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Laws of Timed State Machines

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State machines are widely used in industry and academia to capture behavioural models of control. They are included in popular notations, such as UML and its variants, and used (sometimes informally) to describe computational artefacts. In this paper, we present laws for state machines that we prove sound with respect to a process algebraic semantics for refinement, and complete, in that they are sufficient to reduce an arbitrary model to a normal form that isolates basic (action and control) elements. We consider two variants of UML-like state machines, both enriched with facilities to deal with time budgets, timeouts and deadlines over triggers and actions. In the first variant, machines are self-contained components, declaring all the variables, events and operations that they require or define. In contrast, in the second variant, machines are open, like in UML for instance. Laws for open state machines do not depend on a specific context of variables, events and operations, and normalization uses a novel operator for open-machine (de)composition. Our laws can be used in behaviour-preservation transformation techniques. Their applications are automated by a model-transformation engine.

Keywords: UML; robotics; verification; normalization; CSP; refinement

1. INTRODUCTION

In both the industrial and research communities, state machines are widely used [1–3] to record and convey designs and simulations of (embedded) control software [4]. For long now, state machines have also been incorporated in more general modelling notations, notably, the very popular UML [5] and SysML [6].

In this paper, we present laws of state machines. We consider two different notations: one for self-contained components that define behavioural models in the context of identified variables, events and operations, and one for open machines, whose context is defined in other components of the models, such as (active) classes. Self-contained components can be analysed in isolation, and are convenient for compositional verification. Open machines are akin to those adopted in UML, and support a flexible approach to modelling. Verification of an open machine typically needs to be in context, rather than compositional.

For decades, laws [7] have been recognized as useful results to support reasoning about programs [8], designing correct compilers [9–11] and, when interpreted as program transformations, supporting informal programming practices such as refactoring [12–14]. Laws of Occam [15] capture useful properties of concurrency and communication. Laws of functional programming are elegantly addressed in [16]. Laws of logic programming are presented in [17]. Laws of object orientation can be found in [18], and for a variant of Java for safety-critical systems in [19]. Laws of hardware synthesis are the subject of [20].

In all these works, a normal form is used to attest the expressiveness of a proposed set of laws by establishing a relative notion of completeness via an associated strategy for normalization. For example, a (relative) notion of completeness for laws of concurrent operators can be established by showing that the laws

are powerful enough to reduce arbitrary concurrent programs to a sequential program that uses a restricted subset of the language constructs, that is, a normal form. This is done, for instance, for Occam [15]. Similarly, the purpose of the laws in [18] is to capture algebraic properties of object-oriented constructs. By showing that an arbitrary program in an object-oriented language like Java can be reduced, using the laws, to an imperative subset, that is, to a normal form, a measure of the comprehensiveness of the laws is provided.

For state machines, there are numerous formal semantics. We can find formalizations using tailored semantic domains [21–23], graph transformations [24], programs [25] and process algebra [26, 27]. Besides UML machines, there are semantics for SysML [28] and Stateflow [29]. For a very specific notion of state machine, used to represent data structures and types in a program context, there is a seminal calculus [30]. We are, however, not aware of a set of algebraic laws for a state-machine notation that includes constructs to define time properties, and that have been proved sound using an independent denotational model.

Both our self-contained and open machines define behaviour in terms of variables, events and operations. Events represent interactions (via sensors and actuators, for example). Operations represent computational mechanisms potentially defined by further machines. In both notations, state machines can be hierarchical, and the action language is well-defined, including extra time constructs, not available in UML, for modelling of temporal properties: budgets, timeouts and deadlines. Well-formedness conditions rule out inter-level transitions following accepted good practice [31].

A self-contained state machine encapsulates a declaration of a context of variables (local and required), events and required

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operations that can be used in its definition. In concrete terms, we consider the state-machine notation adopted in a domain-specific language for robotics called RoboChart [32]. In particular, we consider the RoboChart constructs to specify time budgets, timeouts and deadlines, over triggers and actions, and also use of clocks, to capture time properties of control designs.

A number of domain-specific languages have been proposed [33]. RoboChart is distinctive in its semantics, and support for (automatic) verification of design properties [34]. The semantics is defined in a timed variant *tock*-CSP of the process algebra for refinement CSP [35]. We use this semantics in the work presented here to prove soundness of our laws.

An open state machine can be used in any context where their elements are, or can be regarded to be, in scope. In this respect, they are similar to UML state machines, but we retain a well-defined action language, timed constructs, and rule out inter-level transitions. For open machines, we define in this paper a *tock*-CSP semantics to support the proof of soundness of the laws.

Our primary contribution here is two sets of laws, for RoboChart and for open machines. The notion of equality is that embedded in the notion of refinement in *tock*-CSP. Precisely, equality indicates that the processes for the equated terms refine each other, so that the diagrams define the same behaviour in terms of possible timed interactions and deadlocks. Here, an interaction corresponds to a required variable access, event occurrence or operation call. For machines that define operations, equality considers all contexts in which the operation can be called.

Additional contributions are a compositional account of RoboChart semantics, a novel semantics for open state machines, proof of soundness of the laws and notions of completeness for the two sets of laws. In each case, we define a normal form that characterizes a machine whose control structure embedded in (hierarchical) states, and actions, including those involving timed statements, is revealed. For that, we use operation calls to replace actions, and, in the case of open state machines, a novel machine combinator.

These normal forms do not flatten the structure of a model (as usual in works on algebraic semantics). Instead, they isolate the action and control flow constructs, so that a machine is expressed using a small number of primitive patterns. This means that model transformation techniques (for refactoring or translation to other notations, for instance) can be significantly simplified to consider just these patterns. A normalization strategy establishes that our laws are enough to normalize any RoboChart or open machine.

Next, we give an overview of our notations for RoboChart and open state machines. Our normal forms are defined in Section 3. The laws are presented in Section 4 as part of the description of normalization procedures. Evaluation of our work comes in three forms: in Section 5 we present examples and a tool that mechanizes our laws and normalization strategies, and in Section 6 we describe our proofs of the soundness of the laws. We conclude in Section 7.

2. OUR MACHINE NOTATIONS

The core notation for the state machines considered here is, by far and large, standard. To illustrate the constructs, we present a model for the system in [36]: an efficient robot to harvest apples in an orchard in which the tree branches are trained along a trellis. We capture the algorithm in [36]. It seems to have some limitations, but given the use of an informal notation for its

description, there may be ambiguities in the description rather than in the actual implemented algorithm. It is not our objective, however, to redesign the algorithm; to illustrate the use of our notations and laws, a faithful account of the work in [36] is more interesting. (We leave it as future work to analyse the application and possibly produce a modified design.)

The robotic platform for the harvester is an arm, with a custom manipulator and end-effector with six degrees of freedom. To define a self-contained component that models its control software, we define in Fig. 1 some interfaces. First, the interface **ArmOperations** declares operations that represent facilities of the platform to move the arm to various positions and to manipulate the apples. The system also includes a camera; it is represented by an event **takePic** in the interface **Camera**. This (input) event communicates an image, represented here as an element of a type **Image**, whose definition (omitted in Fig. 1) simply gives its name. The complete RoboChart model is available¹.

Additional interfaces in Fig. 1 define variables, events and operations that are not provided by the platform. These extra variables are either local to machines or shared among machines. The extra events are used for communication between machines, rather than with the platform. Finally, the extra operations are implemented for the application, rather than embedded in the platform. In the example, the extra interface **GlobalVariables** in Fig. 1 declares two variables. We have a record of the set of **apples** found in the current image via their coordinates in 3D. For each of them, we also record a tuple with three **positions**: these are the joint positions (of type **JointPos**) for the arm to approach, pick and store the apple. The values of these variables are defined with the help of an operation **CHTBA()**, which models a **Vision** algorithm that uses Circular Hough Transformation (CHT) and blob analysis to identify the apples. Using **positions**, a **TravellingSalesman** algorithm defines the **NearestNeighbour()** apple.

The interfaces **SolverControl** and **GoHomeControl** declare events used to control the flow of execution. Populating **positions** using an inverse kinematic solver, and manoeuvring the arm to a home position occur in parallel. The events control the forking.

Finally, the interfaces **TimeConstants** and **Locations** declare constants used to specify time properties of the control software, and the home and store positions of the arm (**homePos** and **storagePos**).

Figure 2 shows a RoboChart state machine **AppleHarvestControl** for the harvester control software. This component uses the interfaces in Fig. 1 to declare its required (⊗) variables and operations, and the events and local constants that it defines (⊙). In addition, **AppleHarvestControl** declares three local variables **img**, **localized** and **nextApple**. In what follows, we describe how the machine uses all the elements in this context.

A state machine has a unique initial junction (represented by a black circle with an *i*). In **AppleHarvestControl**, it has a single transition out of it into the state **Prepare**. States have **entry**, **during** and **exit** actions, executed when the state is entered, while it is active, and when it is exited. In **Prepare**, the **entry** action first calls the platform operation **hideArm()** to take the arm out of the way of the camera.

In sequence (;), we have a **wait** statement, which can be used to define a time budget: an amount of time to wait, that is, pause, before proceeding. In this case, this is an amount of time between 0 and **hideTime** time units, which, in an implementation, is used to allow the effect of the call **hideArm()** to take place, and the arm to position itself out of the way. The nondeterminism in the time budget indicates that an implementation may allow for almost no

¹ robo-star.cs.york.ac.uk/case_studies/



Figure 1. Data model for the apple harvester.

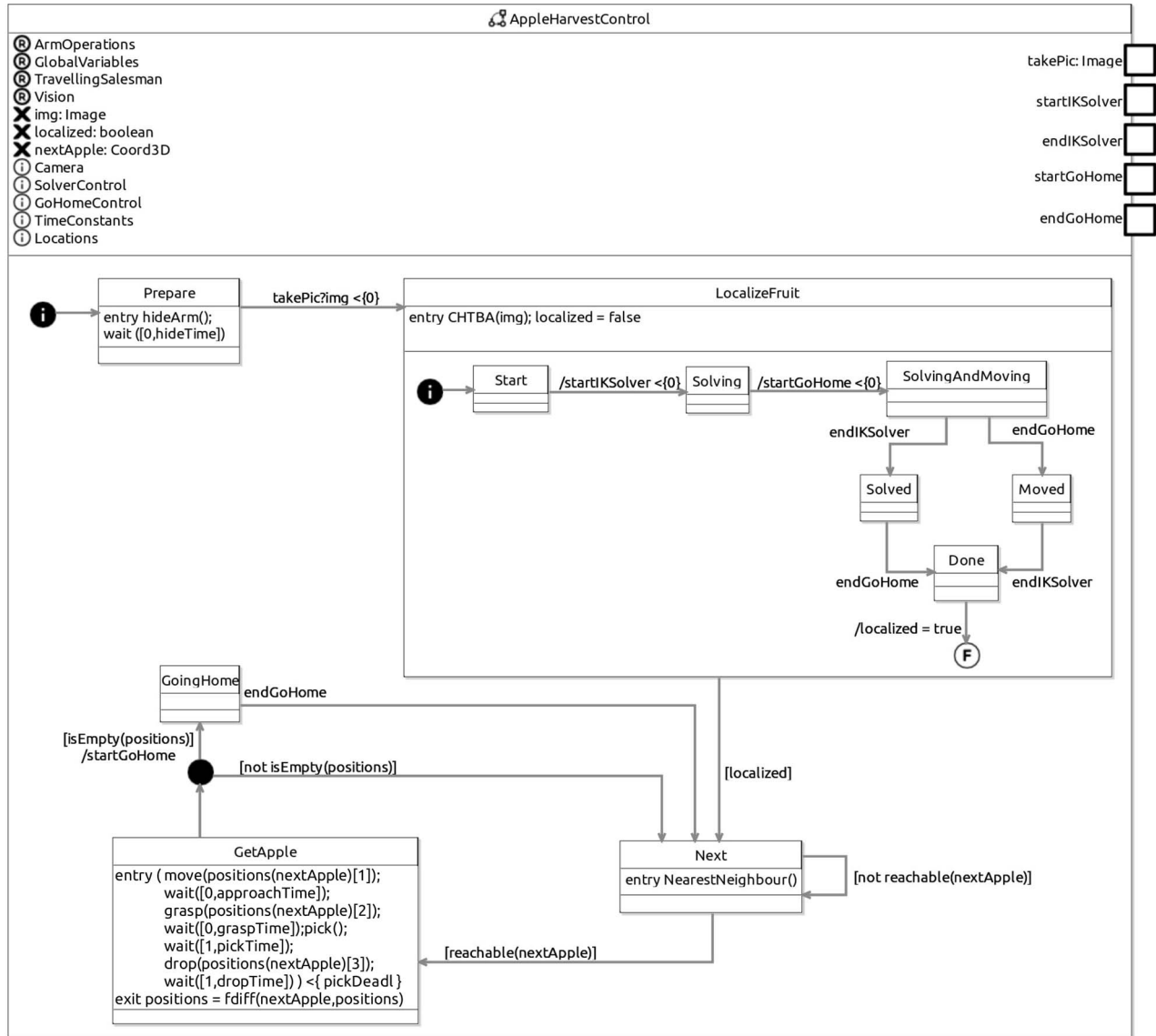


Figure 2. Main state machine for the apple harvester.

time, if the arm is very fast, or is already hidden, for example, or take up to `hideTime` time units. Here, `hideTime` is a constant whose value is not defined in the model, and depends on the specific arm and environment design.

Once a state is entered, the transitions out of it become available if their guards, if any, hold and their trigger events, if any, can occur. For `Prepare`, its single transition has a trigger: `takePic`. Events take place when a communication via the connection with this event is available. For `takePic`, the connection is ultimately with the platform to receive an image from the camera. Since connections with a platform are normally asynchronous, it is expected that an image is immediately available. This is recorded by a deadline

0 (`<{0}`) on the trigger. The input image is recorded in the local variable `img`.

The transition from `Prepare` leads to a composite state `LocalizeFruit`. It has an entry action that calls the software operation `CHTBA()`, which updates the global variable `apples`. The entry action also assigns `false` to a local variable `localized` that records whether the localization effort is concluded.

A composite state has itself a state machine that defines behaviour that takes place while the composite state is active. If the composite state has a `during` action, it takes place in parallel with the behaviour of the machine. In our example, localization involves defining the positions of the joints to deal with the

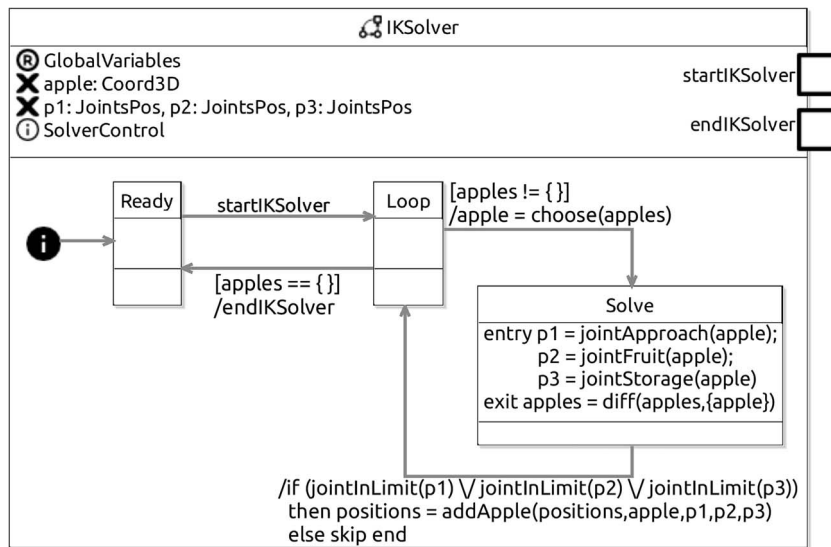


Figure 3. IK solver of the apple harvester.

apples found, and moving the arm to the home position. This is achieved by the machine in **LocalizeFruit**. Its initial junction leads to a state **Start**, with a transition that has no guard or trigger, and so is immediately taken. This transition has an event action, **startIKSolver**, which takes place immediately. This event (declared in the interface **SolverControl**) is used to communicate with the machine **IKSolver** in Fig. 3.

The behaviour defined by **IKSolver** is initiated upon occurrence of the event **startIKSolver**. This machine provides an inverse kinematics solver to obtain joint solutions for three positions: the approach, the fruit and the storage positions, which are recorded in the variable **positions** (declared in the interface **GlobalVariables**). Once **startIKSolver** happens, **IKSolver** goes to a state **Loop**. If the set of **apples** is not empty (**apples != {}**), a transition to the state **Solve** takes place. The action of this transition assigns to a local variable **apple** a value chosen from **apples**, defined by a function **choose** (whose definition is omitted here).

In **Solve**, three functions, **jointApproach**, **jointFruit** and **jointStorage**, are used to calculate joint positions and assign them to local variables **p1**, **p2** and **p3**. The **apple** is removed from **apples** (using the set difference operator) and then control moves back to **Loop**. In the transition back, the action is a conditional. It checks if the joint positions are all feasible (in the limits of the joint abilities and of the workspace). If so, they are added to **positions** using a tailored (omitted) function **addApple**. Otherwise, nothing is done, as defined by the action **skip**. So, the positions are discarded.

When there are no more apples (**apples == {}**), control moves back from **Loop** to the state **Ready**, where the machine **IKSolver** waits for the next **startIKSolver** event. In moving to **Ready**, **IKSolver** communicates with **AppleHarvestControl** using the event **endIKSolver**, to indicate that it has finished its work.

In **AppleHarvestControl**, in the composite state **LocalizeFruit**, after the communication via **startIKSolver**, in the state **Solving**, another transition communicates with a machine **GoHome** via the event **startGoHome**. That machine, omitted here, uses the platform operation **goHome** to move the arm to the home position. Now in the state **SolvingAndMoving**, end signals **endIKSolver** and **endGoHome** from **IKSolver** and **GoHome** are accepted in either order. When both occur, **localized** is set to **true**. Now, the transition out of **LocalizeFruit** is enabled and the state **Next** is entered.

The behaviour of **AppleHarvestControl** after entering **Next** is defined using constructs already explained.

There are two forms of open machine. A basic open state machine can be just like a RoboChart machine, but it does not have declarations. For example, by removing the declarations of the RoboChart machines in Figs 2 and 3, we obtain basic open state machines. As already mentioned, that context is defined elsewhere in a complete model. Open machines, however, can also be defined by a combination of other open machines. In this case, the composed machines are fragments of a state machine that refer to other fragments, and composing all those fragments produces a basic open state machine. In this way, control flow, besides being embedded in actions and transitions, is also defined at the machine level. Such an operator facilitates transformation of machines, by allowing us to decompose a machine into smaller components that can be rearranged in a stepwise fashion.

We do not necessarily suggest that behavioural models are defined in this way. The combinator for open state machines, however, is useful in defining a normal form with a small number of machine patterns as described in Section 3. Equally, it can be useful to combine models for components of larger granularity.

Figure 4 presents an alternative model for the inverse kinematic solver that is defined by the combination of two open machines. The first, on the top, has a transition to a connecting node indicated by **<Solve>**. This is a reference to a node (state or junction) that, in a complete model, is defined in another machine. Connection nodes in open state machines resemble connection point references of UML, but connect different state machines.

In the second machine, the connecting state **Solve** is defined as an entry point, as indicated by the **[@]** inside its block. This machine also has a connecting node, **<Loop>**, that refers back to an entry point of the first machine. The machines are combined via the **⊙** operator, which matches the connecting nodes of one machine to the entry points of the other.

A connecting node cannot be the source of a transition, just the target. Junctions, however, can be an entry point for a connecting node, and, therefore, in open machines, they are named. In addition, a connecting node does not need to be defined as an entry point in the other machine. For example, the second machine in Fig. 4 did not need to have a definition for **Solve**. If this were

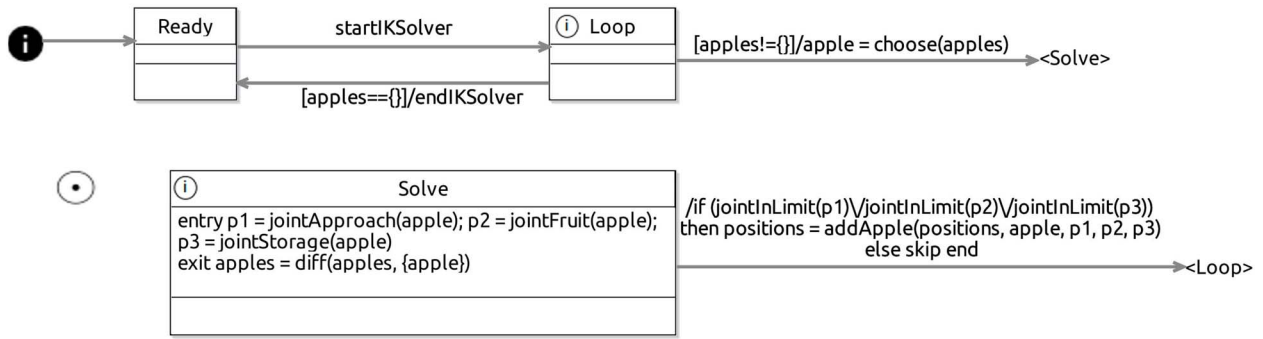


Figure 4. Open machine for the IK solver.

the case, however, combination with other machines would be required to define a complete model, where all connecting nodes have one definition.

We next describe our normal forms (and normalized versions of *AppleHarvestControl* and *IKSolver*).

3. NORMAL FORMS

To structure the presentation of our laws, and to equip them with a notion of completeness, we define in this section normal forms for RoboChart self-contained state machines (in Section 3.1) and open machines (in Section 3.2). In Section 4 we present our laws and their use in strategies to normalize models.

3.1. RoboChart normal form

A RoboChart model is normalized if every state machine in that model is in normal form, whether it is used to define behaviour for a controller, such as *AppleHarvestControl*, *IKSolver* and *GoHome* (omitted here) in our example, or to define operations, such as *CHTBA* and *NearestNeighbour* (omitted).

In Fig. 5, we provide the definition of the RoboChart meta-model for state machines. Classes depicted in grey are abstract; attributes whose names are written in *italics* are inherited; and those in **bold face** are compulsory. We are here concerned with a *StateMachineBody*, which can be a *StateMachineDefinition* or an *OperationDefinition*. *AppleHarvestControl* and *IKSolver* are examples of *StateMachineDefinitions*. An instance of *OperationDef* specifies an operation that may be called from a machine; that specification can itself be a state machine. As shown in Fig. 5, however, in contrast with a *StateMachineDefinition*, an *OperationDefinition* can have **parameters**. In our example, *CHTBA*, for instance, has a parameter of type *Image*.

A *StateMachineBody* is a *NodeContainer* with nodes, that is, *States* and *Junctions*, and transitions. A *State* can be *Final*, and a *Junction* can be *Initial*. Like in UML, a *Junction* is a decision point, where, in contrast with a *State*, the control flow does not pause. An *Initial* state is a *Junction* because, at the start, a transition from the *Initial* state to a proper *State* is immediately taken.

A *StateMachineBody* defines also a *Context*, which is a self-contained component. For that it records the *variableList*, *events*, and *clocks* local to the state machine, and its required *operations*. Variables, events and operations can also be declared via interfaces: with required variables and operations (*rinterfaces*) or defined (local) variables and events (*interfaces*).

