in \mathbf{seq}(Tree) \wedge$
  $seqLink \in \mathbf{seq}(\mathbf{BOOL})$
INITIALISATION
  $branchOne, branchZero, selectedPorts := \emptyset , \emptyset , \emptyset \parallel$
  $treePorts, seqTree, seqLink := \emptyset , \emptyset , \emptyset \parallel$
  $setLastTree(\mathbf{card}(Subtree))$
```

```
OPERATIONS
TruthTable2BDD =
  ANY $src$ WHERE
    $src \in TruthTable \wedge src \notin BDD$
  THEN
    BDD_NEW($src$) ;
    BddInput_NEW($InputPort$) ;
    BddOutput_NEW($OutputPort$) ;
    BDD_Addports($bdd$, $InputPort \cup OutputPort$)
  END;

SelectPort =
  ANY $port$ WHERE
    $InputPort \neq \emptyset$
     $\wedge\ port \in BddInput$
     $\wedge\ port \notin cellPort[selectedCells]$
     $\wedge\ maxPort(port, selectedRows)$
     $\wedge\ \mathbf{ran}(seqTree) \cap Leaf = \emptyset$
  THEN
    SELECT
      $port \in selectedPorts$
    THEN
      $seqTree := seqTree \leftarrow (treePorts(port))$
    WHEN
      $port \notin selectedPorts$
       $\wedge\ \neg\ (\ \exists\ portBis\ .\ (portBis \notin cellPort[selectedCells]$
              $\wedge\ maxPort(portBis, selectedRows)$
              $\wedge\ portBis \in selectedPorts))$
    THEN
      Subtree_NEW($port$) ;
      BEGIN
        $selectedPorts := selectedPorts \cup \{port\}\ ||$
        treePorts($port$) $:= lastTree\ ||$
        $seqTree := seqTree \leftarrow (lastTree)$
      END ;
      IF $lastTree = 1$ THEN
        Tree_SetOwnerBDD($lastTree$, $bddPorts(port)$)
      END
    END ;

    SELECT $zeroCells(port) \neq \emptyset$ THEN
      Cells_SetSelected($zeroCells(port)$, TRUE) ||
      $branchZero := branchZero \cup treePorts[\{port\}]\ ||$
      $seqLink := seqLink \leftarrow$ (FALSE)
    WHEN $oneCells(port) \neq \emptyset$ THEN
      Cells_SetSelected($oneCells(port)$, TRUE) ||
      $branchOne := branchOne \cup treePorts[\{port\}]\ ||$
      $seqLink := seqLink \leftarrow$ (TRUE)
    END
END;
```

```
setLinks =
   ANY $t1$, $t2$ WHERE
      $t1 = \mathbf{first}(seqTree) \wedge t2 = \mathbf{first}(\mathbf{tail}(seqTree))$
       $\wedge\ \mathbf{ran}(seqTree) \cap Leaf \neq \emptyset$
       $\wedge\ \mathbf{card}(seqTree) > 1$
   THEN
      IF $\mathbf{first}(seqLink)$ = TRUE THEN
         Subtree_SetTreeForOne($t1$, $t2$) ||
         $seqLink := \mathbf{tail}(seqLink)$
      ELSE
         Subtree_SetTreeForZero($t1$, $t2$) ||
         $seqLink := \mathbf{tail}(seqLink)$
      END ||
      $seqTree := \mathbf{tail}(seqTree)$
   END;

Continue =
   SELECT
      $\mathbf{card}(seqTree) = 1 \wedge \mathbf{ran}(seqTree) \cap Leaf \neq \emptyset$
   THEN
      $seqTree := \mathbf{tail}(seqTree)$
   END ;

Transform =
   ANY $row$ WHERE
      $row \in selectedRows$
       $\wedge\ \mathbf{card}(selectedRows) = 1$
      $\wedge\ \forall\, cc\ .\ (cc \in cells^{-1}[\{row\}] \wedge cellPort(cc) \notin OutputPort \Rightarrow Cell\_selected(cc) = \mathbf{TRUE})$
   THEN
      IF $\mathbf{card}(outputCells(row)) > \mathbf{card}(assignPort[outputCells(row)])$ THEN
         ANY $as$ WHERE $as \in outputCells(row) \wedge as \notin Assignment$ THEN
            Assignment_NEW($as$, $cellPort(as)$, $Cell\_value(as)$)
         END
      ELSE
         Leaf_NEW ;
         $seqTree := seqTree \leftarrow (lastTree)$ ;
         Assignments_SetOwner($outputCells(row)$, $lastTree$) ;
         Cells_Free($inputCells(row) \cup outputCells(row)$) ;
         $selectedPorts := selectedPorts$ -
               $\{app \mid app \in selectedPorts \wedge treePorts(app) : (branchZero \cap branchOne)\}$;
         Row_Free($row$)
      END
   END
END
```