States may have actions: *EntryActions*, *DuringActions* and *ExitActions*. A *State* is also a *NodeContainer*, since a composite state contains nodes and transitions of its own. *Transitions* connect two nodes: a *source* and a *target*. They may be triggered by a *Communication*,

guarded by a *condition*, and contain an *action* that is executed when the transition is taken. We can also specify a *deadline* for a transition and *reset* a clock when the transition is taken. The clock is reset when the *trigger* occurs and the *condition* is true.

A *ClockReset* is a *Statement*. Every *Action* also has a *statement*. The metamodel for *Statements* is presented in Fig. 6. These include the usual *Assignment*, operation *Call*, sequence (*SeqStatement*) and conditional (*IfStmt*) statements. We also have *Wait* statements, and *TimedStatements*, which impose a *deadline* for the termination of a statement (*stmt*). They are both illustrated in Fig. 2. A communication statement (*CommunicationStmt*) identifies a *communication* via an *event*. Finally, a *ParStmt* is a parenthesized statement, needed to define scope for *deadlines*.

The *Expression* language is not surprising, but includes a construct *sinceEntry(S)* to denote the time since a state *S* has been entered. It avoids the need to declare and control a clock to account for that time, and is particularly useful when *S* is a composite state. In this case, entering *S* may involve an elaborate control flow that complicates the identification of the points in which the clock would need to be reset.

The normal forms for *StateMachineDefinitions* and *OperationDefinitions* defined below impose different restrictions on their *StateMachineBody*. Below, we consider first *StateMachineDefinitions*.

Definition 3.1. (Normal form for *StateMachineDef*). A

normalized *StateMachineDefinition* is specified by a *StateMachineBody* that is a *NodeContainer* that satisfies **both** conditions NCNF1 and NCNF2 in Fig. 7.

NCNF1 and NCNF2 are defined in terms of the metamodel in Fig. 5. With those restrictions, we ensure that the data manipulations and the time control of the machine, normally defined in actions, are all encapsulated in operations, which are called in the actions and transitions of the *StateMachineDefinition*. NCNF1 and NCNF2 apply to all *Statements* and *Transitions* occurring anywhere in the *StateMachineBody*, including those in the *nodes* and *transitions* of the composite *States*.

In Fig. 8 we present a normalized version of the *IKSolver* state machine for the harvester example in Fig. 3. In this version, all actions are calls to operations, such as *normal'IKSolver't2'op()* and *normal'IKSolver'entry'op()*, defined elsewhere and required by the normalized *IKSolver* via new interfaces, such as *l'normal'IKSolver't2'op()* and *l'normal'IKSolver'entry'op()*, declaring operations.

The *StateMachineBody* of a normalized *OperationDefinition* can satisfy different restrictions.

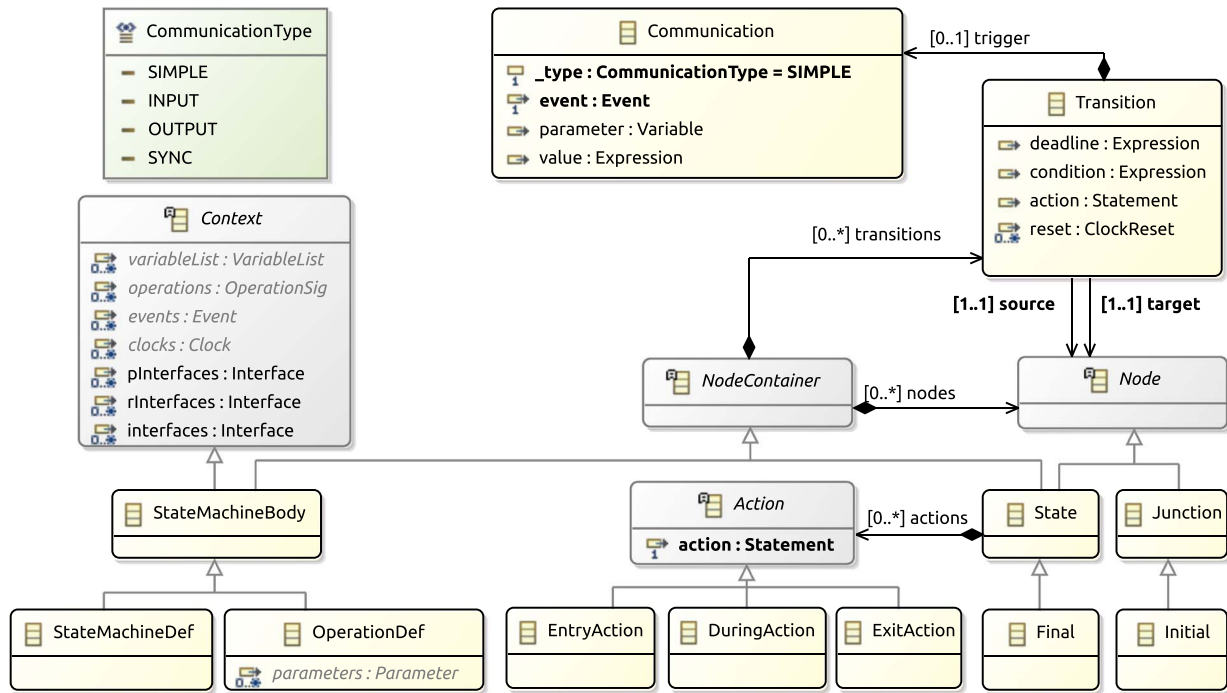


Figure 5. Metamodel for state-machine bodies, defining controller behaviour or operations.

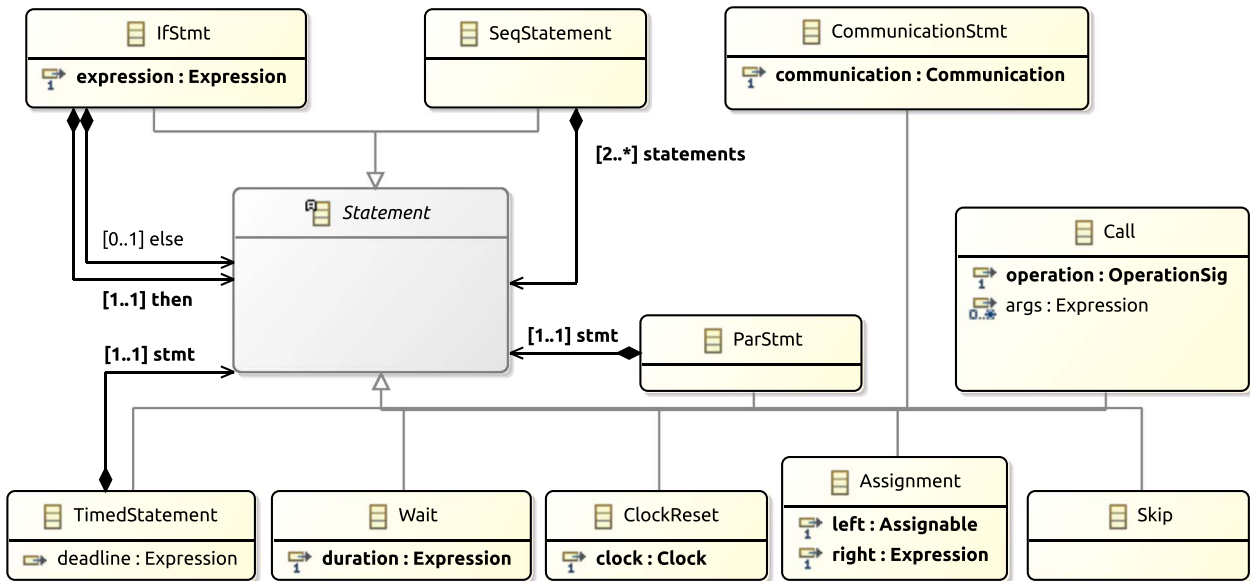


Figure 6. Metamodel for statements.

NCNF1 Every Statement in an Action or Transition is an operation Call.
 NCNF2 In every Transition, the optional deadline is not present: it is null, and there is no use of a sinceEntry expression.

Figure 7. Normal form for a NodeContainer—a normalized NodeContainer satisfies both conditions.

Definition 3.2. (Normal form for OperationDef). A normalized OperationDefinition is specified by a StateMachineBody that is a NodeContainer that satisfies either OPDNF1 or OPDNF2 in Fig. 9. With the normalization condition OPDNF2, we cater for OperationDefinitions whose bodies are normalized in the sense already specified for StateMachineDefinitions.

OperationDefinitions that satisfy OPDNF1 instead are called basic. To define the restrictions that are satisfied by basic operations, we use the notion of an action operation. This is an OperationDefinition whose set of nodes includes just an Initial junction and a Final state, and whose set of transitions includes just one Transition between them with an optional action (and no other element). OPDNF1 allows for an action operation whose Statement encapsulates one data or time statement, but no control flow: no conditionals or sequences, a limited form of deadline or a clock reset.

Figure 10 presents the definition of `normalIKSolver't'op()` used in Fig. 8. Its only action is an assignment, originally in the transition from Loop to Solver in the machine IKSolver in Fig. 3.

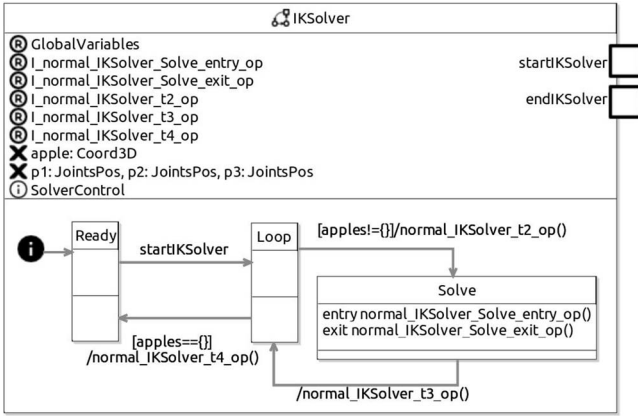


Figure 8. IK solver of the apple harvester—normalized.

OPDNF1 It is an action operation whose Statement is an Assignment, Skip, a CommunicationStmt, a TimedStatement of the form $tStop() < \{d\}$, for any integer expression d , or a ClockReset.
OPDNF2 The conditions NCNF1 and NCNF2 hold.

Figure 9. Normal form for an OperationDef—a normalized OperationDef satisfies **one** of these conditions.

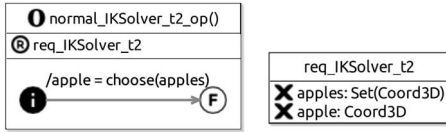


Figure 10. Basic operation in the normalized IK solver.

So, in summary, in a normalized RoboChart model, **StateMachineDefinitions** use operation calls for data and time services. And the **OperationDefinitions** themselves are either basic or also use calls to further operations that provide data and time services.

OPDNF1 also ensures that a deadline is only imposed on a call to the operation $tStop()$ (see Fig. 11), which is itself normalized according to OPDNF2. This operation simply deadlocks and never terminates.

We can use this restricted form of deadline to express any deadline. First of all, we can indirectly impose a deadline on a trigger by effectively imposing it on an action, and making the trigger the only way to terminate that action within the deadline. For instance, in Fig. 2, we have a deadline 0 on the communication `takePic?img` used as a trigger on the transition from **Prepare** to **LocalizeFruit**. We can instead record that deadline using a **during** action $tStop() < \{0\}$ in **Prepare** that imposes the deadline 0 on the termination of $tStop()$. Since this **Statement** does not terminate, to satisfy that deadline, we have to leave the state **Prepare** to interrupt its **during** action. So, the transition out of **Prepare** has to be enabled in time: its event trigger needs to occur with deadline 0, as required. The **during** action $tStop() < \{0\}$ can be specified as a call to a (normalized) operation that satisfies OPDNF1. This approach works for all values of deadline, not only 0 as in the example.

Similarly, deadlines on an action can be imposed by having it in parallel with $tStop() < \{d\}$, and making termination of that action the only way to terminate $tStop()$ within the deadline. For instance, in the machine in Fig. 2, we have a deadline 0 on the action `startIKSolver` in the transition from **Start** to **Solving** in **LocalizeFruit**. We can instead call the operation `deadlineAction(0)` whose definition is shown in Fig. 12.

The operation `deadlineAction(d:nat)` executes `startIKSolver`, which is the action of a transition that is reached as soon as `deadlineAction(d:nat)` is started, in parallel with $tStop() < \{d\}$, which is in a **during** action of a (composite) state **S1**, also reached as soon as the operation is started. Here, d is the parameter for `deadlineAction(d:nat)`, defined as 0 in the call. Since $tStop()$ cannot terminate and meet the deadline, the state **S1** has to be exited for its **during** action to be interrupted and the deadline to be met. For that, the transition out of **S1** has to be taken, and so the guard g of that transition has to hold. Since g is a local variable initialized to **false**, the transition to the final state of **S1** has to take place, and the action `startIKSolver` terminate, so that g is assigned **true** and the transition is enabled. So, the deadline is (indirectly) imposed on `startIKSolver`. Since `deadlineAction(d:int)` uses $tStop()$, its definition requires the interface `ItStop` that declares this operation.

Normalization of `deadlineAction(d:nat)` requires just replacing its actions with calls to basic operations that perform them. In Section 4, we describe how any machine can be transformed (using our laws) to use just the restricted form of `deadline tStop() < \{d\}`.

A basic operation cannot include **Wait** statements. Instead, it can call either of the operations `waitOp(i:nat)` or `waitInterval(m:nat,n:nat)` in Fig. 11. They are both normalized according to OPDNF2. They both use a clock C , which is reset ($\#C$) at the start, to encode a **wait** period. For that, `waitOp(i: nat)` has a state **Waiting** with a single transition to a final state. The guard on that transition uses a `since(C)` expression to require that it is taken only once the clock has recorded the passage of i time units. So, when in the state **Waiting**, the control flow pauses for i time units, since the only transition out of **Waiting** requires that i time units pass.

In the case of `waitInterval(m:nat,n:nat)`, it uses a call `waitOp(1)` to pause one time unit. An interface `IwaitOp` declares `waitOp(i:nat)`, and `waitInterval(m:nat,n:nat)` declares `IwaitOp` as a required interface. In the machine for `waitInterval(m:nat,n:nat)`, two transitions out of a junction encode the nondeterminism of a `wait([m,n])` statement. Once m time units have passed (that is, `since(C) >= m`), a transition may be taken to the final state, so that `waitInterval(m:nat,n:nat)` may terminate. While n time units are not over (`since(C) < n`), however, another self-transition is enabled that allows another time unit to pass: `waitOp(1)` instead of terminating.

Our normal form for open machines, defined next, enforces the above restrictions on node containers, but allows further structure in the construction of the body.

3.2. Open-machines normal form

The metamodel for open state machines is shown in Fig. 13. An **OpenStateMachine** can be basic (**BasicOpenStateMachine**) or composite (**CompOpenStateMachine**), that is, defined using \odot . A well-formedness condition ensures that a **BasicOpenStateMachine** has at most one **InitialState**. Similarly, at most one of the **left** and **right** machines of a **CompOpenStateMachine** has an **Initial** state.

A **BasicOpenStateMachine** is similar to a **StateMachineBody** from RoboChart's metamodel, in that it is a **NodeContainer** (but not a **Context**). As such, it has **nodes** and **transitions**. The classes in Fig. 13 marked with an arrow on the top right-hand corner are those already presented in Fig. 5. We have, in this context, however, a new form of **Node**, namely, a **NodeNameRef**, whose attribute `ref` is the identifier of a node that is (expected to be) defined in another machine.

The states and junctions, including the initial junctions and final states, are similar to those of RoboChart, but have an extra boolean attribute, which indicates whether the **Node** is an **entry-point**. We have classes **EState**, **EFinal**, **EJunction** and **EInitial**, which

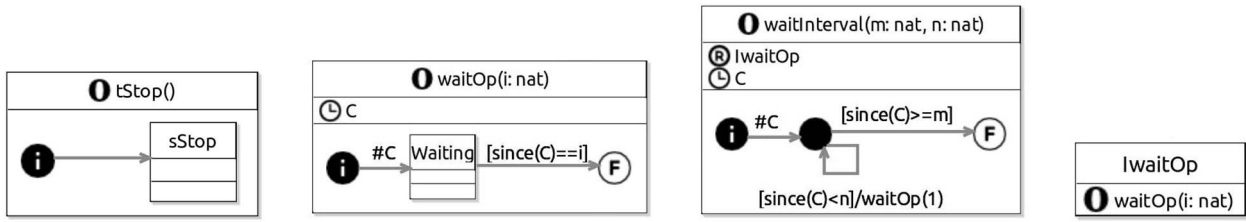


Figure 11. Normalized basic operations.

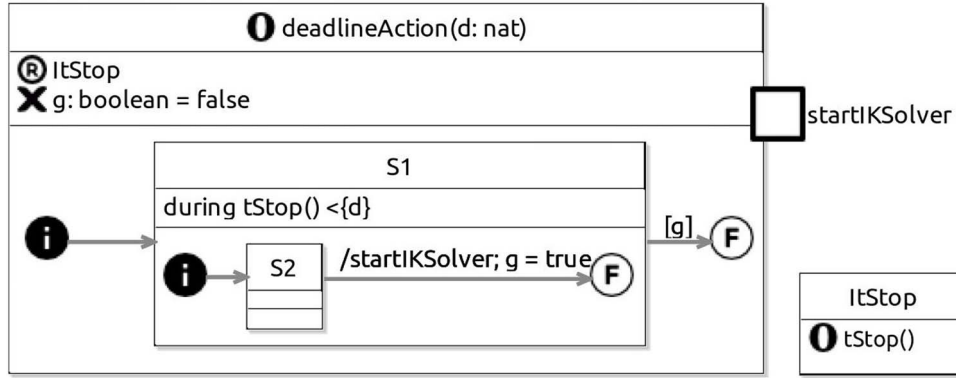


Figure 12. Example: deadline—not normalized.

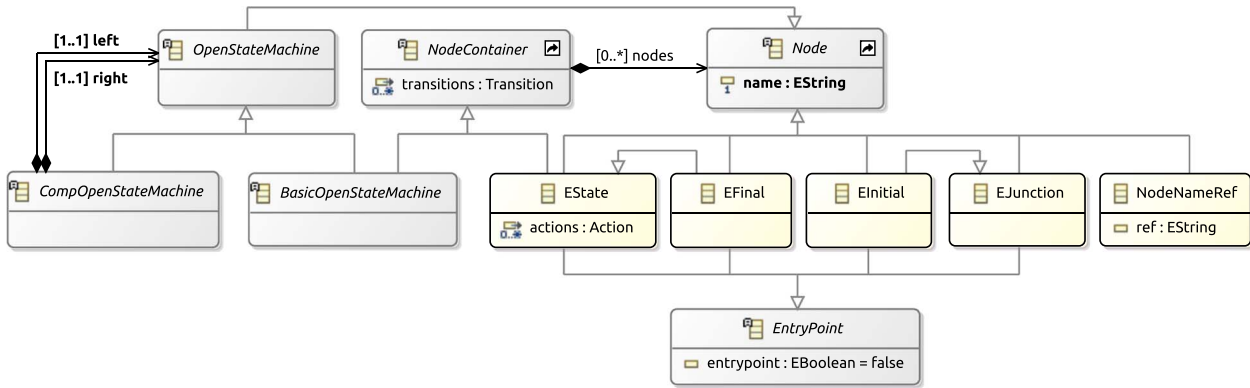


Figure 13. Metamodel for open machines.

are similar to the **State**, **Final**, **Junction** and **Initial** classes of the RoboChart metamodel (Fig. 5), but inherit from a new class **EntryPoint**, with the extra attribute.

In addition, all **Nodes** have a **name** as an attribute. This includes the **Junctions** and **Final** states, since they can all be the target of a transition via a **NodeNameRef**, which uses a name to identify a **Node**. (A modelling tool can easily generate names for **Nodes**, other than **States**, and hide those not relevant, to avoid burdening the modellers and cluttering the models.)

Since an **OpenStateMachine** is a **Node**, a composite state can use the new composition operator to define its machine. So, we can take advantage of the new operator for stepwise compositional transformation of machines at all levels. Well-formedness conditions ensure that a composite state either includes one **OpenStateMachine** with exactly one **InitialState**, or one or more nodes of other types, but not both, and that **OpenStateMachines** are not the target or source of transitions.

The notion of normalization for **OpenStateMachines** in general is standard, in that it requires them to be a composition of normalized machines. For a **BasicOpenStateMachine**, we have the

conditions already presented for **NodeContainers**, and an extra condition.

Definition 3.3. [Normal form for **OpenStateMachine**] An **OpenStateMachine** is normalized if it is a normalized **BasicOpenStateMachine**, or a **CompOpenStateMachine** whose left and right **OpenStateMachines** are normalized. A **BasicOpenStateMachine** is normalized if it is a normalized **NodeContainer**, according to NCNF1-2 (Fig. 7) and BOMNF1-2 in Fig. 14. With BOMNF1, we ensure that there is at most one non-connecting node in a normalized **BasicOpenStateMachine**. So, every transition is either a self-transition or a transition to a **NodeNameRef**. With BOMNF2, we ensure that any machines in composite states are also normalized, potentially as a **CompOpenStateMachine**. Together, these conditions ensure that the control flow of a normalized **OpenStateMachine** is fully exposed using the state machine combinator \odot .

BOMNF1 The subset of nodes that are not Node-NameRefs is either empty or a singleton.
BOMNF2 All its OpenMachines are normalised.

Figure 14. Normal form for a BasicOpenStateMachine—a normalized BasicOpenStateMachine satisfies NCNF1, NCNF2 and BOMNF1 and BOMNF2 here.

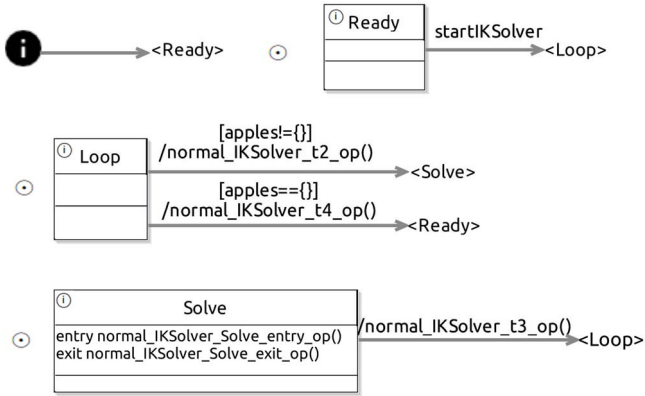


Figure 15. IK solver—Open Machine normalized.

Fig. 15 shows a normalized version of the open machine for the IKSolver on the top of Fig. 4. In Fig. 15, to ensure that every basic open machine has at most one node that is not a reference to a node defined in another machine, decompositions using the \odot operator split the initial state, and the states Ready, Loop and Solve into different machines. In addition, the statements in all actions are operation calls.

Next, we define how we can normalize an arbitrary machine via the systematic application of three sets of algebraic laws for StateMachineDefinitions, OperationDefinitions and OpenStateMachines.

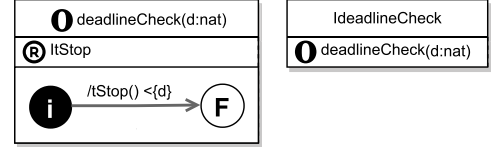
4. NORMALIZATION AND LAWS

We structure the presentation of our laws by describing their role in normalization strategies for RoboChart and open machines. In Section 4.1 we present the procedure for StateMachineDefinitions; in Section 4.2, we have the procedure for OperationDefinitions; and, finally, in Section 4.3, we have the procedure for open machines. In each case, we show that the procedure terminates and produces a normalized machine, thus establishing a relative notion of completeness for our sets of laws.

4.1. normalization: StateMachineDef

We first consider a procedure `normSMB()` to normalize a RoboChart StateMachineDefinition according to Definition 3.1. This procedure is shown in Fig. 16. (It applies more widely to any StateMachineBody, but we focus here on normalization of a StateMachineDefinition. In Section 4.2, we explain that `normSMB()` is useful, although not enough, to normalize an OperationDefinition too.) The approach is first to eliminate all `sinceEntry` expressions (Step 1), introduce operations that execute each of the Statements, and associated interfaces that declare those operations, and finally use them to replace all Statements with operation Calls (Step 2). Next, we eliminate the deadlines in transitions: we again declare new operations and interfaces (in Steps 3 and 4), later used (in Step 5) to encode the deadlines using Calls.

1. Apply Law 1 exhaustively.
2. Apply Laws 2 and 3 exhaustively whenever `s` is not a Call.
3. Apply Law 4 with argument `tStop()` in Figure 11, and Law 5 with argument `ltStop` in Figure 12.
4. Apply Laws 4 and 5 with the operation and interface below as arguments.



5. Apply exhaustively Law 6.

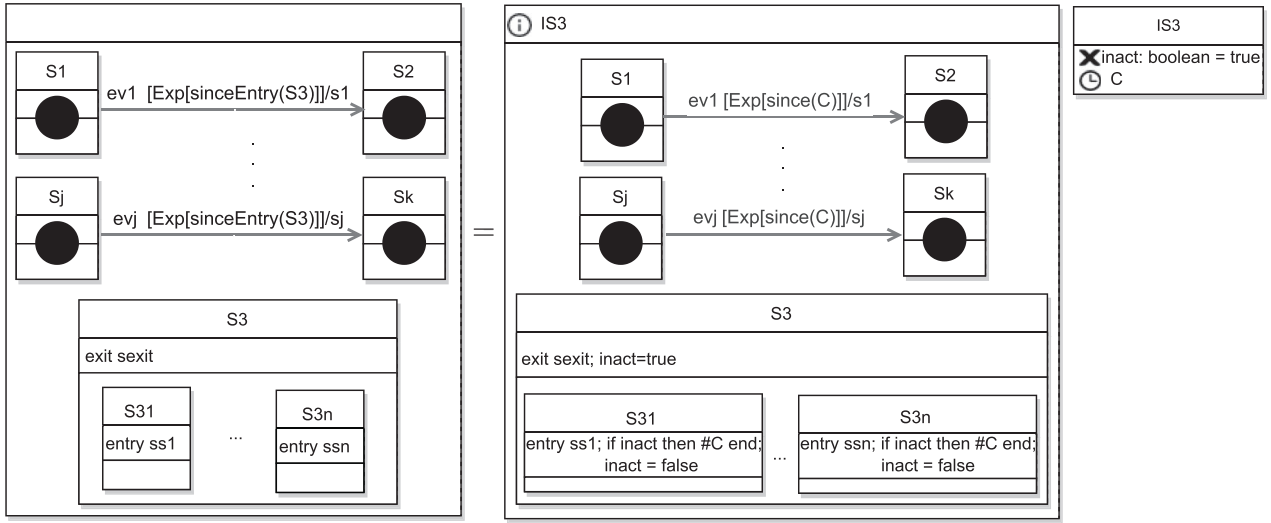
Figure 16. `normSMB()`—normalization of StateMachineBody.

Below, we describe each of the steps. For each of them, we present and describe the laws that are needed. In a law definition, we name it, identify its arguments and use a(n informal) diagrammatic notation to describe an equality. All laws, however, are also stated formally as described in Section 6. Law definitions may also include a **provided** clause that imposes restrictions that must be satisfied for a law application to be valid. Finally, a law definition can include a **where** clause that defines elements in the body of the law (equality and **provided** clause) that are not given as argument or defined by pattern matching. In our normalization procedures we apply all laws from left to right, although they are all equalities.

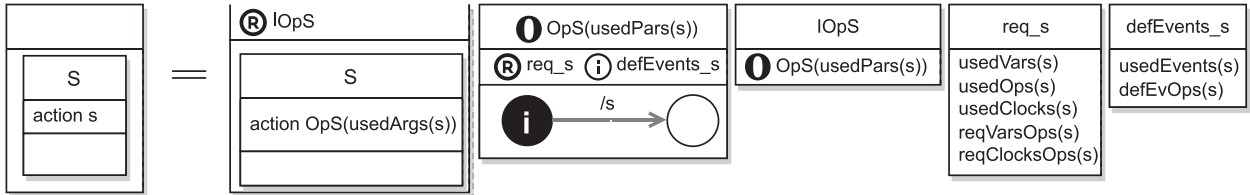
Step 1 Here, for each state `S3` for which there exists one or more `sinceEntry(S3)` expressions (necessarily in transition guards, which is the only context where such expressions can occur), we apply Law 1 once.

Law 1 establishes that we can replace all occurrences of `sinceEntry(S3)` expressions with `since(C)`, where `C` is a new clock that is initialized once `S3` is entered. On the left-hand side of the equality in Law 1, the block named `S3`, inside the unnamed block, stands for any State in a StateMachineBody. As stated in the proviso, the blocks named `S31`, ..., `S3n` are those identified by the function `innermostInitialStates(S3)`. They are the innermost states of `S3`, if any, that can be reached by a sequence of transitions, starting from the transition from the initial junction of the machine of `S3`, and including only transitions from initial junctions of composite states or from junctions. If `S3` is not a composite state, this set of states is empty. If `S3` is composite, and its state machine has a transition from the initial junction to another junction, and from there to two non-composite states `S31` and `S32`, for example, then this set includes `S31` and `S32`. (For compatibility with UML, there can be only one transition from the initial junction.) If `S31` or `S32` is composite, then, instead of including it, we consider the initial junction of its machine, and so on. So, the innermost states so defined are not composite. The exit action `sexit` of `S3`, and the entry actions `ss1`, ..., `ssn` of `S31`, ..., `S3n`, if any, are explicitly indicated. Finally, the transitions where `sinceEntry(S3)` occurs have arbitrary triggers `ev1`, ..., `evj` and actions `s1`, ..., `sj`. The state blocks named `S1`, ..., `Sj`, `S2`, ..., `Sk`, with a junction symbol inside, represent Nodes: States or Junctions. The transitions identified in Law 1 can be between any Nodes, including those inside `S3`, if any.

On the right-hand side of Law 1, a new interface `IS3` declares a new boolean variable `inact`, which is initialized to `true`, and the new clock `C`. This interface is declared as defined in the StateMachineBody, so that `inact` and `C` are added to its local context. The clock is reset (`#C`) after the entry actions `ss1`, ..., `ssn` of the inner

Law 1. elim-sinceEntry

provided The names $IS3$, $inact$, and C are fresh, and $innermostInitialStates(S3) = \{ S31, \dots, S3n \}$

Law 2. intro-call-for-act-state()

provided The names OpS , $IOpS$, req_s , and $defEvents_s$ are fresh.

states $S31, \dots, S3n$, since it is after executing one of these actions that entering $S3$ is concluded. This clock reset, however, should occur just the first time these states are entered, as a result of the machine entering $S3$. For example, if $S31$ has as self-transition, or the control flow leads back to $S31$ in any other way, without having left $S3$, then C should not be reset because C is used to record the time since the last entry in $S3$. For this reason, we use $inact$ to flag whether it is the first time an inner state has been entered. At the end of **entry** actions of $S31, \dots, S3n$, $inact$ is set to **false**, and then set back to **true** only when $S3$ is exited: after its exit action **sexit**.

The proviso of Law 1 requires the names of the new interface, variable and clock to be fresh in the model. The particular names used are not important, and soundness is guaranteed as long as they are fresh and used consistently as determined in the law definition.

Law 1 captures the meaning of **sinceEntry(S)** expressions. It also highlights the convenience of the availability of these expressions, since control based on clocks can become convoluted.

Step 2 Here, for each **Statement** that defines an action in a **State** or **Transition**, and is not already a **Call**, we apply Law 2 or 3. These laws are applied, exhaustively, that is, until all **Statements** are a **Call**.

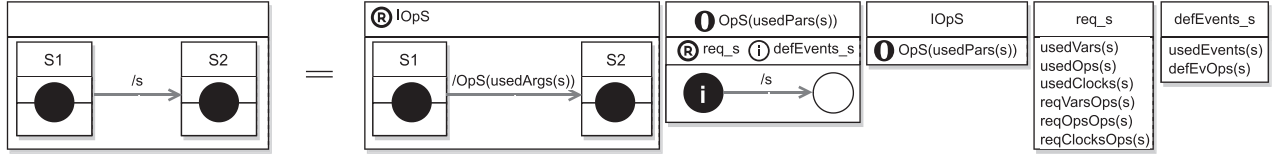
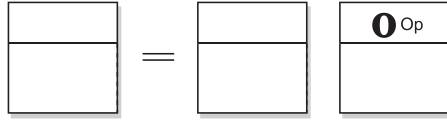
Law 2 establishes that any **Statement** s in any action of any state S of a **StateMachineBody** can be replaced with a **Call** to an action operation OpS for s . On the left-hand side of the equality, **action**

s stands for an **EntryAction**, **DuringAction** or **ExitAction** with **Statement** s . On the right-hand side, $OpS(usedPars(s))$ and its associated interface $IOpS$ are defined, the **StateMachineBody** declares $IOpS$ as a required interface, and the **Statement** s in the state S identified on the left-hand side is replaced with a **Call** to $OpS(usedArgs(s))$. Finally, on the right-hand side, the interfaces req_s and $defEvent_s$ used in the definition of OpS are declared.

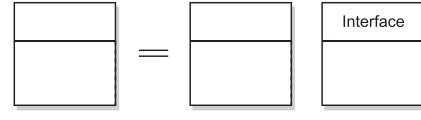
The proviso of Law 2 requires the names of the new operation and interfaces to be fresh. Like in Law 1, the particular names used are not important, and soundness is guaranteed if they are fresh and used as indicated.

As noted, Law 2 and **normSMB()** are applicable to any **StateMachineBody**, not only a **StateMachineDefinition**. If Law 2 is applied to an **OperationDefinition**, as opposed to a **StateMachineDefinition**, the **Statement** s may use parameters of the operation. With the application **usedArgs(s)** of a simple syntactic function, we identify the list of names of these parameters, which are passed as arguments in the call to OpS . Moreover, with **usedPars(s)**, we determine the matching declarations of the parameters. These are used to specify the signature of OpS in its definition. If there is no use of parameters in s , **usedArgs(s)** is the empty list of arguments, and, of course, **usedPars(s)** is the empty list of declarations. When Law 2 is applied to a **StateMachineDefinition**, which has no parameters, it is certain that **usedArgs(s)** and **usedPars(s)** are empty lists.

In the interfaces req_s and $defEvent_s$, we declare all the variables, operations, clocks and events used in the **Statement** s . Using

Law 3. intro-call-for-act-transition()**Law 4.** intro-op(Op)

provided $\text{id}(\text{Op})$ is a fresh name.

Law 5. intro-interface(Interface)

the applications $\text{usedVars}(s)$, $\text{usedOps}(s)$, $\text{usedClocks}(s)$ and $\text{usedEvents}(s)$ of additional syntactic functions, we determine the declarations of the variables, operations, clocks and events directly referenced in s . Via $\text{reqVarsOps}(s)$ and $\text{reqClocksOps}(s)$, we get the declarations of the variables and clocks in the definitions of the operations in $\text{usedOps}(s)$. These variables and clocks can be declared in interfaces or directly in the definition of an operation in $\text{usedOps}(s)$. Similarly, with $\text{defEvOps}(s)$, we get the declarations of events in the operations in $\text{usedOps}(s)$. Since all these functions may identify no declarations, or rather empty sets of declarations, the new interfaces req_s and defEvents_s may be empty. Additionally, in req_s and defEvents_s , we get the union of the sets of declarations identified by the function applications. So, no repeated declarations are included in the interfaces.

The definition of OpS requires req_s and defines defEvents_s . Since events are points of interaction, they cannot be required, but are always defined.

For the machine IKSolver in Fig. 3, after the exhaustive application of Law 2, we have declarations for operations $\text{normal'IKSolver'entry'op}()$ and $\text{normal'IKSolver'exit'op}()$. The entry and exit actions of the state Solve in IKSolver are replaced with calls to these operations as shown in Fig. 8.

Soundness of Law 2 is discussed in Section 6.2.1.

Law 3 is similar to Law 2, but considers all actions s in **Transitions**. After the exhaustive application of Law 3 to IKSolver , the operation definition in Fig. 10 as well as definitions for $\text{normal'IKSolver't3'op}()$ and $\text{normal'IKSolver't4'op}()$, and associated interfaces, such as, req'IKSolver't2 in Fig. 10, are introduced in the model. In addition, the definition of IKSolver is transformed to that shown in Fig. 8.

Steps 3 and 4 Here, we introduce in the model the definitions of the operations $\text{tStop}()$ in Fig. 11 and $\text{deadlineCheck}(d:\text{nat})$ in Fig. 16, and the associated interfaces ItStop in Fig. 12 and IdeadlineCheck also in Fig. 16. These definitions are used in the following step to eliminate deadlines from transitions. We apply Laws 4 and 5 to introduce these definitions.

Law 4, named **intro-op**, establishes that we can always introduce a new operation in a model. Accordingly, its proviso requires the name $\text{id}(\text{Op})$ of the **OperationDefinition** Op given as argument to be fresh. In the body of Law 4, the left-hand side of the equality has an unnamed block, which, as already explained, stands for an arbitrary **StateMachineBody**. On the right-hand side of the equality, we extend the model with Op . This is indicated by repeating the unnamed block and including a block labelled Op .

Law 5, which is similar to Law 4, establishes that we can declare a new interface in a model.

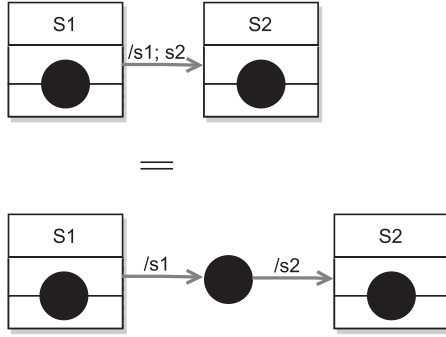
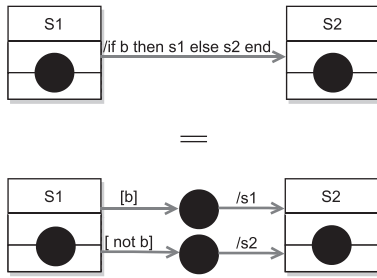
For simplicity, we assume that the names of the operations and interfaces defined in Steps 3 and 4 are fresh. If this is not the case, different fresh names need to be used. The particular names adopted have no bearing in the soundness of the strategy.

Step 5 Here, we apply Law 6 exhaustively to remove the deadlines in transitions by replacing, or introducing, **during** actions in the source states S of these transitions with calls to operations dop'ds . To eliminate a deadline from a transition, Law 6 uses an operation dop'ds to enforce that deadline using a machine in a composite state $S0$ defined in dop'ds . If S has a **during** action, its statement ds is run in parallel with that machine, as required: it becomes a **during** action of the state $S0$.

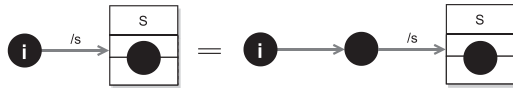
The deadline d of a transition becomes relevant only once its guard holds. So, the machine of $S0$ remains in a state $S1$ until the guard g of the original transition holds. At that point, it moves to the state $S2$, where a call $\text{deadlineCheck}(d)$ enforces the deadline d . In $\text{deadlineCheck}(d)$ (see Fig. 16, Step 4), a call $\text{tStop}()$ blocks, but has a deadline d to terminate. Since $\text{tStop}()$ does not terminate, for this deadline to be met, $\text{dop'ds}()$ has to be interrupted. This can be achieved only by S exiting, when its **during** action $\text{dop'ds}()$ is interrupted. For that, the transition labelled $e[g]$, or some other transition out of S , must take place. In either case, the original deadline d on the transition is enforced.

Law 6 captures precisely the semantics of a deadline on a transition: it is not a deadline on its trigger. First, the deadline is relevant only if the guard holds. Secondly, if some other transition is taken, the deadline is cancelled. What we actually have is a deadline on exiting the source state of the transition. Soundness of Law 6 is the topic of Section 6.2.2.

To summarize, first of all, $\text{normSMB}()$ terminates. The potential sources of non-termination are the exhaustive law applications in Steps 1, 2 and 5. In each iteration of the Steps 1 and 5, however, Laws 1 and 6 are applied from left to right, eliminating the patterns to which they apply. So, the steps terminate when all the instances of these patterns are eliminated. In Step 2, termination is ensured by the restriction that Law 2 is applied only for statements s that are not a **Call**, and such statements are replaced with **Call** statements. So, when all such statements are eliminated, Step 2 terminates. Secondly, following Step 2, NCNF1 holds. Moreover, after Steps 3 and 4, Law 6 applies to every transition with a deadline. So, after Steps 1 and 5, NCNF2 holds. Overall, NCNF1 and NCNF2 both hold and the **StateMachineDef** is normalized as required.

Law 8. split-sequence()**Law 9.** split-conditional()

provided S1 is not an Initial junction.

Law 10. intro-junction-from-initial-junction()

(`deadlineAction's(d:nat,usedArgs(s))`) to enforce the deadline in place of the original `s<{d}`.

The definition of `deadlineAction's` is slightly simpler than that of `dop's` in Law 6 because it does not deal with a guard (or trigger) in the transition. In `normAO()`, Law 11 is applied to machines arising from the application of Steps 1–4 and Laws 7–13 to an action operation. Since an action operation does not have a guard or a trigger in its only transition, and they are not added by any of the Steps 1–4 and Laws 7–13, Law 11 is only applied to transitions without guards or triggers.

The operation `deadlineAction's(d:nat,usedPars(s))` executes `s` in parallel with `deadlineCheck(d)`, via the definition of a composite state `S0` with `deadlineCheck(d)` as a *during* action and with `s` in an action of a transition from a substate `S1` of `S0` to a final state. To satisfy the original deadline, `s` must be executed, and finished, before more than `d` time units have passed. To ensure execution of `s`, exit from `S0`, and so termination of `deadlineAction's`, is predicated on a transition with a guard `g` being enabled. This is possible only after `s` is executed, since `g` is initialized to `false`, and assigned `true` only after `s` finishes. To ensure that no more than `d` time units are passed, the operation `deadlineCheck(d)` is used. We recall that it enforces the deadline on `tStop()`, and that can be met only when `S0` is exited so that `deadlineCheck(d)` is interrupted. In this way, the deadline is indirectly enforced on `s`, because exit from `S0` is predicated on its outgoing transition being enabled.

The proviso of Law 11 requires that the operation `deadlineCheck(d:nat,usedPars(s))` and an interface that declares it are in scope. In `normAO()`, this is ensured by Step 2. So, deadlines in actions are all eliminated.

Finally, we have Laws 12 and 13 to eliminate **Wait Statements** in favour of use of the operations in Fig. 11 already explained. They use a clock to capture the timed behaviour of **Wait Statements**.

Laws 7–13 are applied in our strategy just to action operations, or to machines arising from the application of these laws to action operations. As a consequence, we have not considered in these laws the possibility that the transitions have guards or triggers. The generalization of these laws is, however, straightforward. In all cases, except in Laws 8 and 9, the guard and trigger, if any, do not need to be changed. In the case of Law 8, they are to be part of the label of the transition to the new junction, and in Law 9, they need to be duplicated in the transitions to the new junctions.

After applications of Laws 8–10, the **OperationDefinition** is no longer an action operation. In this case, Step 6 ensures that it satisfies OPDNF2 by exhaustive application of Law 3. If, however, Laws 8–10 have not been used, the result is still an action operation.

In summary, if we apply `normSMB()`, as established in the previous section, the result is an operation definition that satisfies OPDNF2, which corresponds to the normal form definition for **StateMachineDefinitions**. If we use `normAO()` termination is guaranteed because, in Step 5, each law eliminates the pattern to which it applies, and does not introduce it or the pattern relevant for any of the other laws, with one exception. As said, Law 10 potentially introduces a pattern to which Law 9 might apply, but Law 10 applies at most once for each initial junction. Moreover, in Step 6, termination is guaranteed by the proviso that the statement `s` is not a **Call**. (This step is similar to Step 2 of `normSMB()`.) Finally, we note that with the exhaustive application of Laws 7 and 11–13, we enforce OPDNF1. In detail, the forms of **Statement** disallowed by OPDNF1 are eliminated as follows.

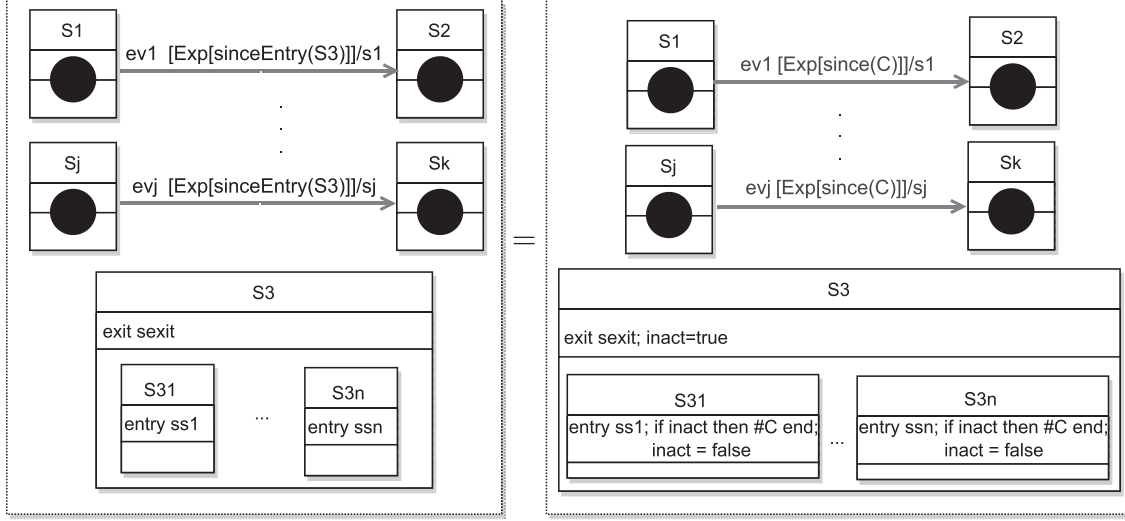
- **ParStmt** is a parenthesized **Statement**, which is eliminated by Law 7.
- Sequences (**SeqStatement**) and conditionals (**IfStmt**) are not present, since Laws 8 and 9 have been applied exhaustively.
- **TimedStatement** is a deadline, eliminated by Law 11 (using additional operations).
- **Wait** is a wait, eliminated by Law 12 or 13, depending on whether it is nondeterministic or not.

Overall, the resulting **OperationDefinition** is normalized according to the normal form in Definition 3.2.

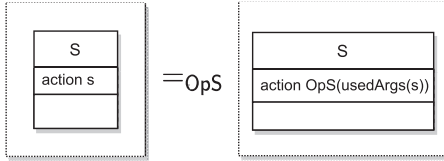
4.3. Normalization: open machines

To normalize an **OpenStateMachine**, we use the procedure `normOM(openM)` in Fig. 18 that takes a machine `openM` as argument. If `openM` is a **BasicOpenStateMachine**, then in Step 1a we use a procedure `normNC()` for **NodeContainers**. This procedure is very similar to `normSMB()` from Fig. 16; it is presented in Fig. 19. The differences are related to the Laws 1, 2, 3 and 6 used in `normSMB()` that apply to a **StateMachineBody** and enrich its **Context** with an additional interface. For `normNC()`, we need similar laws that, however, apply to a **NodeContainer**, without a **Context**. In addition, in `normNC()` there is no need to declare operations and interfaces for later use. That suitable operations are used is ensured by the provisos of the new laws as detailed in the sequel.

After an application of `normNC()`, all `sinceEntry(S)` expressions are eliminated, all actions become operation **Calls**, and all deadlines are eliminated. Afterwards, in Step 1b of `normOM(openM)`,

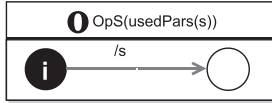
Law 14. `elim-sinceEntry-nc()`

provided The names `inact` and `C` are fresh, and $\text{innermostInitialStates}(S3) = \{ S31, \dots, S3n \}$

Law 15. `intro-call-for-act-state-nc()`

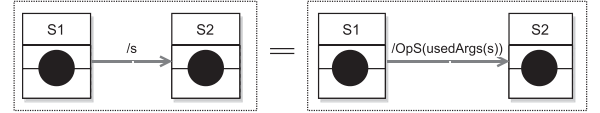
provided

- The name `OpS` is fresh.
- `OpS` is defined as follows.



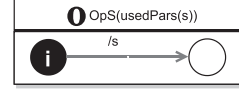
that, as illustrated in Law 15, an operation definition identifies the name of the operation, its parameters and its behaviour (using, for instance, a state machine). As formalized in Section 6.2, with $OM_1 =_{Op} OM_2$ we establish that OM_1 and OM_2 are equal provided, when an operation whose name is that of Op is called, then OM_1 and OM_2 both call Op itself. In an open machine, the operation that is called using a given name is not identified in the machine. Such an open machine can be used in the scope of various definitions for the named operation. The equality $OM_1 =_{Op} OM_2$, therefore, fixes the association of Op to its name. More generally, the equality $OM_1 =_{OpDS} OM_2$ similarly fixes the association of all operation definitions on $OpDS$ to their names. In Law 15, the operation `OpS` is not called in the open machine on the left-hand side, since the proviso requires that the name `OpS` is fresh.

In the procedure `normNC()`, law applications with different arguments are used: one operation definition for each action in a state or transition that is not a `Call`, for example. Overall, `normNC()` establishes equality parametrized by the set of all operation definitions used as arguments. This follows from the fact that $OM_1 =_{Op1} OM_2$ and $OM_2 =_{Op2} OM_3$ imply that $OM_1 =_{\{Op1, Op2\}} OM_3$.

Law 16. `intro-call-for-act-transition-nc()`

provided

- The name `OpS` is fresh.
- `OpS` is defined as follows.



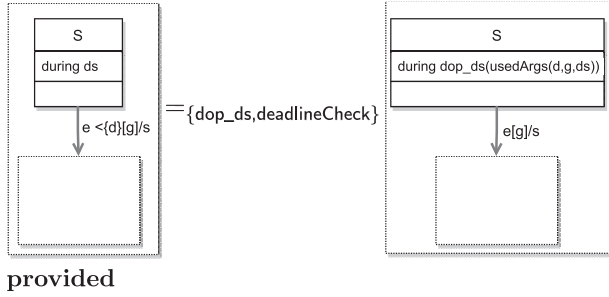
Generally, $OM_1 =_{S01} OM_2$ and $OM_2 =_{S02} OM_3$ imply $OM_1 =_{S01 \cup S02} OM_3$.

Laws 16 and 17 are similar to Laws 3 and 6, but, like Law 15, do not introduce operations and interfaces.

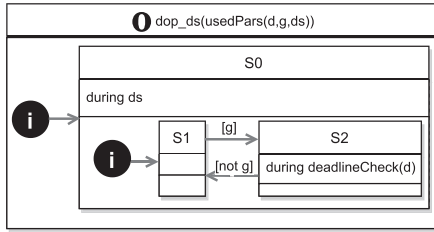
In Steps 3 and 4 of `normSMB()`, we introduce operation definitions and interfaces for use in the last step. These are not needed in `normNC()`. Instead, we have a step similar to Step 5, which applies Law 17. It is similar to Law 6, and establishes equality with the definitions for `dop_s` and `deadlineCheck` as arguments.

Procedure `decompBOM(openM)` The core of this procedure is the application of Law 18, which splits a `BasicOpenStateMachine` by isolating its entry points in separate machines combined by \odot . For example, in a traditional machine (such as a UML machine), the single `EntryPoint` is the initial junction, with a single transition from that `EntryPoint` to a different `Node S`. In this case, applying Law 18, we obtain the \odot composition of two `BasicOpenStateMachines`. The first has the initial state with a transition to a `NodeNameRef` to `S`. The second has all states and transitions of the original machine, except the initial junction and its transition; in this machine, `S` becomes an `EntryPoint`. Fig. 21 shows the result for the IK solver in Fig. 3, taken as an `OpenMachine`, after an application of Law 18.

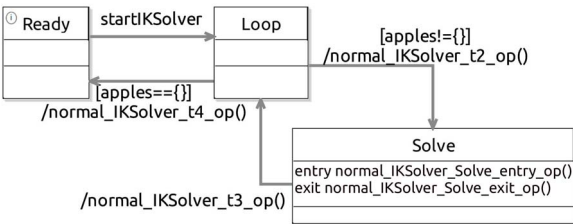
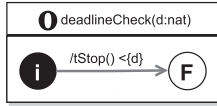
In general, Law 18 applies to a `BasicOpenStateMachine` with any number of `EntryPoints`, defining a `BasicOpenStateMachine` for

Law 17. elim-deadline-transition-nc()

- The names `dop_ds` and `deadlineCheck` are fresh.
- `dop_ds` is defined as follows.



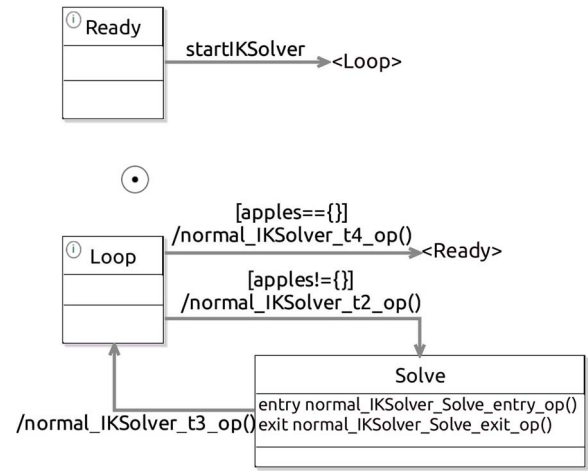
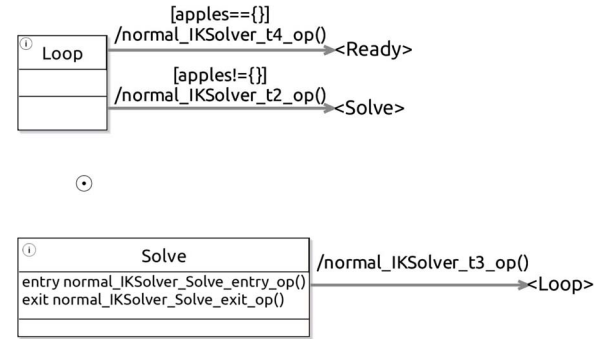
- `deadlineCheck` is defined as follows.

**Figure 21.** IK solver—Open Machine—Step 1a—First iteration of `decompBOM(IKSolver)`.

each of them. The equality it establishes has the empty set of operation definitions as argument, which is omitted for simplicity. From each **EntryPoint** S_1, \dots, S_n , there may be self-transitions, or transitions to a **NodeNameRef** (indicated by $\langle S_{i1} \rangle, \dots, \langle S_{i1} \rangle$) or to any other form of **Node** (S_{1m}, \dots, S_{nm}), that is, **Junction** or (**Final**) **State**. The first two forms of transition are untouched by Law 18; the latter are replaced with new **NodeNameRefs** to the original **Nodes**.

A final **BasicOpenStateMachine** includes (a) all the actual **Nodes** S_{1m}, \dots, S_{nm} , which become **EntryPoints**; (b) the sets of all other **Nodes**; (c) **Transitions** from the original machine that do not target one of the original **EntryPoints** S_1, \dots, S_n ; (d) **Transitions** that target those original **EntryPoints** S_1, \dots, S_n , with a new **NodeNameRef** for those **EntryPoints** as a target; (e) the new **NodeNameRefs** as needed for (d). This replacement of the targets of the transitions is indicated in Law 18 using the substitution $[S_1, \dots, S_n \langle S_1 \rangle, \dots, \langle S_n \rangle]$.

Figure 22 shows the result of applying Law 18 to the right machine in Fig. 21. Because it has only one **EntryPoint**, the decomposition gives rise to just two **BasicOpenStateMachines**. The first

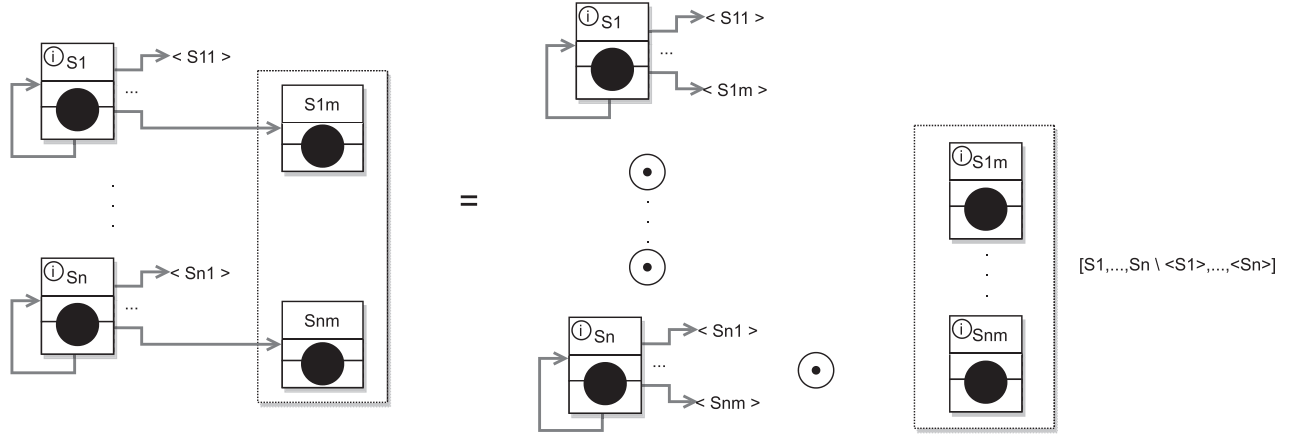
**Figure 22.** IK solver—Open Machine—Second iteration of `decompBOM(IKSolver)`.**Figure 23.** IK solver - Open Machine - Third iteration of `decompBOM(IKSolver)`.

is normalized. The second needs to be further decomposed via additional applications of Law 18. There, the transition from **Loop** back to **Ready**, which is an **EntryPoint**, is now a transition to a **NodeNameRef** that names **Ready** instead.

The normalization procedure `decompBOM(openM)` for a **BasicOpenStateMachine** `openM` applies Law 18 whenever `openM` has at least one **EntryPoint** with a transition t to a different **Node** that is not an **EntryPoint** or a **NodeNameRef** (Step 1), or, if not, when it has multiple **EntryPoints** (Step 2). In the first case, `openM` has more than one node that is not a **NodeNameRef**: at least the **EntryPoints** and the target of the transition t . This violates BOMNF1, so in Step 1a, Law 18 is applied to split `openM`. Since the rightmost machine `right` that results from applying Law 18 needs to be considered, in Step 1b a recursion `decompBOM(right)` deals with it.

In Fig. 22, the right machine has the state **Loop** as an **EntryPoint** with a transition to the State **Solve**, which is not an **EntryPoint**. So, with the recursive call to `decompBOM`, we apply Law 18 to that machine to obtain the result in Fig. 23. Since in the right machine the only transition is to a **NodeNameRef**, and that machine has a single **EntryPoint**, no more changes arise from a recursive call to `decompBOM`.

In Step 2, we consider the case where there are multiple **EntryPoints**, but no transitions to a **Node** that is not an **EntryPoint** or a **NodeNameRef**. In this case, we apply Law 18 in Step 2a, but there is no need for a recursive call. Since there are no **Nodes** besides the **EntryPoints**, the rightmost machine resulting from applying Law 18 is empty and omitted.

Law 18. comp-from-entry-points()

To summarize, the procedure $\text{normOM}(\text{openM})$ terminates and normalizes any **OpenStateMachines**. If openM is a **BasicOpenStateMachine**, it terminates because $\text{normNC}()$ and $\text{decompBOM}(\text{openM})$ do: the argument for termination of $\text{normNC}()$ is similar to that for $\text{normSMB}()$, and termination of $\text{decompBOM}(\text{openM})$ is considered next. If openM is a **CompOpenStateMachine**, it terminates because there is a finite number of **BasicOpenStateMachines** composed.

The procedure $\text{decompBOM}(\text{openM})$ terminates because the rightmost machine generated by Law 18, to which it is applied recursively, has a number of **Nodes** that are not **NodeNameRefs** strictly smaller than those of the original machine. This is because the **EntryPoints** of the original machine, which cannot be **NodeNameRefs**, are removed from it. In addition, no new **Nodes** that are not **NodeNameRefs** are introduced. So, since the original machine has a finite number of **Nodes**, after a finite number of recursive calls, there are no more **Nodes** that become new **EntryPoints**, indicating the need for further decomposition via recursive calls.

Finally, the result of $\text{normOM}(\text{openM})$ is a normalized **OpenStateMachine**. Again, we have an inductive argument. If openM is a **BasicOpenStateMachine**, it is normalized by $\text{normOM}(\text{openM})$ because $\text{normNC}()$ ensures **NCNF1** and **NCNF2**, and in sequence exhaustive application of $\text{decompBOM}(\text{openM})$ ensures **BOMNF1** and **BOMNF2**. If openM is a **CompOpenStateMachine**, it is normalized because the recursive calls normalize the combined machines openM.left and openM.right .

To see that $\text{decompBOM}(\text{openM})$ ensures **BOMNF1**, we note that all machines generated by an application of Law 18, except the rightmost one, satisfy **BOMNF1**. For that rightmost machine, either we have a recursive call to decompBOM , so that **BOMNF1** is ensured by induction, or it is empty. The empty **BasicOpenStateMachine** is normalized, but it is also the unit for \odot , and can be eliminated. **BOMNF2** is ensured by exhaustively applying decompBOM .

In the next section, we present examples and a tool, addressing the practical relevance of our work. We consider soundness of our laws later on in Section 6.

5. EXAMPLES AND TOOL

As said, the normal forms provide a notion of completeness for our laws. They are enough to reduce any machine to a normal form, and capture properties related to control flow and time

in the state-machine notations. Here, we present in Section 5.1 the normalization of the machine **AppleHarvestControl** in Fig. 2, and then the normalization of a similar, but open, machine that defines the same control software. After that, in Section 5.2, we describe the tool we have developed to normalize models. It has been used with our examples and others². Finally, Section 5.3 discusses and illustrates practical applications.

5.1. Normalization: Examples

In this section, we present the normalization of two examples: a RoboChart machine (Section 5.1.1) and a similar, but open, machine (Section 5.1.2).

5.1.1. Normalization: RoboChart

AppleHarvestControl (Fig. 2) is a **StateMachineDef**, and so can be normalized using the procedure $\text{normSMB}()$ (Fig. 16). In Step 1, since **AppleHarvestControl** does not use $\text{sinceEntry}(S)$ expressions, Law 1 is never applied. After Step 2, with the exhaustive application of Laws 2 and 3, the definition of **AppleHarvestControl** is as shown in Fig. 24. All actions are now operation **Calls**, and the context requires interfaces (whose names start with $I_normal_$) that declare these operations. Actions in (sub)states of composite states also become **Calls**. In [37] we find the definitions of the new operations and interfaces. No other changes are made.

In Steps 3 and 4 of $\text{normSMB}()$, no changes affect **AppleHarvestControl** directly. The laws applied in these steps enrich the scope to include definitions for the operations $\text{tStop}()$ and deadlineCheck , with their associated interfaces $I\text{tStop}$ and $I\text{deadlineCheck}$.

In the last step, we deal with the deadline in the transition from the state **Prepare** to the state **LocalizeFruit**. With an application of Law 6, we obtain the state machine in Fig. 25. The deadline is removed from the transition, and a **during** action that **Calls** a new operation $\text{normal'AppleHarvestControl'Prepare't1'dop}()$ is added to **Prepare**. This new operation and a new interface are introduced; see [37] for their definitions.

Some, but not all, of the **OperationDefinitions** introduced by an application of $\text{normSMB}()$ are already normalized. They are all action operations, and are already normalized if its single **Statement** satisfies the restrictions in **OPDNF1** (see Fig. 9). In our example, most new operations are normalized or are very easy to normalize (see [37] for details). A more interesting example is

² robostar.cs.york.ac.uk/

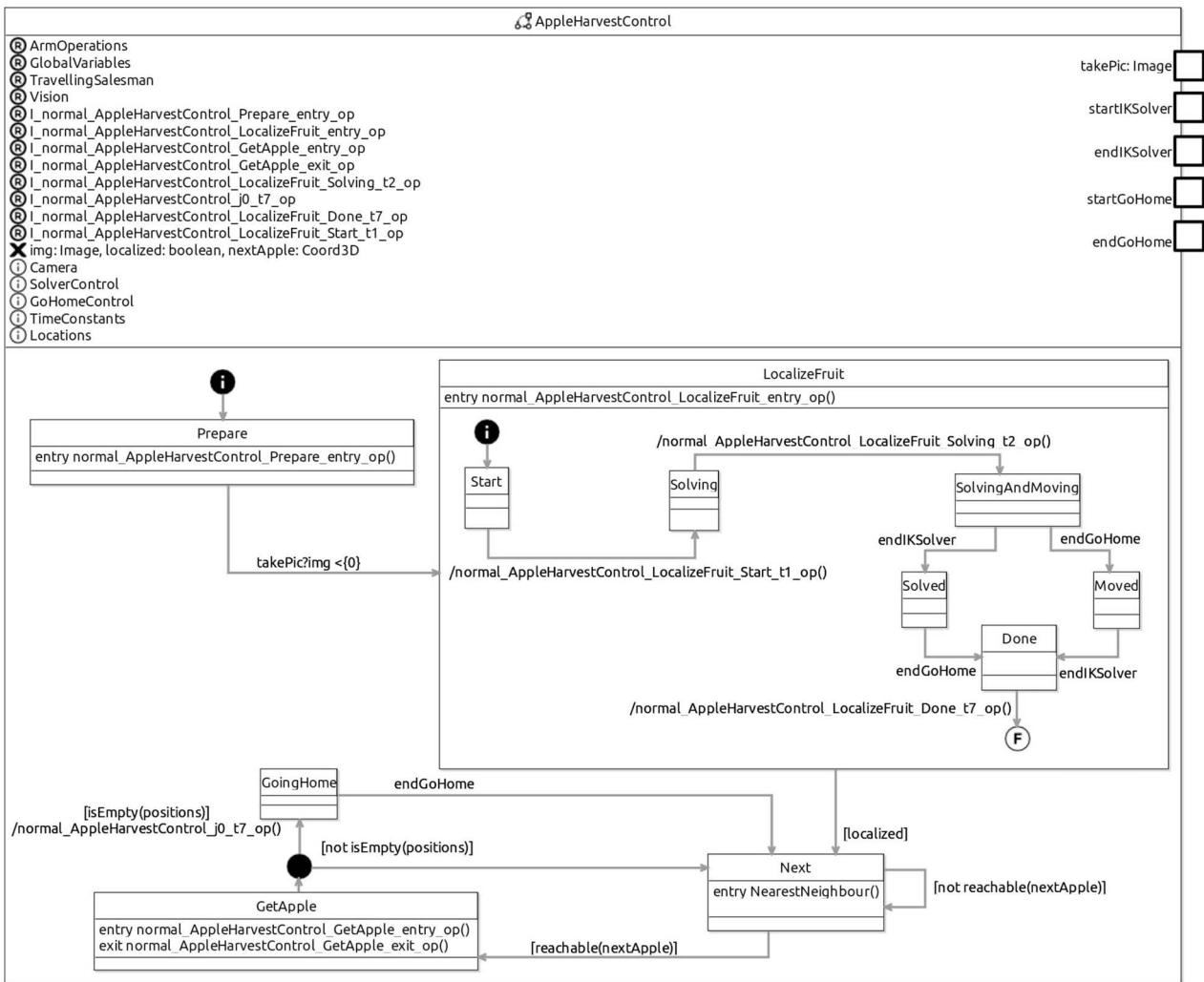


Figure 24. AppleHarvestControl after Step 2 of normSMB().

provided by the operation that we reproduce in Fig. 26; it is called `normal AppleHarvestControl GetApple entry op()`. To normalize it, we apply the procedure `normAO()` (Fig. 17).

Steps 1–4 of `normAO()` declare operations (and associated interfaces) that are used to capture the meaning of time primitives in the model and are already normalized. More interesting is Step 5, which applies the laws that remove the control flow from the action exhaustively. At first, only Law 11 applies, since the **Statement** is a deadline. The operations resulting from the application of this law are in Fig. 27. The interfaces used there are in [37].

The transformed definition in Fig. 27 for the operation `normal AppleHarvestControl GetApple entry op()` is now normalized. The new operation at the bottom of Fig. 27 has, however, the original **Statement** restricted by the deadline in a transition action in a composite state, and needs to be normalized. Since it is not an action operation, we first use `normSMB()`, which replaces the transition action with a call to the operation in Fig. 28. The relevant interface is in [37].

The action in the new operation in Fig. 28 is a sequence, and we apply Law 8 to decompose it. Fig. 29 shows the result of one application of Law 8 at the top, and, at the bottom, the result of its later exhaustive application after one application of Law 7 to remove the outer parentheses. (The spurious parentheses

are introduced in the application of Law 11 to ensure that in `s; g = true`, the assignment to `g` follows `s` as stated. Without the parentheses, there is the possibility that `g = true` becomes captured, for instance, in the `else` branch of a conditional.)

At this point, there are three transitions with a `wait` statement. They are all nondeterministic, and we eliminate them with three applications of Law 13. The result is in Fig. 30. The order in which the laws are applied in Step 5 of `normAO()` does not matter. We can, for example, apply Law 13 as soon as an applicable transition is introduced by an application of Law 8.

This completes Step 5 of `normAO()`. The result, however, as shown in Fig. 30, is no longer an action operation. The decomposition of the original action introduced several transitions, and so normalization according to OPDNF1 does not hold. We then pursue normalization according to OPDNF2, which amounts to NCNF1 and NCNF2. Presence of `sinceEntry(S)` expressions and deadlines is not an issue, since they are removed by `normSMB()`, so NCNF2 is guaranteed. We may, however, need to introduce further operation **Calls**. In our example, most of the actions in the transitions in Fig. 30 are already **Calls**. In Step 6 of `normAO()`, we need to introduce just one more operation for the action in the transition to the final state.

The result is shown in Fig. 31, which is a normalized version of the operation in Fig. 28. This is obtained with an application of

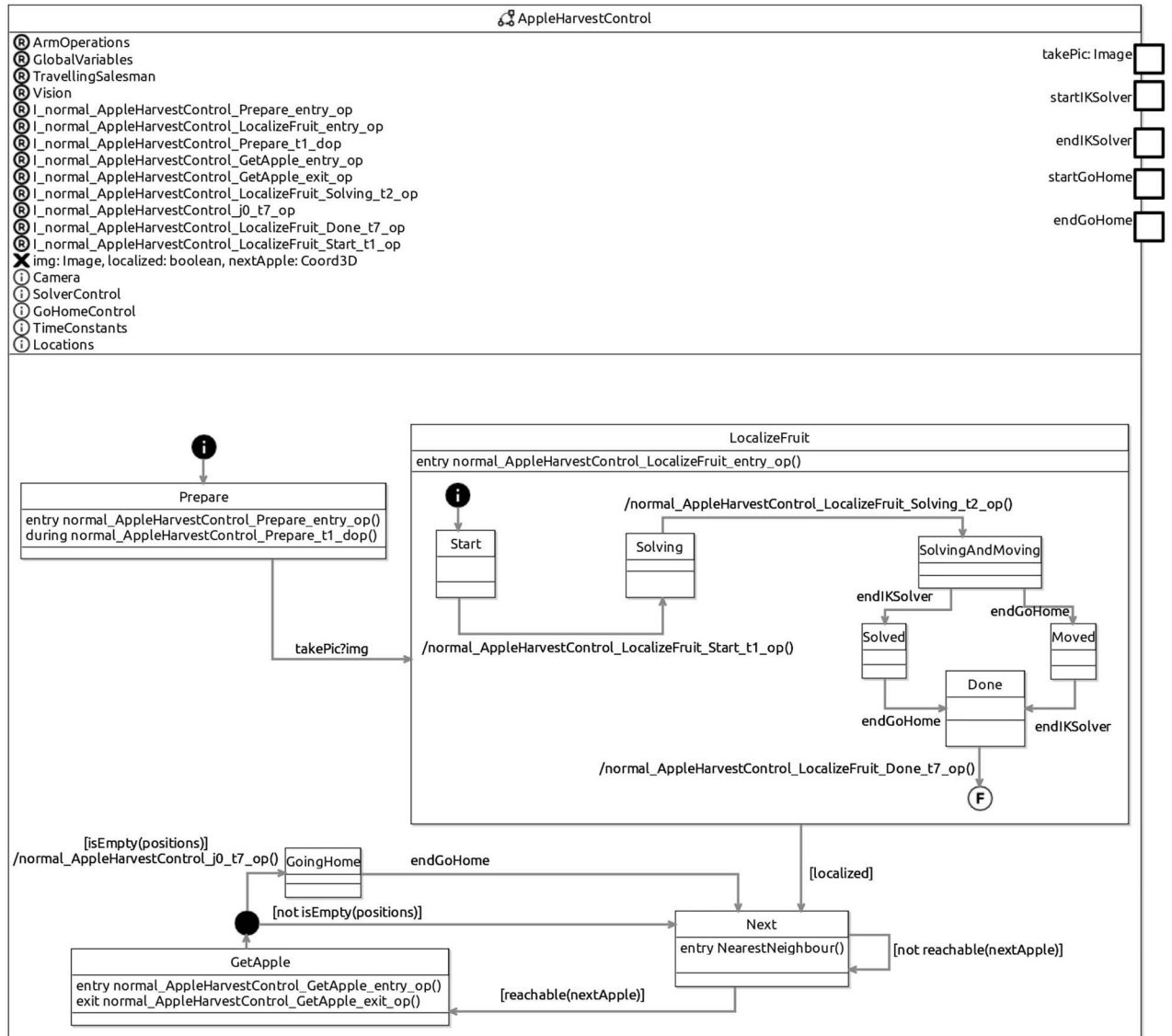


Figure 25. AppleHarvestControl after Step 5 of normSMB().

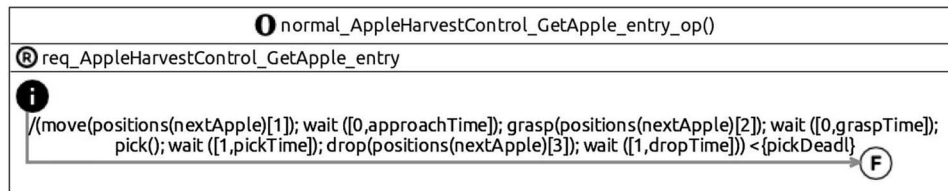


Figure 26. Example for use of normAO().

Law 3. The extra action operation called in the transition to the final state is in [37]; it is normalized. In [37] we also present the new interface that is needed in this step.

The state machines presented here have been automatically generated from the original model (Fig. 2) using the tool described in Section 5.2. Our examples here illustrate how a model containing just normalized **StateMachineDefinitions** and **OperationDefinitions** can be obtained using our procedures.

5.1.2. Normalization: open machines

We now consider the normalization of an **OpenStateMachine** using the procedure **normOM** in Fig. 18. As said, for a **BasicOpen**

StateMachine, first of all, in Step 1a, we apply a procedure **normNC()** that is very similar to **normSMB()** already illustrated. For example, if our starting point is an **OpenStateMachine** that is similar to the RoboChart machine **AppleHarvestControl** in Fig. 2, the result of Step 1a is a machine similar to that in Fig. 25. The difference is that an **OpenStateMachine** does not have a context. As we have discussed in Section 6, their semantics differ accordingly, as does the statement and proof of the relevant laws.

Step 1b of **normOM** applies **decompBOM** to both **AppleHarvestControl** itself and to the machine of its composite state **LocalizeFruit**. We illustrate first the application to **AppleHarvestControl**. The Step 1 is similar to that for the machine **IKSolver** presented in the

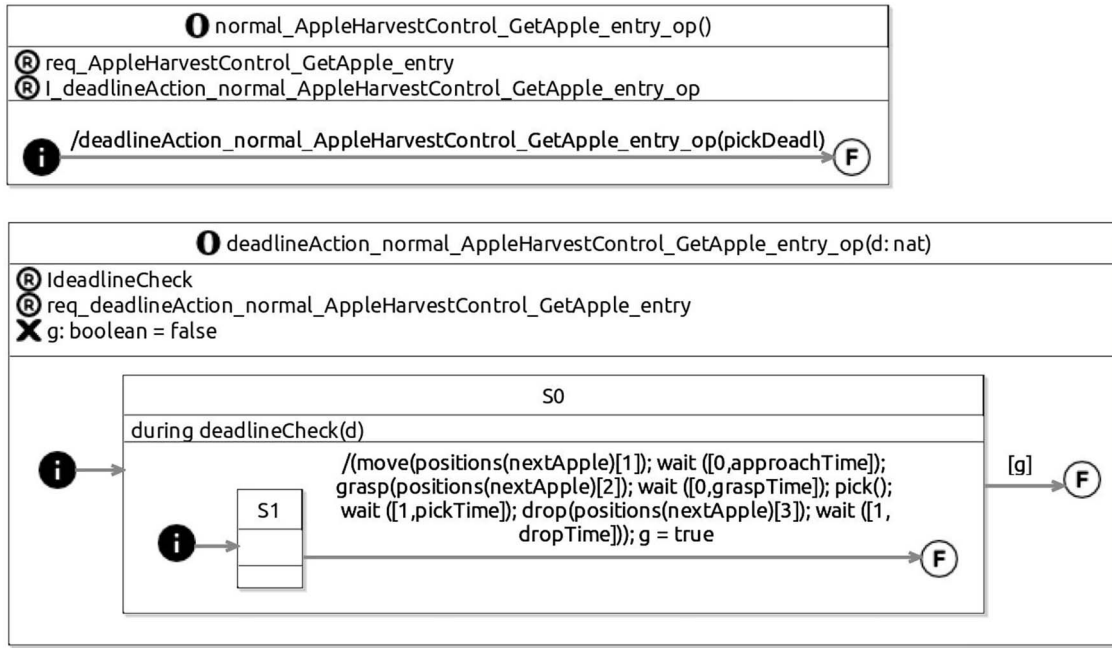


Figure 27. normAO(): application of Law 11.

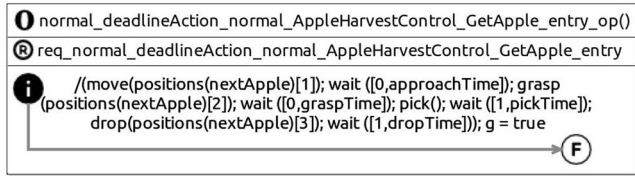


Figure 28. Action operation from normSMB().

previous section (see Fig. 21). *AppleHarvestControl* has, of course, a single *EntryPoint*: its initial junction, which, by a well-formedness condition, has a single transition that is not a self-transition. The target of that transition is the state *Prepare*, which is not a *NodeNameRef*. The application of Law 18 in Step 1a isolates the initial junction with a transition to a *NodeNameRef* connecting to *Prepare*. In the second machine in the composition, *Prepare* is an *EntryPoint*.

In Step 1b of *decompBOM(AppleHarvestControl)*, a recursion leads to the application of *decompBOM* to the new machine with *Prepare* as a single *EntryPoint*. It has a transition to the composite state *LocalizeFruit*, which is not a *NodeNameRef*. Applying Law 18 to this machine, we get the result shown in Fig. 32.

Another iteration of the recursion splits *LocalizeFruit* and introduces a machine where the state *Next* is the single *EntryPoint*. Yet another recursion splits out *Next* and introduces a machine where *GetApple* is the *EntryPoint*. The new machines with *Next* and *GetApple* as *EntryPoints* are in Fig. 33. The self-transition of *Next* stays in the machine where this state occurs. The transitions to *Next* in the second machine become transitions to *NodeNameRefs* referencing *Next*.

In the next iteration, *GetApple* is isolated, with its transition to the *Junction* going to a new *NodeNameRef*, and the *Junction* becoming an *EntryPoint* of a new machine. The result is shown in Fig. 34. As mentioned before, *Junctions* have names, just like states. In diagrams, we normally hide such names. (Our tool, presented in the next section, generates fresh names for them automatically.) When, however, a junction is used as an *EntryPoint*, its name needs

to be used, and it is shown in our example. In Fig. 34, the *Junction* is called *j0* and its status as an *EntryPoint* in the new machine is marked by an *i* inside the *Junction* symbol.

The next iteration of the recursion applies to the new machine with *j0* as *EntryPoint*, and isolates *j0*: see Fig. 35. Yet another machine is defined; it has the state *GoingHome* as *EntryPoint*. Since the only transition from *GoingHome* is to a *NodeNameRef* (to *Next*), and *GoingHome* is the single *EntryPoint* of this new machine, a recursive application of *decompBOM* to it has no effect. The procedure application *decompBOM(AppleHarvestControl)* is now finished.

For *LocalizeFruit*, after four iterations of the recursion, we get the machines in Fig. 36. The rightmost machine (at the bottom of Fig. 36) has two *EntryPoints*: the states *Solved* and *Moved*. The fifth iteration splits that machine into three as shown in Fig. 37: one for each *EntryPoint* and one with the rest of the nodes. Since *Solved* and *Moved* have each a single transition, both to the state *Done*, the extra machine has again a single *EntryPoint*: *Done*.

The next iteration of the recursion separates out *Done*, leaving just the *Final* state. Figure 38 shows the result. The diagram for the last machine reveals the name of the *Final* state, and uses an *i* to indicate that it is an *EntryPoint*. A recursive application of *decompBOM* to this machine has no effect. The normalization of *LocalizeFruit* is concluded.

Next we describe our implementation in *RoboTool* of the normalization procedures.

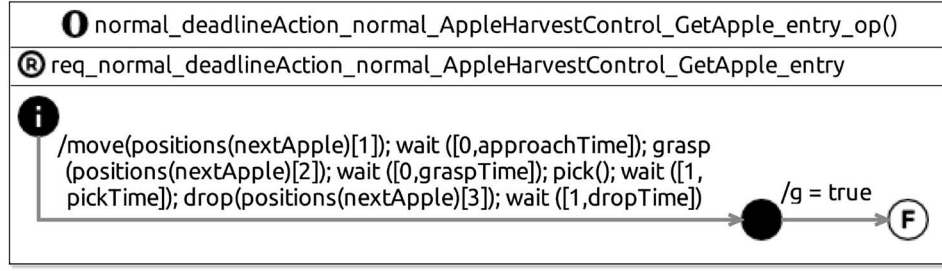
5.2. RoboTool

For a preliminary validation of our laws and procedures, we have implemented them. We have used the model-transformation engine *Epsilon*³ [38], an open-source framework with a set of languages and facilities for the management and development of models with rich Eclipse integration. We have integrated our implementation with *RoboTool*⁴, a modelling and verification tool for *RoboChart*.

³ www.eclipse.org/epsilon/

⁴ robostar.cs.york.ac.uk/robotool/

(A)



(B)

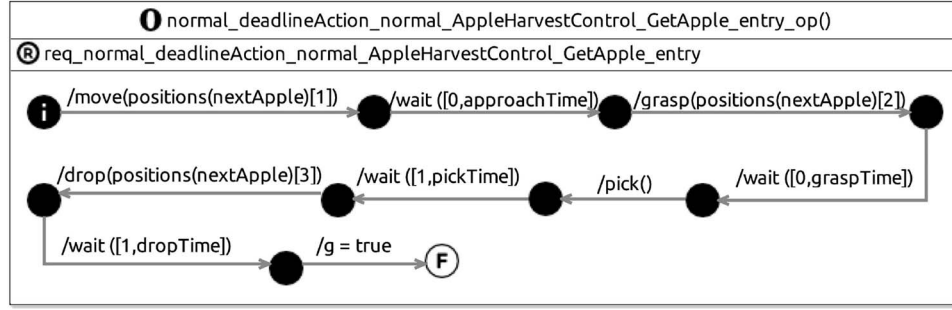


Figure 29. Law 8: (A) once and (B) exhaustively.

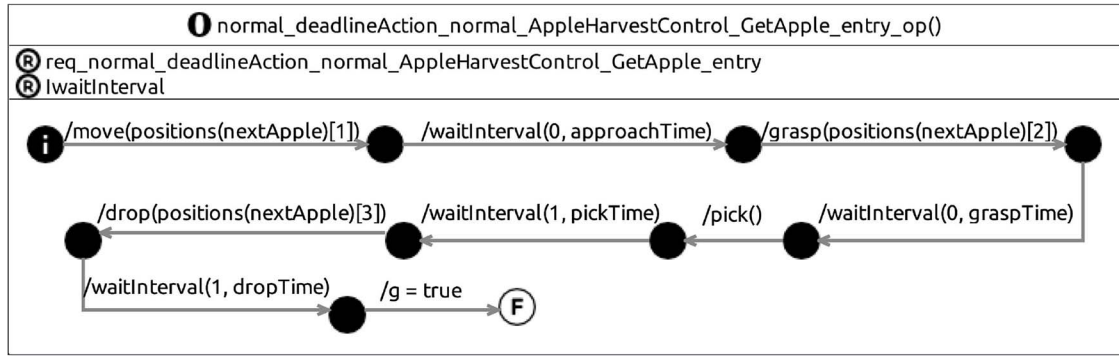


Figure 30. Law 13, three times.

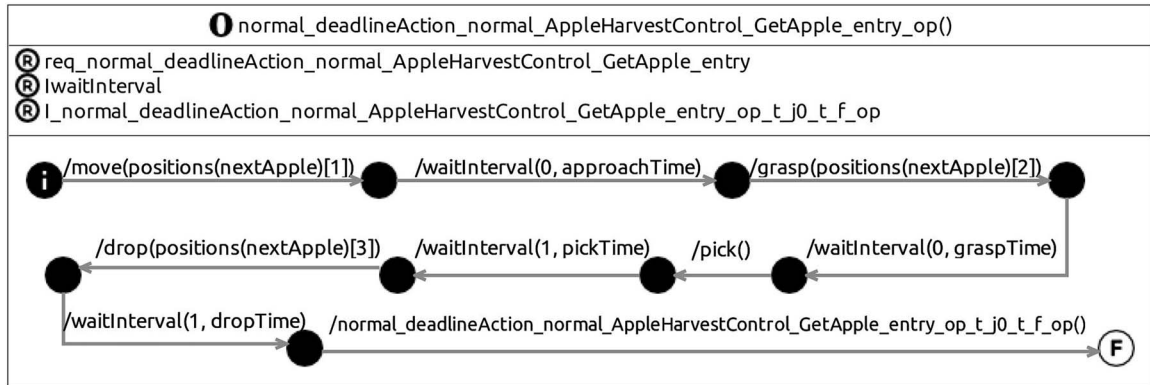


Figure 31. normAO(): final result.

RoboTool is a set of Eclipse plug-ins that provides textual and graphical editors, implemented using the Xtext⁵ and Sirius⁶ frameworks. RoboTool generates, automatically, a (tock-)CSP and a reactive modules semantics [39] for RoboChart models. It is

integrated with the FDR [40] and PRISM [41] model checkers to prove behavioural and quantitative properties.

With our implementation, and the testing it has enabled, we have established that the laws are well-typed, and have gathered evidence for the correctness of the procedures. Our test suite⁷

⁵ eclipse.org/Xtext/

⁶ www.eclipse.org/sirius/

⁷ github.com/UoY-RoboStar/roboschart-normalization-tests

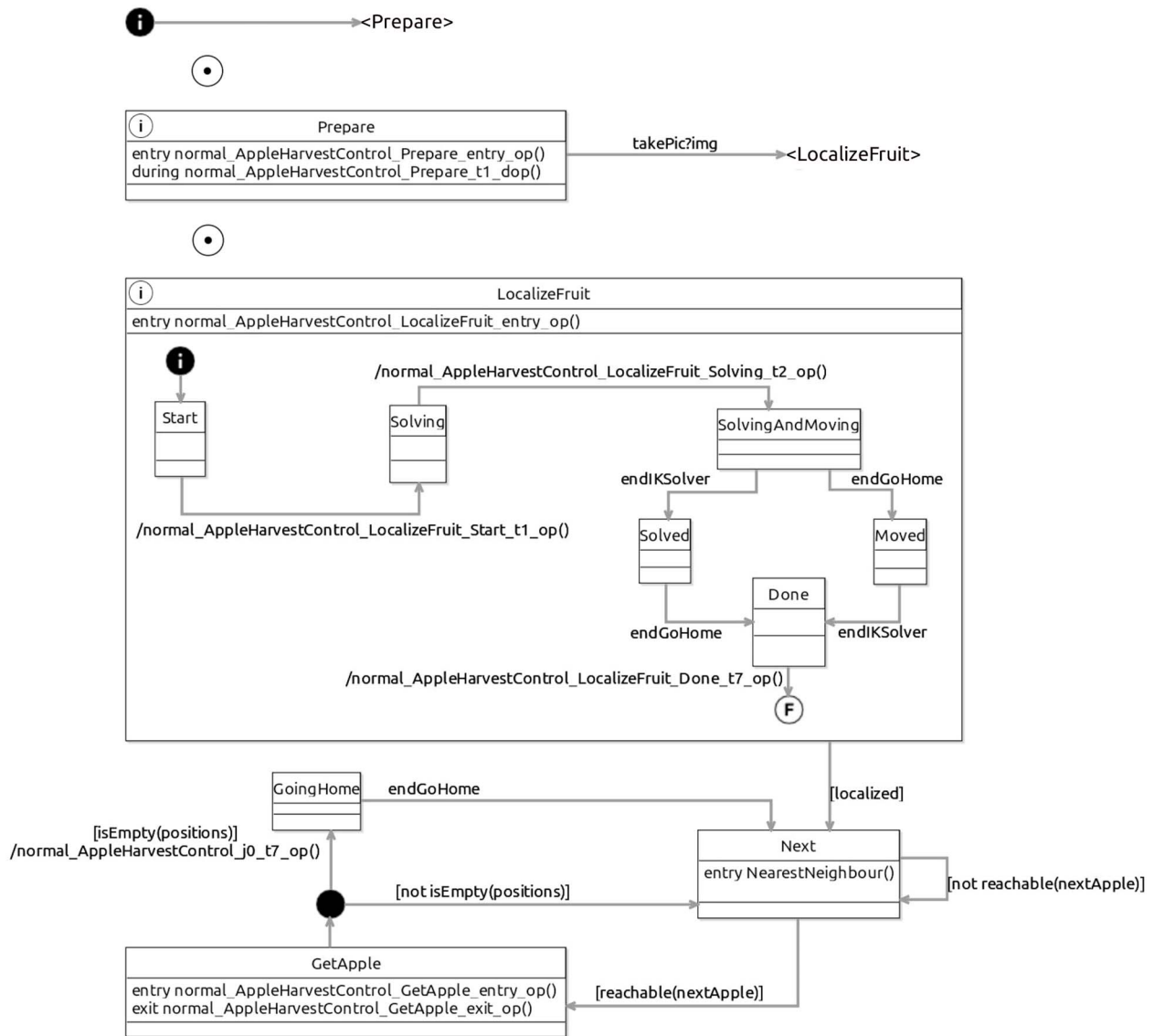


Figure 32. decompBOM(AppleHarvestControl): after 2nd recursion.

contains models that, together, include at least one instance of every class of the metamodels and whose normalization requires the application of every law presented here. A test execution includes the comparison of the tock-CSP semantics of the original and normalized machines.

In fact, the laws and procedures described in the previous section are the result of our experience with the development and use of our tool. This effort has led to the identification of missing declarations in the body and provisos of some laws (such as Laws 2 and 6) that ensure that the machines that are defined by their application are well formed. Our experiments have also revealed early the need for adjustments in the order in which the laws are applied. For example, for the procedure `normAO()`, the experiments have made apparent the need for the extra Step 6.

Each law is implemented as a transformation pattern using the Epsilon Pattern Language (EPL)⁸, a language based on pattern matching for specifying and detecting structural patterns for model-to-model transformation. The implementation of each law captures a structural pattern of interest (based on the left-hand

side of the law as presented here) to produce in-place modifications of the model (reflecting the result of the law application defined by its right-hand side). As an example, we present in Fig. 39 a fragment of the EPL pattern that implements Law 2.

An EPL pattern is defined by named and typed elements of the metamodel, called roles. For Law 2 (see Fig. 39), we define three roles (lines 2-4): a machine body (`smb`), a state (`s`) of such a machine, and, finally, an action (`s`) of `s`. The types prefixed by **RoboChart!** refer to classes of the RoboChart metamodel. Types without such a prefix are native to Epsilon.

The implementation of Law 2 creates the new operation, `ops`, and sets its name (lines 9-10). As defined by Law 2, `ops` contains a single **Transition** from an **Initial** junction to a **Final** state. The junction and the state are recorded in the variables `ops_I` and `ops_F` defined on lines 11-14. These variables are used to set the source and target of the transition `ops_Tr` (lines 18-19). The action of this transition is the original action of the state `s` (line 20). The new elements (that is, `ops_I`, `ops_F` and `ops_Tr`) are, finally, added to the set of nodes and transitions of `ops` (lines 22-23).

The signature of `ops` is defined on lines 27-28 for inclusion in the interface `rops` defined on lines 29-31. On line 32, we

⁸ www.eclipse.org/epsilon/doc/epl

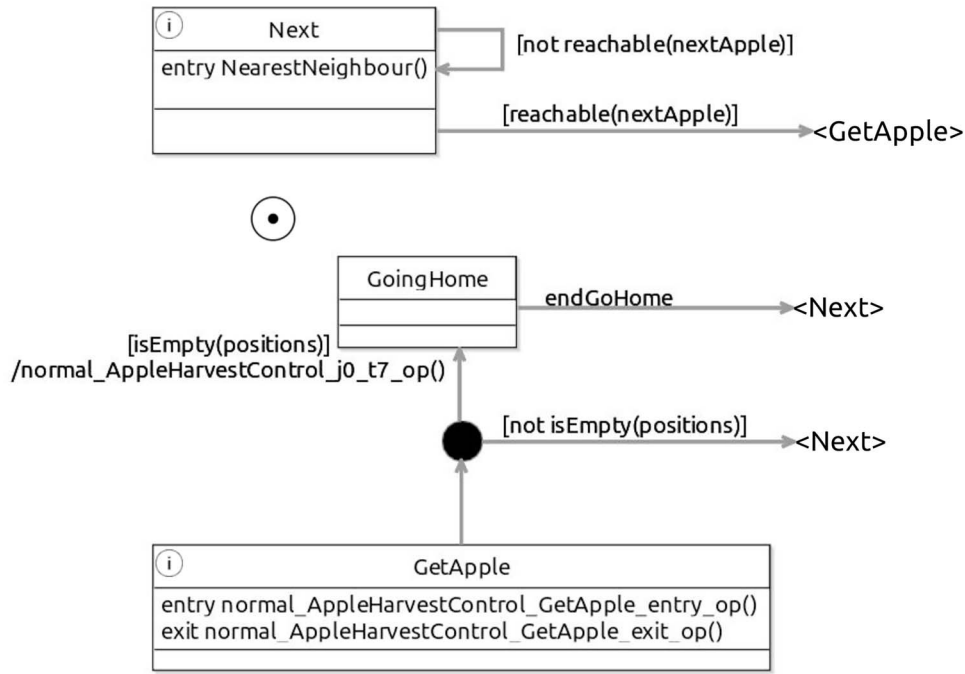


Figure 33. decompBOM(AppleHarvestControl) After fourth recursion.

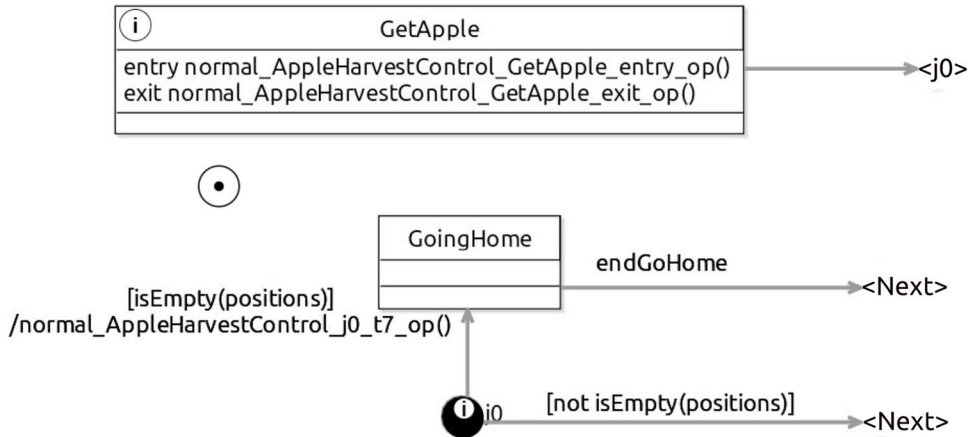


Figure 34. decompBOM(AppleHarvestControl) After fifth recursion.

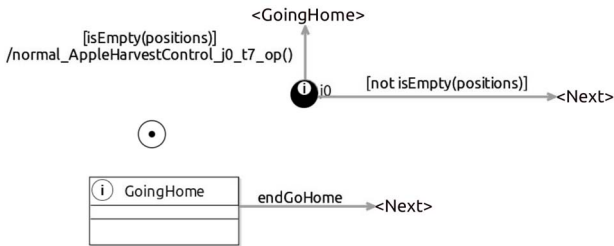


Figure 35. decompBOM(AppleHarvestControl) After sixth recursion.

add `IOps` to the set `rInterfaces` of required interfaces of the `StateMachineBody`. The other interfaces `req_s` and `defEvents_s` in Law 2 are defined and included in a similar way (omitted in Fig. 39).

The main goal of Law 2 is to use an operation `Call` to replace an action of a state. This is effectively implemented in lines 36–38,

where a `Call` (`OpS_Call`) is created for the new operation, and the original action of the state `s` is defined to be this `Call`.

We have also implemented the normalization procedures for a `StateMachineBody`, `normSMB()` and for action `OperationDefinitions`, `normAO()`. For `OpenStateMachines`, `decompBOM(openM)`, the core of `normOM(openM)` is implemented. The additional procedure `normNC()` used in `normOM(openM)` is not implemented because it is similar to `normSMB()`.

Each procedure is implemented as an ANT-based Epsilon workflow⁹, a mechanism called target for performing model management and transformation activities. In our implementation, each target corresponds to a normalization procedure. The execution of a workflow performs a sequence of EPL tasks, specified using an `epsilon.epl` clause. Each task corresponds to a step of the target procedure as defined in Section 4. As illustration, we present in Fig. 40 a sketch of the implementation of `normSMB()`. (A workflow is defined using an XML-based notation.)

⁹ ant.apache.org

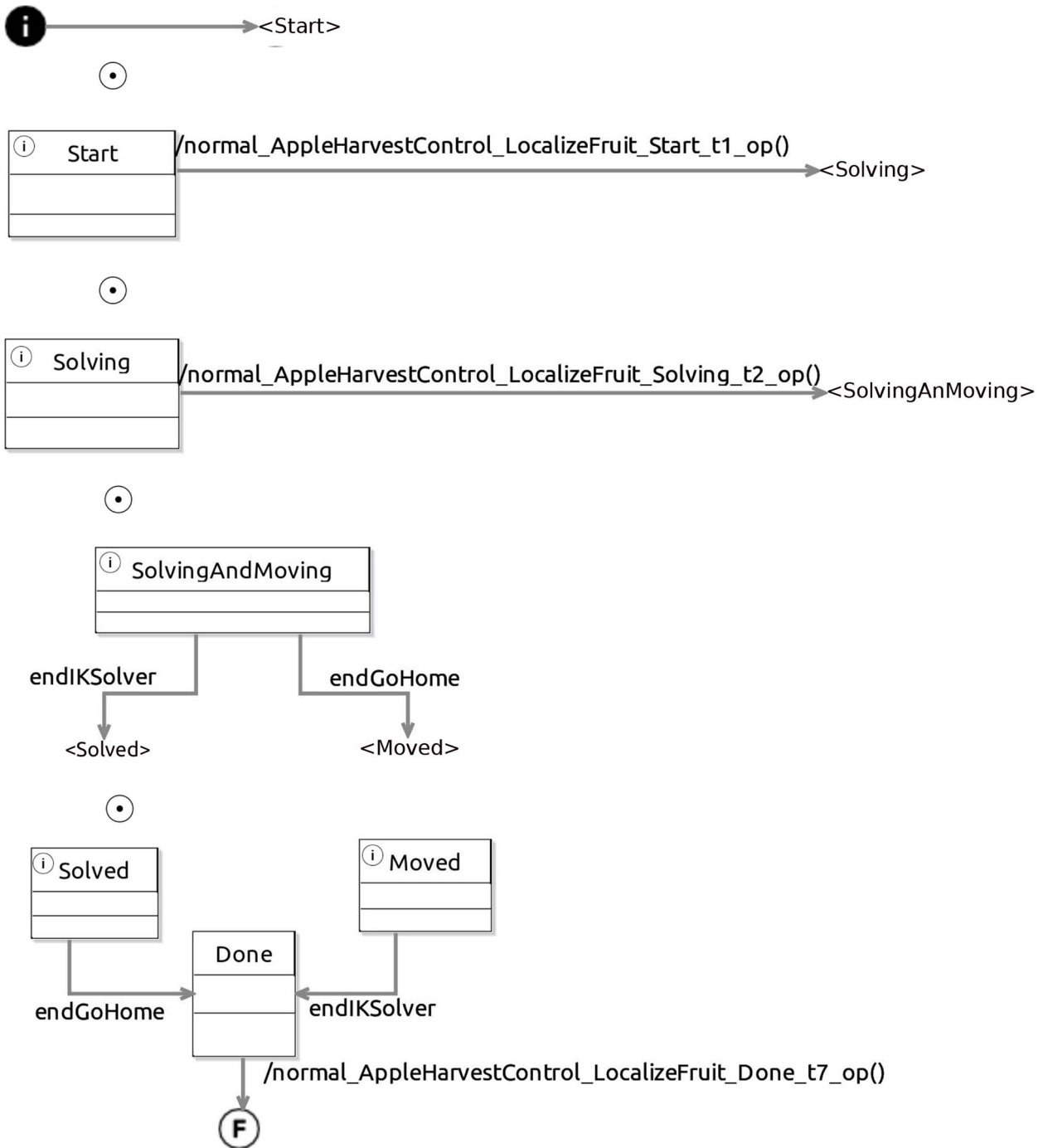


Figure 36. decompBOM(LocalizeFruit): after fourth recursion.

As depicted in Fig. 40, the first task in the workflow for `normSMB()` implements Step 1, as specified by the `uri` attribute in its `epsilon.ep1` clause. Internally, `Step1.ep1` calls Law 1 1 (`elim-sinceEntry`). `Step1.ep1` is repeated as long as successful matches of the pattern in that law in the model (RoboChart) are found, since the clause `repeatWhileMatches` is set to `true`. When there are no more matches, the task is finished, and the subsequent task is executed. Step 2 in the definition of `normSMB()` (see Fig. 16), however, is applied while there are actions that are not a `Call`. In ANT, there is no direct mechanism to implement tactics for iterative applications of transformations based on patterns other than those in the laws. We have, therefore, encoded the

termination condition for each law where relevant. So, in addition to the code fragment presented in Fig. 39, our implementation of Law 2 actually includes the following match condition:

```
match : nots.action.isTypeOf(RoboChart!Call)
```

This ensures that Law 2 is applied only when the action is not a `Call`. The target `normSMB` ends after the task that calls Step 5 and its execution is completed.

As an optimization in our tool, given a model, we apply in parallel the procedures described above to all machines and

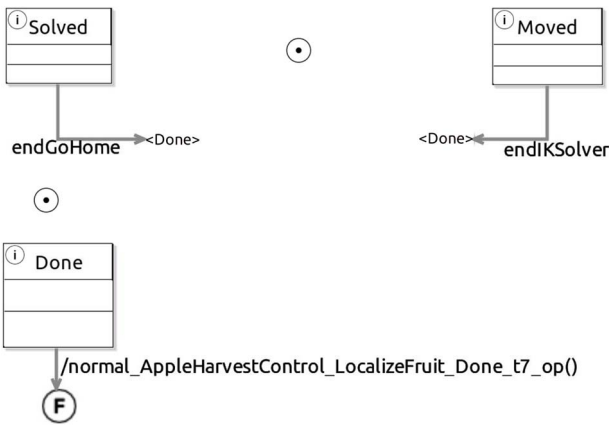


Figure 37. decompBOM(LocalizeFruit): after fifth recursion.



Figure 38. decompBOM(LocalizeFruit): after sixth recursion.

operations. This includes the operations that might be introduced as the result of an application of a law. In the case of Law 11, which is used in Step 5 of `normAO()`, it introduces an operation `deadlineAction's(d:nat)` to which we need to apply `normSMB()`. As part of our optimization, the definition for `deadlineAction's(d:nat)` that we introduce is already the result that would be obtained by `normSMB()`.

In RoboTool, the implemented procedures are encapsulated by a plug-in, called *NormalForm Generator*, and are applied in the following order: `normSMB()`, `normAO()`, and `decompBOM()`. This also reflects the optimization previously described, which applies the procedures to machines and operations. So, when a RoboChart model is loaded, the *NormalForm Generator* can be invoked by clicking on the menu item *NormalForm* in its toolbar, as shown in Fig. 41. The normalized RoboChart and OpenMachine models are stored in the project directories `/normalForm/robochart` and `normalForm/openMachine`, respectively.

The examples presented here, and many others, have been developed using RoboTool.

5.3. Applications

A model or program normalization procedure is an effective technique to establish a notion of (relative) completeness of a set of algebraic laws, as we have already pointed out and illustrated in Section 4.

Moreover, additional applications of such laws arise from the benefit of using normalization as a preliminary step in the translation into other notations. Some other transformation techniques, however, like refactoring, involve law applications with a different purpose: improving readability and reuse, and reducing complexity of models. In this section, we briefly illustrate law-based refactoring transformations.

```

1  pattern intro_call_for_act_state
2    smb : RoboChart!StateMachineBody,
3    S : RoboChart!State from: nodes(smb),
4    s : RoboChart!Action from: S.actions {
5  do {
6
7    ...
8
9    var OpS = new RoboChart!OperationDef();
10   OpS.name = setName(smb,S,s);
11   var OpS_I = new RoboChart!Initial();
12   OpS_I.name = "i";
13   var OpS_F = new RoboChart!Final();
14   OpS_F.name = "f";
15
16   var OpS_Tr = new RoboChart!Transition();
17   OpS_Tr.name = "t";
18   OpS_Tr.source = OpS_I;
19   OpS_Tr.target = OpS_F;
20   OpS_Tr.action = s.action;
21
22   OpS.nodes.addAll(Set{OpS_I,OpS_F});
23   OpS.transitions.add(OpS_Tr);
24
25   ...
26
27   var OpSig = new RoboChart!OperationSig();
28   OpSig.name = OpS.name;
29   var IOpS = new RoboChart!Interface();
30   IOpS.name = "I_" + OpS.name;
31   IOpS.operations.add(OpSig);
32   smb.rInterfaces.add(IOpS);
33
34   ...
35
36   var OpS_Call = new RoboChart!Call();
37   OpS_Call.'operation' = OpSig;
38   s.action = OpS_Call;
39   }
40 }

```

Figure 39. Implementation of Law 2.

```

<target name="normSMB">
  <epsilon.epl uri="Step1.epl"
    repeatwhilematches="true">
    <model ref="RoboChart"/>
    ...
  </epsilon.epl>
  ...
  <epsilon.epl uri="Step5.epl"
    repeatwhilematches="true">
    <model ref="RoboChart"/>
    ...
  </epsilon.epl>
</target>

```

Figure 40. Implementation of `normSMB()`.

To avoid bias, we use an existing RoboChart model with some slight simplifications: a robot in a swarm acting under the Alpha

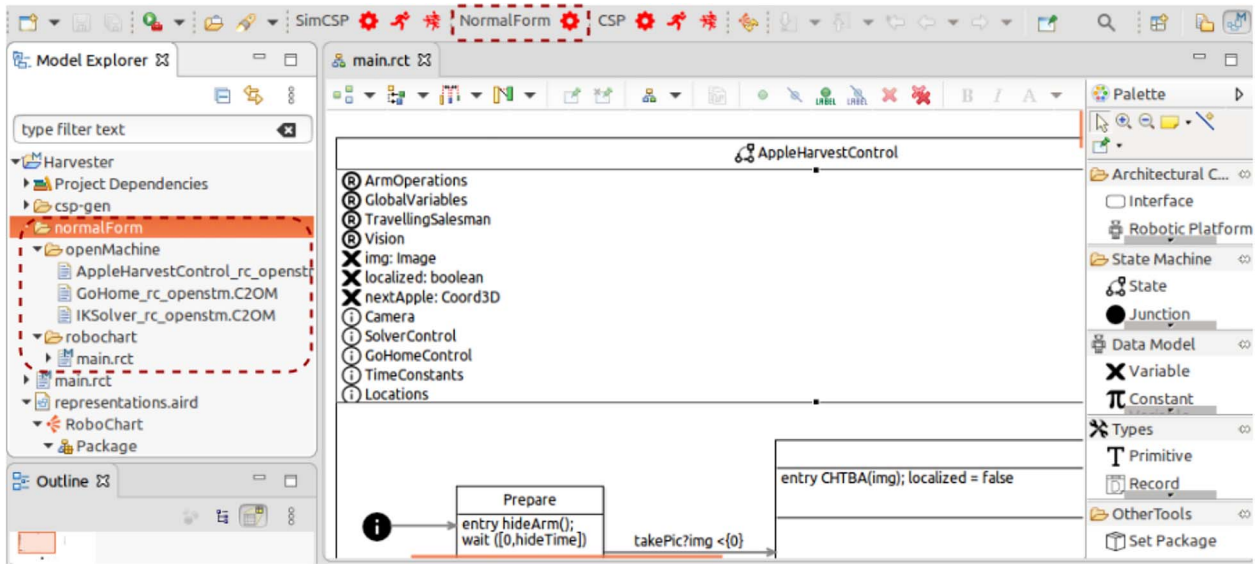


Figure 41. RoboTool interface.

Algorithm [42]. This example includes one machine capturing the behaviour of the robot's movement, and another modelling the communication with the other robots. Our focus is on the **Movement** machine: see Fig. 42.

Its initial transition includes an action that resets the clock MBC, and targets the composite state **MovementAndAvoidance**. Entering this state happens only after executing the entry action ($\text{move}(\text{lv}, 0)$) of the state **Move**. This operation is parametrised by a linear and an angular velocity, in this order.

When an occurrence of an **obstacle** is detected, if less than MB-360/av time units have passed, the transition from **Move** to **Avoid** is triggered. In this case, the entry action of **Avoid** (a conditional that determines an angular motion, based on the robot's position) is executed, and a period of time must pass (as stated in the **wait** action) before returning back to **Move**.

Another control path is via the transition from **MovementAndAvoidance** to **Turning**; it is enabled when at least MB time units have passed since the last clock reset. The action associated with this transition is a sequence formed of the reset of the MBC clock, an input action that reads the number n of neighbouring robots, and an assignment of the value **false** to a control flow flag **turned**. Once in the state **Turning**, the robot is required to either turn 180 degrees (top transition to final state) if n is below a threshold α or, otherwise, perform a random turn (bottom transition). In any case, the control flag takes the value **true** to allow the triggering of the transition back to **MovementAndAvoidance**.

There are opportunities to both modularize and simplify this model. For example, there are four occurrences of a call to **move** followed by a **wait** statement: two in the entry action of **Avoid** and two on the transitions of **Turning**; the differences are only in the values of the arguments. Therefore, there is benefit in introducing a new operation, called say **turn**, that encapsulates this pattern of use of **move** and **wait**, and calling this operation with the appropriate arguments, instead of duplicating actions across the model.

To replace the two occurrences in the entry action of **Avoid**, we first note that the **then** and **else** branches of the conditional include only the invocation of the operation **move**. A single **wait** statement comes after the conditional. This is a nice example that illustrates the need for combining complementary sets of algebraic laws in

practical applications of model and program transformation. In this particular context, we need a simple law of the conditional statement that allows distributing a statement after a conditional into its branches (at the end of the **then** and **else** branches):

$$\begin{aligned} & \text{if } c \text{ then } s1 \text{ else } s2 \text{ end; } s3 \\ & = \\ & \text{if } c \text{ then } s1; s3 \text{ else } s2; s3 \text{ end} \end{aligned}$$

Applying this law, we can rewrite the conditional in the entry action of **Avoid** as in Fig. 43. A seminal paper includes several such laws of programming [7]; they are not our focus here, but are complementary to our laws of state machines. The combined use of these sets of laws justifies very expressive transformation strategies.

After applying the above law, we can apply Law 2 to replace the sequential actions in the **then** and **else** branches of the conditional in Fig. 43 with calls to **turn**. The result is in Fig. 44. The first call can be introduced with a direct application of Law 2, introducing the interface, the definition of **turn**, and the call. The second call can be introduced using a slightly simplified version of the law that introduces only the call to the already declared **turn** operation.

Similarly, to refactor the actions in **Turning**, we first isolate the call to **move** followed by the **wait** statement into an action of a separate transition. This is justified by two applications of Law 8. Afterwards, we apply Law 3 to replace these sequential actions with calls to **turn**, in the same way as performed in the entry action of **Avoid**. The result is in Fig. 45.

Now we combine the actions in the top and bottom transitions of **Turning** back into sequential actions. This is justified by two applications of Law 8, from right to left. The result is in Fig. 46.

At this stage, we can combine the two transition actions of **Turning** into a conditional action. This is justified by applying Law 9, also from right to left. Furthermore, the transition from the initial junction to a junction can be eliminated by an application of Law 10, once more, from right to left. The effect of these two transformations is presented in Fig. 47.

The resulting model of the **Movement** machine after all these transformations is depicted in Fig. 48. It is possible to carry out

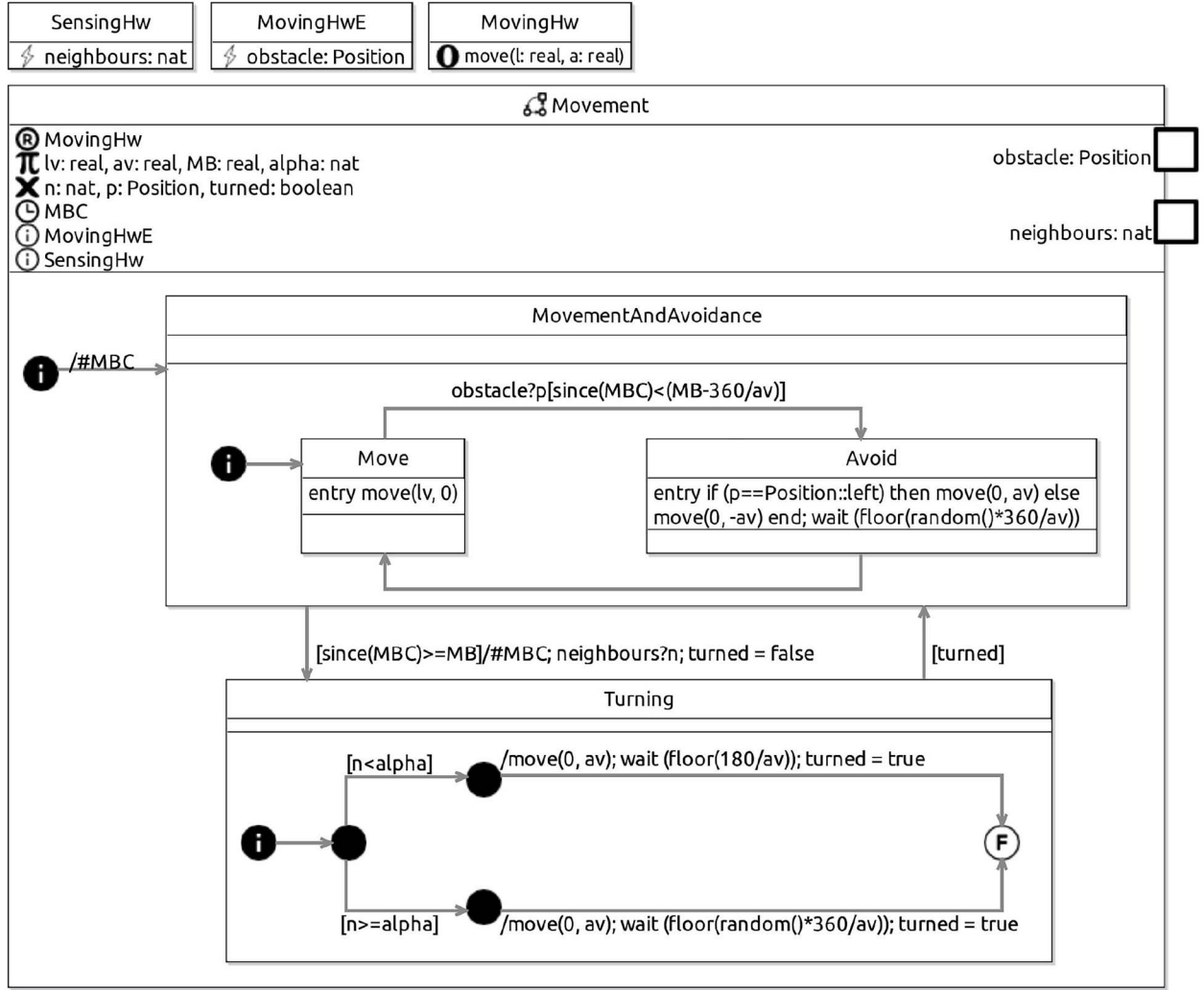


Figure 42. Alpha Algorithm.

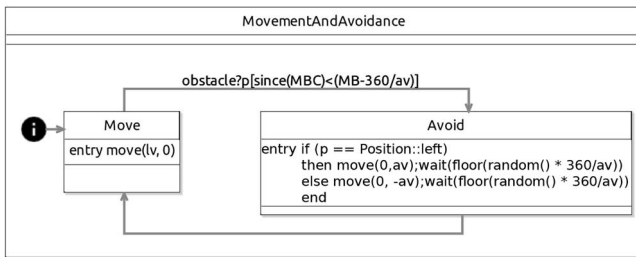


Figure 43. Alpha Algorithm - Step 1.

the transformations that are based on the laws presented in this paper using our encoding of these laws in RoboTool and Epsilon facilities to select and direct the application of laws¹⁰. Encoding of the laws of programming is not in the scope of our work, but the facilities of Epsilon make this a simple task.

In our ongoing work, we are using normalization to facilitate transformation of RoboChart models into simulation models (described using another diagrammatic notation called RoboSim [43]). Any such technique for RoboChart and open machines is

simplified by adding normalization as a first step, and then proceed with transformations that need to consider just normalized models. These normalized models exhibit only a very reduced number of patterns for transformation, characterized by the Definitions 3.1, 3.2, and 3.3 of the normal forms.

For all the above applications, soundness of the laws is paramount. We address this point next.

6. SOUNDNESS

Soundness of the normalization is justified using the formal semantics presented next in Section 6.1. Proofs of soundness of selected laws are sketched in Section 6.2. Complete proofs are available in [37].

6.1. Semantics

In this section, we define a discrete-time semantics in *tock-CSP* [44] for RoboChart and open state machines. Besides providing a novel semantics for open machines, we give a new compositional account of the meaning of operations in RoboChart. This is important for establishing soundness of our laws, which make extensive use of operations to encapsulate behaviour.

The process algebra *tock-CSP* is a timed variant of CSP [35]; it is part of a large family of notations for specifying concurrent

¹⁰ At github.com/UoY-RoboStar/robochart-normalization.

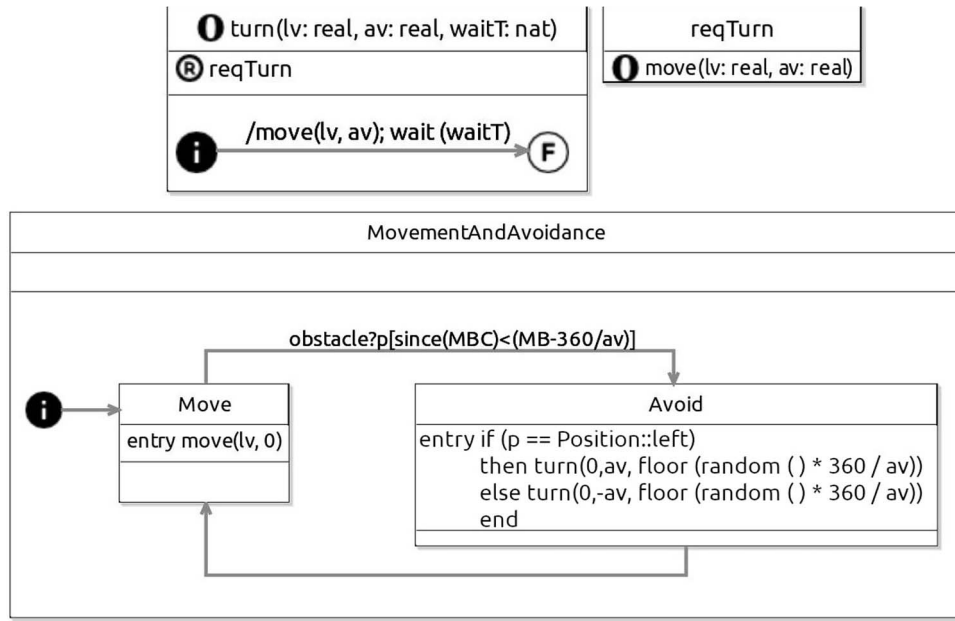


Figure 44. Alpha Algorithm - Step 2.

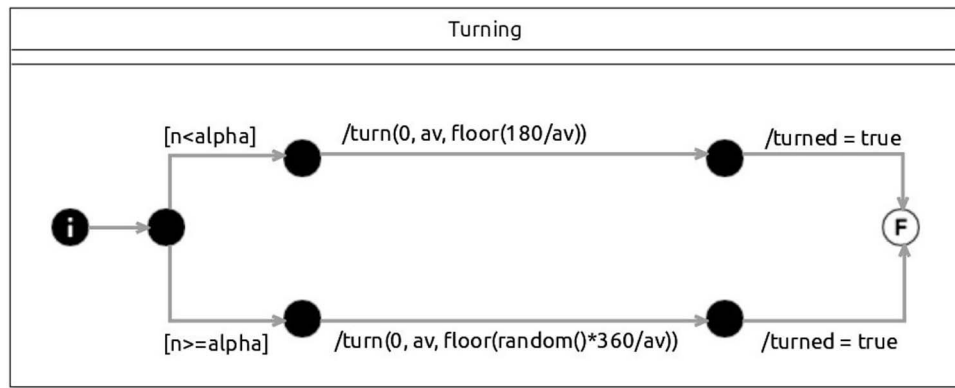


Figure 45. Alpha Algorithm - Step 3: State Turning.

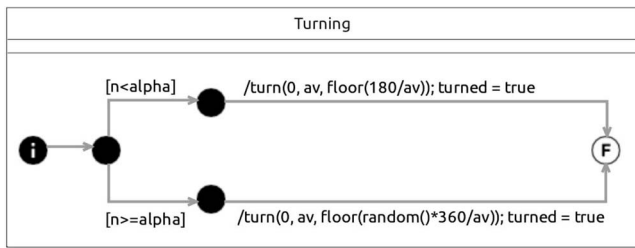


Figure 46. Alpha Algorithm - Step 4.

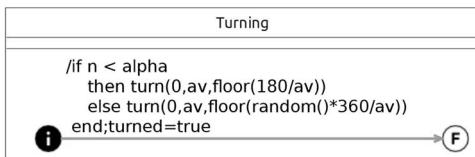


Figure 47. Alpha Algorithm - Step 5.

systems, including CCS [45], Pi-Calculus [46] and ACP [47]. CSP is distinctive in its denotational semantics, giving rise to notions of refinement useful for stepwise development. Processes specify

patterns of interaction via synchronization on channels, taking into account aspects such as (non)determinism, deadlock, and termination. Process definitions can also be made via parallel composition. Communications between parallel processes or with the environment are instantaneous, atomic events, that can carry values: inputs and outputs. The dialect *tock*-CSP, in addition, allows processes to specify time budgets and deadlines using a special event called *tock*.

In Table 1 we summarize the *tock*-CSP operators that we use in our work. To illustrate the notation we present a simple example of a one-place timed buffer.

Example 1.

$$TB = in?x \rightarrow (TB \sqcap (Wait(1); out!x \rightarrow TB))$$

The buffer is defined by the process `TB`. Initially it is prepared to receive (?) a value `x` on the channel `in` via a prefixing (`in?x →`), and then offers an external choice (\sqcap) to the environment between accepting a new value, via the recursion on `TB`, or delaying the output (!) of the current value. The delay of one time unit (`Wait(1)`) is sequentially composed (;) with a prefixing on `out`. An external choice is resolved by the environment synchronizing on events,

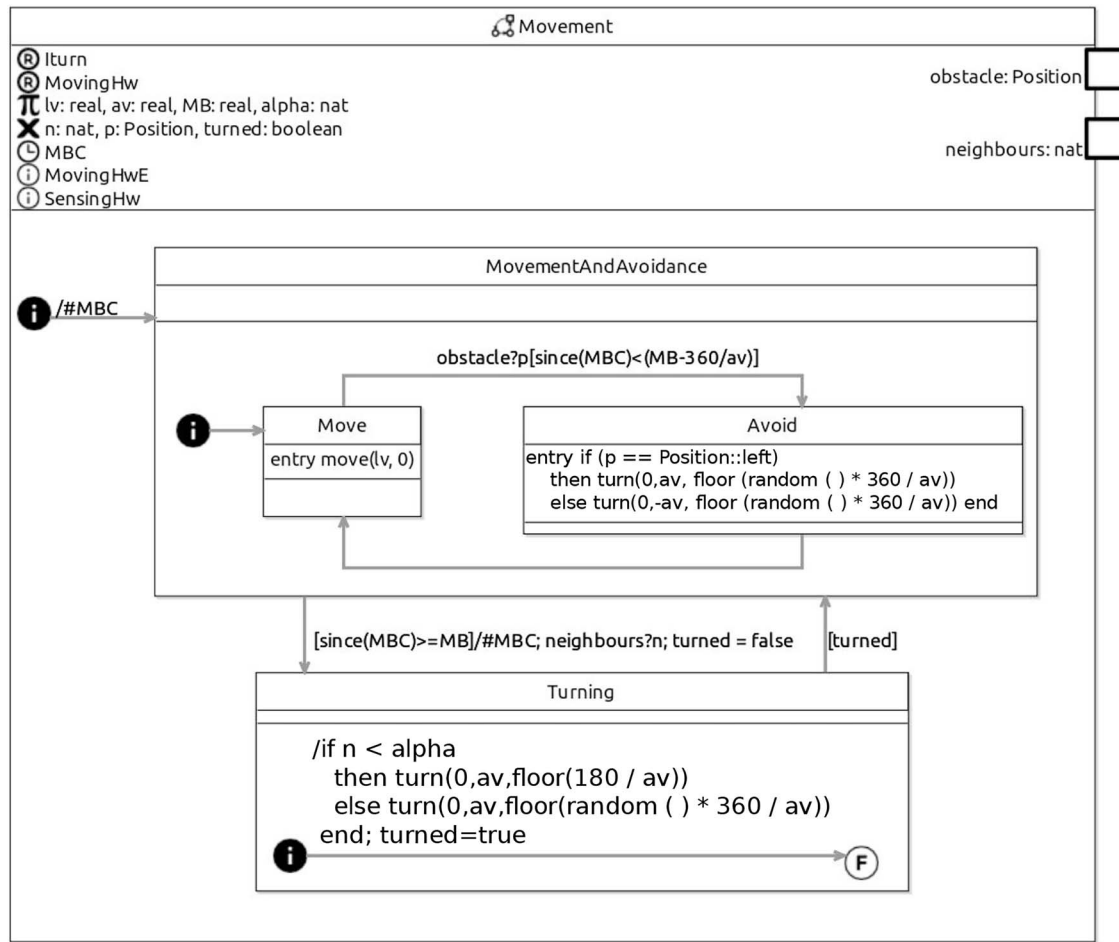


Figure 48. Alpha Algorithm - Refactored model.

or by termination. Here $in?x$ is syntactic sugar for accepting events $in.x$, where x ranges over the type of the channel in , left unspecified in this example. The prefixing on $out!x$ communicates the value of x as introduced into context by $in?x$.

The denotational semantics of $tock\text{-}CSP$ [44] forms a complete lattice under the refinement order \sqsubseteq . Here $P \sqsubseteq Q$ means that Q refines P , and is true exactly when every timed behaviour of Q , denoted by a trace that records interactions, refusals, and passage of time, is also a behaviour of P . The semantics of a recursive process, such as TB , is the greatest fixed point of TB , taken as a function from processes to processes.

Section 6.1.1 gives an overview of our semantics. Section 6.1.2 details the semantics of RoboChart state machines, and Section 6.1.3 of open machines.

6.1.1. Overview

The structure of our $tock\text{-}CSP$ semantics is illustrated in Fig. 49. It is formalized by semantic functions that define, for the various elements of the metamodel for RoboChart and open machines, $tock\text{-}CSP$ processes or terms used to specify such processes. The semantic functions are used to define the notions of equality that we use in the laws, based on mutual refinement of the processes defined by the functions.

At the core of the semantics of a state machine is a parallel composition of processes that capture the semantics of its **Nodes**, taking into account any transitions with deadlines, and of processes for the **Transitions**. These processes synchronize on the CSP channels below that model the control flow. In what

follows, we use grey and underlined text to indicate terms of the metanotation used to define the semantics.

- *end*, used to control termination of state machines, and operations, when a **Final** state is activated;
- *enter.id(n)*, used to activate a node \underline{n} , uniquely identified by a metafunction \underline{id} ;
- *entered.id(n)*, used to indicate completion of the activation of a node \underline{n} ;
- *exit*, used to deactivate the currently active state;
- *exited*, used by the currently active state to indicate it has completed its deactivation;
- *interrupt.id(n)*, used to interrupt the execution of \underline{n} , for example, when a transition is triggered.

Although the semantics of **Nodes** is defined by a parallel composition, the control flow of a **NodeContainer** is sequential, and so only one of its **Nodes** is active at a time, as constrained by the parallel composition with the process semantics of its **Transitions**.

Activation of a **State** \underline{n} leads to the execution of its entry action and the activation of its substates, if there are any. As said, completion is indicated via synchronization on the channel *entered.id(n)* used to:

- communicate to (the process for) a parent **State** \underline{p} of \underline{n} , that its child **State** \underline{n} has completed activation;
- enforce any deadlines on outgoing transitions from \underline{n} , as modelled by a **Transition** *deadlines* process as indicated in the innermost box in Fig. 49;

Table 1. tock-CSP operators, with basic processes at the top, followed by composite processes: P and Q are metavariables that stand for processes, d for a numeric expression, e for an event, a and c for channels, x for a variable, I for a set, v for an expression, g for a condition, and X for a set of events. For a channel c , $\llbracket c \rrbracket$ is a set of events; if c is a typed channel then events are constructed using the dot notation, so that $\llbracket c \rrbracket = \llbracket c.v_0, \dots, c.v_n \rrbracket$, where v_i ranges over the type.

Process	Description
Skip	Termination: terminates immediately
Wait(d)	Delay: terminates exactly after d units of time have elapsed
Stop	Timed deadlock: no events are offered, but time can pass
Stop _U	Timelock: no events are offered and time cannot pass
$e \rightarrow P$	Prefix operator: initially offers to engage in the event e while permitting any amount of time to pass, and then behaves as P
$a?x \rightarrow P$	Input prefix: same as above, but offers to engage on channel a with any value, and stores the chosen value in x
$a?x : I \rightarrow P$	Restricted input prefix: same as above, but restricts the value of x to those in the set I
$a!v \rightarrow P$	Output prefix: same as above, but initially offers to engage on channel a with a value v
if g then P else Q	Conditional: behaves as P if the predicate g is true, and otherwise as Q
$P \square Q$	External choice of P or Q made by the environment
$P \sqcap Q$	Internal choice of P or Q made non-deterministically
$P; Q$	Sequence: behaves as P until it terminates successfully, and, then it behaves as Q
$P \backslash X$	Hiding: behaves like P but with all communications in the set X hidden
$P \parallel Q$	Interleaving: P and Q run in parallel and do not interact with each other
$P \parallel [X] Q$	Generalized parallel: P and Q must synchronize on events that belong to the set X , with termination occurring only when both P and Q agree to terminate
$P \llbracket a \leftarrow c_1, \dots, a \leftarrow c_i \rrbracket$	Renaming: replaces uses of channel a with channels c_1 to c_i in P
$P \Delta Q$	Interrupt: behaves as P until an event offered by Q occurs, and then behaves as Q
$P \Delta_d Q$	Strict timed interrupt: behaves as P , and, after exactly d time units behaves as Q
$P \Theta_X Q$	Exception: behaves as P until P performs an event in X , and, then behaves as Q
$\llbracket X \rrbracket i : I \bullet P(i)$	Replicated generalized parallel: behaves as $P(i)$ in parallel for all i in I synchronizing in X
$\llbracket i \rrbracket : I \bullet P(i)$	Replicated interleaving: behaves as $P(i)$ interleaved for all i in I
$\square i : I \bullet P(i)$	Replicated external choice: offers an external choice over processes $P(i)$ for all i in I
$\sqcap i : I \bullet P(i)$	Replicated internal choice: offers an internal choice over processes $P(i)$ for all i in I

- monitor the time since a state has last been activated, via synchronization with the semantics of **State clocks**, as required to give semantics to transitions whose guards depend on the time elapsed since the most recent activation of a state.

The **State clocks** process monitors time since the occurrence of an event $\text{entered.id}(\underline{n})$ for each non-Final state \underline{n} , and then offers to communicate this time over a channel $\text{get.id}(\underline{n})$. Processes for nodes of type **Junction** do not synchronize on entered events, since they do not have actions or substates, and so become active immediately after synchronizing on enter , and also do not have outgoing transitions with deadlines.

To illustrate the role of events modelling the control flow, in Example 2 we reproduce the semantics of the state **Prepare** of the machine **AppleHarvestControl**.

Example 2. Semantics of state **Prepare**.

let

$$\begin{aligned}
 \text{Inactive} &\triangleq \text{SStop} \Delta (\text{Activation} \square \text{Termination}) \\
 \text{Activation} &\triangleq \text{enter.id}(\text{Prepare}) \rightarrow \text{Active} \\
 \text{Termination} &\triangleq \text{end} \rightarrow \text{Skip} \\
 \text{Active} &\triangleq \llbracket \text{Prepare.entry} \rrbracket_{\text{af}}^{\text{nops}}; \text{Behaviour}; \text{Exiting} \\
 \text{Behaviour} &\triangleq \text{entered.id}(\text{Prepare}) \rightarrow \text{During} \\
 \text{During} &\triangleq \text{SStop} \Delta \text{interrupt.id}(\text{Prepare}) \rightarrow \text{Skip} \\
 \text{Exiting} &\triangleq (\text{SStop} \Delta \text{exit} \rightarrow \text{Skip}); \text{exited} \rightarrow \text{Inactive}
 \end{aligned}$$

within

Inactive

It is defined using processes defined in a **let...within** block. Initially, **Prepare**'s behaviour is **Inactive**, which behaves as **SStop**, but

can be interrupted by **Activation**, via the event $\text{enter.id}(\text{Prepare})$, or **Termination**, synchronizing on end followed by **Skip**. The process $\text{SStop} = \text{share} \rightarrow \text{SStop}$ offers to synchronize indefinitely on the event share , used by processes in the semantics to signal and react to changes in the value of shared variables. An **Inactive** state accepts share to acknowledge that a shared variable has been changed (although this is not relevant to an inactive state). Once **Active**, the state behaves as $\llbracket \text{Prepare.entry} \rrbracket_{\text{af}}^{\text{nops}}$, the process defined by the semantic function $\llbracket _ \rrbracket_{\text{af}}^{\text{nops}}$ for actions. Here, the process models the behaviour of **Prepare**'s entry action **Prepare.entry**. The parameter **nops** defines the semantics of the operations called by **AppleHarvestControl**. The process for **Prepare**'s entry action is sequentially composed with **Behaviour**, which concludes the state's activation by synchronizing on $\text{entered.id}(\text{Prepare})$ and then behaves as **During**.

Because **Prepare** has no during action, the behaviour of **During** is that of **SStop** with the possibility to be interrupted by $\text{interrupt.id}(\text{Prepare})$ and terminate. This leads to **Exiting** in the definition of **Active**. Now, share is offered until there is a request to exit. Next, as **Prepare** has no exit action, it immediately indicates it has exited, and becomes **Inactive**.

In general, once active, a **Node** \underline{n} 's execution may be interrupted, for example, when an outgoing transition is triggered. This is modelled via synchronization on the event $\text{interrupt.id}(\underline{n})$. In addition, active **States** may be interrupted by a transition from a parent **State**. To account for both sources of interruption, in the **Control flow** process for \underline{n} 's parent **NodeContainer** \underline{p} :

- 1) the event $\text{interrupt.id}(\underline{n})$ is relationally renamed to $\text{interrupt.id}(\underline{p})$, if \underline{n} is a **State**;
- 2) and for each **Transition** \underline{t} in $\underline{p}.\text{transitions}$ the event $\text{interrupt.id}(\underline{n})$ is renamed to:

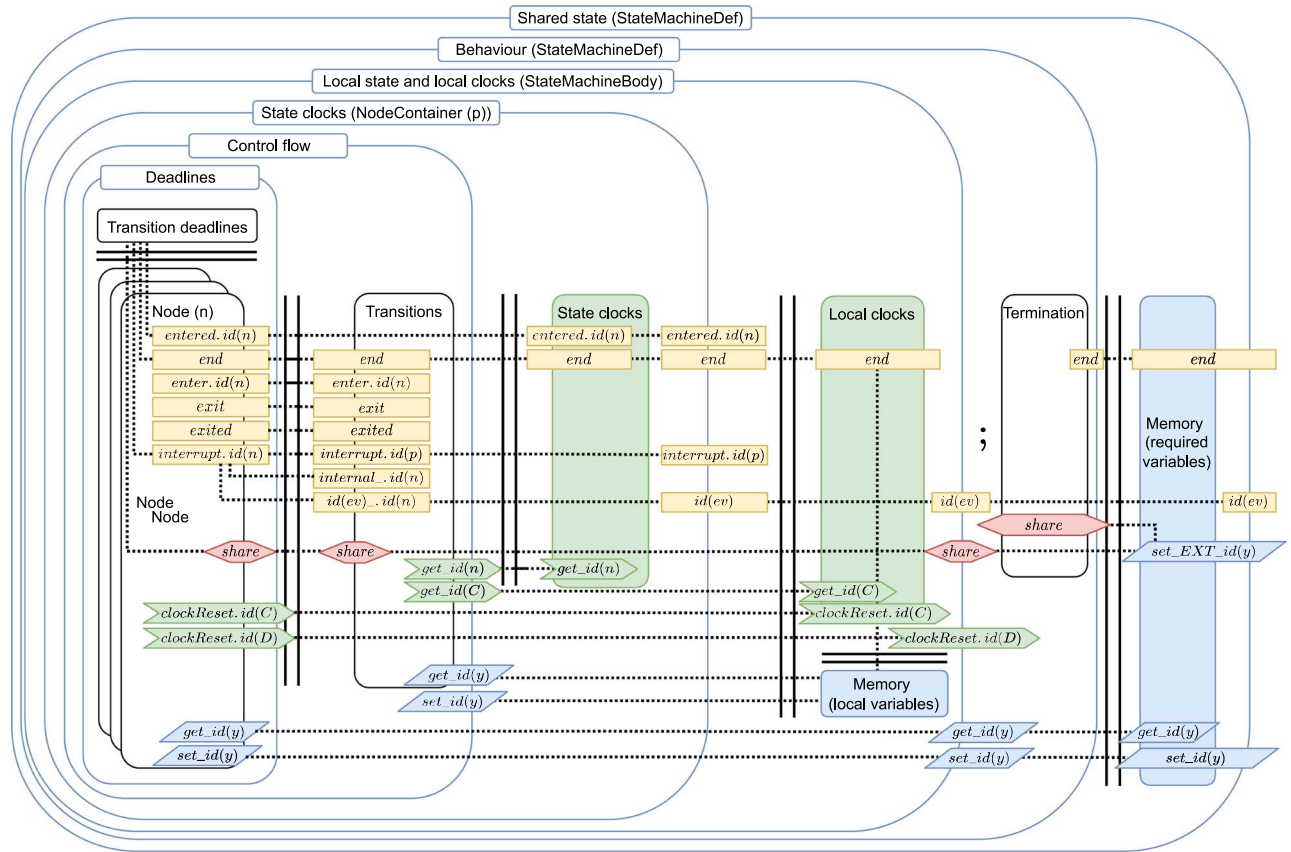


Figure 49. Overall structure of the tock-CSP semantics of state machines shown hierarchically, including that of **NodeContainer**, **OperationDef** and **StateMachineDef**. Stacked components and parallel lines indicate parallel composition. Sequential composition is indicated by the semicolon.

Bordered boxes indicate visible points of interaction, while dashed lines indicate synchronization between processes on channels. In colour: yellow boxes indicate control flow events, green boxes are related to clocks, blue boxes are related to state variables, and red boxes are related to controlling atomic updates to shared state.

- a) $\text{internal.id}(n)$, if t has no trigger;
- b) a channel $\text{id}(\text{ev}).\text{id}(n)$, if t has a trigger; here ev is the trigger Event $t.\text{trigger.event}$.

The first case (1) allows the process for a composite state to synchronize its interruption with that of an active child **State**, so that an outgoing transition of the composite state interrupts its machine. Processes for **Junctions** are not involved in the synchronization, since junctions are decision points and cannot be interrupted.

The second case (2) introduces channels for synchronization with the semantics of **Transitions**, with two possibilities depending on whether they have a trigger. If a transition t does not have a trigger, its trigger is modelled in the semantics by a channel internal . In the process for a **NodeContainer** (see Fig. 49), internal is hidden. This captures the fact that a triggerless **Transition** can be taken as soon as its guard is *true*. If the transition has a trigger ev , it is represented by a channel $\text{id}(\text{ev}).\text{id}(n)$. For every such transition t , in a **NodeContainer** process, $\text{id}(\text{ev}).\text{id}(n)$ is renamed to $\text{id}(\text{ev})$, where ev is $t.\text{trigger.event}$ and n is $t.\text{source}$, the trigger event and the source **State** of t (see Fig. 5). With this semantics, events (in triggers) are used for interaction with other components of the system or its environment. Internal control flow, however, is concealed.

The semantics of **Transitions** accounts for guards by offering, or withholding, synchronization on channels $\text{internal.id}(n)$ and $\text{id}(\text{ev}).\text{id}(n)$, depending on the evaluation of guards. The current

value of a variable x , state clock n , or clock C , as used, for example, in a guard, can be queried via synchronization on channels $\text{get_id}(x)$, $\text{get_id}(n)$, and $\text{get_id}(C)$: see Fig. 49.

Variables and clocks are modelled in different ways in the semantics of RoboChart and of open machines. These are presented separately in the sequel.

6.1.2. RoboChart state machines

The semantics of a **StateMachineDef** and of an **OperationDef** are similar. In both cases, the semantics is defined in terms of the semantic function for a **StateMachineBody** in general (see Figs 5 and 49). The semantics for an **OperationDef**, however, is a function that, when applied to arguments corresponding to the parameters of the **OperationDef**, determines a process that captures the meaning of that **OperationDef** when called with those arguments. In the case of a **StateMachineDef**, the semantics does not need to consider parameters, but in addition accounts for termination and required variables. To cater for termination, the semantics of a **StateMachineDef** defines its contribution to a termination protocol that ensures that it is possible to consider a set of machines running in parallel and sharing a memory, and that guarantees that the set of machines terminates when all its machines terminate. To cater for required variables, the semantics provides a memory process. In contrast, in the semantics of an **OperationDef**, termination occurs when a final state is reached, so there is no need for a protocol, and the required variables are provided by the calling machine, so there is no need for a memory.

As depicted in Fig. 49 the semantics for a **StateMachineDef** is defined as the parallel composition of: (a) the sequential composition of a **StateMachineBody** process with the **Termination** process, and (b) the memory process for required variables. In the semantics of a **StateMachineBody** the internal event *end* is used to terminate its behaviour, when a **Final** state is activated. The process **Termination** subsequently (\circ) offers to synchronize on *end*, so that termination is signalled to other components or the environment.

The semantics of variables and clocks in RoboChart machines is given by a composition with the processes described below, following the hierarchical, component-based nature of RoboChart (see Fig. 49).

- **State clocks:** as previously discussed, account for the time elapsed since activation of every non-final **State n** in a **Node-Container**, with the value available for query via a channel *get_id(n)*;
- **Local clocks:** account for clocks declared in a state machine. The reset of a **Clock C** is modelled by synchronizing on *clockReset.id(C)*, with the time elapsed since then available via a channel *get_id(C)*.
- **Memory (local variables and constants):** a process that accounts for variables and constants declared in a state machine. Assignment of a new value to a **Variable v** is modelled via a channel *set_id(v)*. The current value is available via a channel *get_id(v)*, and similarly for constants.
- **Memory (required variables):** similarly, this process accounts for required variables of **StateMachineDefs**. The difference in this case, however, is that the environment may also provide new values for a **Variable v** via a channel *set_EXT_id(v)*.

A **StateMachineDef** must declare all **Clocks** it directly uses or that are required by operations that it directly calls. Thus, in the process for a **StateMachineDef** any *clockReset* events are concealed as all **Clocks** are local.

Next, we illustrate the semantics using the example of the RoboChart machine **AppleHarvestControl**. What we present is the result of applying the semantic function $\llbracket _ \rrbracket_{\mathcal{SMB}}^{nops}$ to **AppleHarvestControl** and **nops**. That process is presented below, where **stm** stands for **AppleHarvestControl**. It is defined by a parallel composition (\parallel) of processes synchronizing on *end*, to proceed with termination, and channels for getting, and setting the value of the required variables **apples** and **positions**. Data is captured by a process defined by a metafunction **sharedVarMemory(stm)**. The definition of this and other functions to follow can be found in [48].

Example 3. tock-CSP semantics of the RoboChart state machine **AppleHarvestControl**.

$$\begin{aligned} \llbracket \text{AppleHarvestControl} \rrbracket_{\mathcal{SMB}}^{nops} = & \left(\left(\llbracket \text{stm} \rrbracket_{\mathcal{SMB}}^{nops} ; \text{SStop}\Delta\text{end} \rightarrow \text{Skip} \right) \right. \\ & \left. \left[\begin{array}{c} x : \left[\begin{array}{c} \text{set_EXT_id(apples)}, \\ \text{set_EXT_id(positions)} \end{array} \right] \bullet \text{share} \leftarrow x \\ \llbracket \text{share} \rrbracket \end{array} \right] \right. \\ & \left. \left[\begin{array}{c} \text{end}, \\ \text{get_id(apples)}, \text{set_id(apples)}, \\ \text{set_EXT_id(apples)}, \\ \text{get_id(positions)}, \text{set_id(positions)}, \\ \text{set_EXT_id(positions)} \end{array} \right] \right] \\ & \text{sharedVarMemory(stm)} \end{aligned}$$

The semantics of a required variable, for example, **apples**, can be modelled by the parametric and recursive memory process **M** sketched below.

$$M(a) = \left(\begin{array}{l} \text{get_id(apples)}! a \rightarrow M(a) \\ \square \text{set_id(apples)}?x \rightarrow M(x) \\ \square \text{set_EXT_id(apples)}?x \rightarrow M(x) \end{array} \right)$$

For a complete definition, an initial value is provided to reflect the default for the type of the variable being modelled. **M** offers, in an external choice, the possibility to get the current value *a* via *get_id(apples)*, or set a new value *x*, via *set_id(apples)* or *set_EXT_id(apples)*, with the behaviour given by the recursion on **M** with the chosen value *x* as a parameter.

Composed in parallel with **sharedVarMemory(stm)**, in Example 3, is the process semantics of **stm**'s behaviour. At the core is the process $\llbracket \text{stm} \rrbracket_{\mathcal{SMB}}^{nops}$ defined by the semantic function for a **StateMachineBody**. A renaming ($\llbracket _ \rrbracket$) maps the event *share* (\leftarrow) to *set_EXT_id(apples)* and *set_EXT_id(positions)*, to allow external updates to the values of the variables **apples** and **positions** to be observed as *share* events by the process $\llbracket \text{stm} \rrbracket_{\mathcal{SMB}}^{nops}$. If a state machine has no required variables, and thus the renaming relation is empty, the event *share* is not renamed. So, we have a parallel composition with **Skip** synchronizing on *share*. Since **Skip** terminates and does not agree to engage in *share* events, they are blocked, if they are not renamed.

The behaviour of **stm** is defined by the sequential composition of $\llbracket \text{stm} \rrbracket_{\mathcal{SMB}}^{nops}$ and **SStop** $\Delta\text{end} \rightarrow \text{Skip}$. The latter defines the behaviour when $\llbracket \text{stm} \rrbracket_{\mathcal{SMB}}^{nops}$ has terminated and allows the value of required variables to be updated via synchronization on *set_EXT* channels while waiting to agree on termination via *end*. **AppleHarvestControl** has no final state, and so $\llbracket \text{stm} \rrbracket_{\mathcal{SMB}}^{nops}$ never terminates. Next, we sketch $\llbracket \text{stm} \rrbracket_{\mathcal{SMB}}^{nops}$.

Example 4. Sketch of $\llbracket \text{stm} \rrbracket_{\mathcal{SMB}}^{nops}$.

$$\begin{aligned} & \left(\left(\llbracket \text{stm} \rrbracket_{\mathcal{SMB}}^{nops} \llbracket \llbracket \text{interrupt} \rrbracket \text{Skip} \right) \setminus \llbracket \text{entered} \rrbracket \right. \\ & \left[\begin{array}{c} \text{end}, \\ \text{get_id(img)}, \text{set_id(img)}, \\ \text{get_id(localized)}, \text{set_id(localized)}, \\ \text{get_id(nextApple)}, \text{set_id(nextApple)}, \dots \end{array} \right] \\ & \left(\begin{array}{c} \text{varMemory(stm)} \\ \llbracket \text{end} \rrbracket \\ \text{constMemory(stm)} \\ \llbracket \text{end} \rrbracket \\ \text{clocks(stm.clocks)} \end{array} \right) \\ & \setminus \left[\begin{array}{c} \text{end}, \text{get_id(img)}, \text{set_id(img)}, \\ \text{get_id(localized)}, \text{set_id(localized)}, \\ \text{get_id(nextApple)}, \text{set_id(nextApple)}, \dots \end{array} \right] \end{aligned}$$

The semantics defined by $\llbracket \text{stm} \rrbracket_{\mathcal{SMB}}^{nops}$ is reproduced in Example 4. The behaviour is given in terms of the **NodeContainer** semantics of **stm**, defined by another semantic function $\llbracket _ \rrbracket_{\mathcal{NCE}}^{nops}$, which we discuss below. It is constrained, first of all, by a parallel composition with **Skip**, synchronizing on the channel *interrupt* to block it. We recall that, as discussed in subsection 6.1.1, the channel *interrupt* can be used by composite states to synchronize their interruption with their children. A state machine, however, is not interruptible, so this parallel composition makes *interrupt* unavailable.

NodeContainer The `NodeContainer` semantics of the machine `AppleHarvestControl` is sketched in Example 5.

Example 5. Sketch of the semantics of $\llbracket \text{stm} \rrbracket_{\mathcal{N}\mathcal{C}}^{\text{nops}}$.

$$\left(\begin{array}{l} \text{controlFlow}(\text{stm})^{\text{nops}} \\ \quad \backslash \text{ \{enter, exit, exited, internal\}} \\ \left[\begin{array}{l} \text{takePic_id(Prepare)} \leftarrow \text{takePic}, \\ \text{endGoHome_id(GoingHome)} \leftarrow \text{endGoHome} \\ \quad \text{\{ \{end, entered.id(Prepare), get_id(Prepare), ... \}} \\ \text{clocks}(\text{\{Prepare, ... \}} \end{array} \right] \end{array} \right)$$

The behaviour is given, first of all, in terms of another metafunction `controlFlow(stm)nops`, discussed next. The channels `enter`, `exit`, `exited` and `internal` are hidden, and channels modelling transition triggers are renamed to conceal the identifiers of states: `takePic_id(Prepare)`, which accounts for the transition between `Prepare` and `LocalizeFruit`, is renamed to `takePic`; and `endGoHome_id(GoingHome)`, for the transition between `GoingHome` and `endGoHome`, is renamed to `endGoHome`. This process is then composed in parallel with that defined by application of the function `clocks(...)`, synchronizing on `end` and channels `entered.id(n)` and `get_id(n)` for each non-final `State n` in `AppleHarvestControl`. This allows the clocks process to be terminated (`end`), and exchange of relevant information related to time conditions: entering a state is signalled to the clocks process, which records time and can provide the time since entering a state via `get_id(n)` channels. In Example 5 the complete channel set is elided, with only `end` and the channels related to the state `Prepare` shown. The metafunction `clocks`, defined here over a set of `States`, is applied to the set of non-final states of `AppleHarvestControl`, which includes `Prepare`. Finally, the channels for getting the time since entering a state, such as `get_id(Prepare)`, are hidden.

Control Flow The interaction between the **Nodes** and **Transitions** of **AppleHarvestControl** is captured by the semantics sketched in Example 6.

Example 6. Semantics of control flow of stm.

$$\left(\begin{array}{l} \text{composeTimedNodes}(\text{stm})^{\text{nopS}} \\ \left[\begin{array}{l} \text{interrupt.id}(\text{id}_0) \leftarrow \text{internal.id}(\text{id}_0), \\ \text{interrupt.id}(\text{Prepare}) \leftarrow \text{takePic_id}(\text{Prepare}), \\ \text{interrupt.id}(\text{Prepare}) \leftarrow \text{interrupt.id}(\text{stm}), \\ \text{set_id}(\text{positions}) \leftarrow \text{setL_id}(\text{positions}), \dots \\ \llbracket \text{cs} \cup \llbracket \text{share}, \text{setL_id}(\text{positions}), \dots \rrbracket \rrbracket \\ (\text{enter.id}(\text{id}_0) \rightarrow \text{transitions}(\text{stm})^{\text{nopS}}) \\ \left[\begin{array}{l} \text{share} \leftarrow \text{share}, \\ \text{share} \leftarrow \text{setL_id}(\text{positions}), \dots \end{array} \right] \end{array} \right) \end{array} \right)$$

where

$$\underline{\text{cs}} = \left\{ \begin{array}{l} \text{end, enter, exit, exited, interrupt,} \\ \text{internal.\underline{id(i_0)}, takePic_id(Prepare), ...} \end{array} \right\}$$

The behaviour is defined by the parallel composition of the semantics of its **Nodes**, defined by application of a function composeTimedNodes with channels *interrupt* renamed for each transition (as discussed in subsubsection 6.1.1), and the semantics of its transitions. There, the prefixing on enter.id(i₀) requests initialization of **AppleHarvestControl**'s Initial junction *i₀* before proceeding further as defined by the metafunction application transitions(stm)^{nops}. Assignments in the semantics of **Nodes** to **Variables** used to guard transitions need to be synchronized with the semantics of the transitions to ensure the sequential control flow is consistent. For example, the assignment to the variable **positions** in the state **GetApple** may affect the evaluation of the guard on the transition to **GoingHome**, so the processes must synchronize on set_id(positions). On the other hand, an assignment on a transition, such as that between **Prepare** and **LocalizeFruit**, must happen independently, that is, without synchronization. To define this protocol, we use renaming. In the above example, writes from **Nodes** to **positions** take place via set_id(positions). This channel is, however, renamed to a setL_id(positions), which is used to synchronize with the semantics of transitions by renaming *share* both to itself and to setL_id(positions). Thus, any assignment to **positions** by a **Node** is seen by the process transitions as a synchronization on *share*. The new value can be queried via get_id(positions). Finally, after the parallel composition, setL_id(positions) is renamed to set_id(positions) so that other processes can observe the assignments as before. In the example, the renaming and synchronization with *share* involving other variables are elided. The parallel composition also requires synchronization on the channel set **cs**, comprising events *end*, *enter*, *exit*, *exited* and *interrupt* related to control flow, and channels related to triggers of transitions, such as internal.id(i₀) and takePic_id(Prepare). This ensures consistent flow evolution.

This concludes the discussion of the semantics of RoboChart machines. Next, we discuss open machines.

6.1.3. Open machines

In Example 7 we reproduce the semantics of the open state machine depicted in subsubsection 38, of type `CompOpenStateMachine` (see subsection 13), referred to as `ostm`, which is itself composed of two open machines, `ostm.left`, that contains an `EState`

named **Done** with a single transition to a **NodeNameRef** named **f0**, and **ostm.right**, containing an **EFinal** state named **f0**.

Example 7. **decompBOM(LocalizeFruit)**: semantics for the model shown in subsubsection 38.

The semantics is defined by the parallel composition of the semantics of **ostm.left**, obtained by application of a semantic function $\llbracket _ \rrbracket_{\mathcal{OSM}}^{\text{nops}}$, that we explain in the sequel, and that of **ostm.right**, synchronizing on channels **end**, **r_{enter}**, and **share**. The new channel **r_{enter}** allows the processes for **ostm.left** and **ostm.right** to synchronize internally on the activation requests for their shared states, while keeping the actual control flow channel **enter** available for the processes for other machines.

$$\left(\left(\left(\llbracket \text{ostm.left} \rrbracket_{\mathcal{OSM}}^{\text{nops}} \right) \parallel \left(\begin{array}{c} \text{enter.id(f0)} \leftarrow \text{r}_{\text{enter}}.\text{id(f0)} \\ \text{end, r}_{\text{enter}}, \text{share} \end{array} \right) \right) \parallel \left(\left(\llbracket \text{ostm.right} \rrbracket_{\mathcal{OSM}}^{\text{nops}} \right) \parallel \left(\begin{array}{c} \text{enter.id(f0)} \leftarrow \text{enter.id(f0)}, \\ \text{enter.id(f0)} \leftarrow \text{r}_{\text{enter}}.\text{id(f0)} \end{array} \right) \right) \right) \setminus \llbracket \text{r}_{\text{enter}} \rrbracket$$

For example, in **ostm.right**, the entry point **f0** coincides in name with that of a **NodeNameRef** in **ostm.left** that is the target of a transition from **Done**. Thus, the event **enter.id(f0)** is renamed to **r_{enter}.id(f0)** in the process for **ostm.left**, and in the process for **ostm.right** it is renamed to: (a) **r_{enter}.id(f0)**, so that the transition to the **NodeNameRef** can request activation of **f0**; (b) and to **enter.id(f0)**, so that composition with other open machines whose transitions may also target **f0** is feasible by allowing independent synchronization with **enter.id(f0)**. The new event **r_{enter}** is hidden.

The semantics of **ostm.left**, which, we recall, is a **BasicOpenStateMachine**, is sketched in Example 8. In this case, the semantics is not given by a composition with a memory process, as illustrated by Example 3. The semantics of an open machine is closer to that of a **State**, illustrated by Example 2, and is also defined using a **let...within** block. For a machine, however, instead of an **Activation** process, we have just the **Active** process, because a machine does not need to report on the status of its activation. An active machine also has no (entry) actions, so **Active** is simpler. Similarly, a machine has no during action and no need to report on its exiting. Finally, the **Behaviour** of the machine is triggered by an **enter**, rather than **entered**, channel.

Example 8. Semantics of the left-hand machine in **decompBOM(LocalizeFruit)** shown in subsubsection 38.

let

Inactive = $\text{SStop} \Delta (\text{Termination} \square \text{Active})$

Termination = **end** → **Skip**

Active = **Behaviour**; *Inactive*

Behaviour = **enter?***i* : {**id(Done)**} →

$$\left(\left(\left(\text{composeTimedNodes}(\text{stm})^{\text{nops}} \right) \parallel \left(\begin{array}{c} \text{interrupt.id(Done)} \leftarrow \text{internal.id(Done)}, \\ \text{interrupt.id(Done)} \leftarrow \text{interrupt.id(stm)} \end{array} \right) \right) \parallel \left(\begin{array}{c} \text{share, end, enter, exit,} \\ \text{exited, interrupt, internal.id(t_0)} \end{array} \right) \right) \parallel \left(\begin{array}{c} \text{enter.i} \rightarrow \text{transitions}(\text{stm})^{\text{nops}} \\ \setminus (\llbracket \text{enter, exit, exited, internal} \rrbracket \setminus \llbracket \text{enter.id(f0)} \rrbracket) \end{array} \right) \setminus \{\text{end}\}$$

within

Inactive

In **Active**, it offers to synchronize on **enter** with a parameter *i* drawn from the set of identifiers of the machine's entry points. In this example, the set is a singleton, **id(Done)**, since there is only one entry point in **ostm.left**. The value of *i* is then subsequently used to require activation of the state **Done**, similarly to the control flow semantics illustrated in Example 6. The parallel composition and the renaming over **composeTimedNodes** are similar to those in the control flow semantics of a RoboChart machine (see Example 6). The subsequent hiding of channels **enter**, **exit**, **exited**, and **internal** is similar to that of the **NodeContainer** semantics (as illustrated in Example 5), which uses the control flow semantics. The exception here is that events **enter** pertaining to nodes referenced by **NodeNameRefs** are excluded from the hiding, and so the event **enter.id(f0)** is not hidden. This allows the composition with the process for another machine, namely **ostm.right** in Example 7, to reflect the sequential control flow, where, for example, the entry point **f0** in **ostm.right** is activated by the transition out of the state **Done** in **ostm.left**. Similarly to a **Final** state, once a **NodeNameRef** is activated, it can be terminated via synchronization on **end**, which leads to the termination of **Behaviour**. As for RoboChart machines (see Example 3), **end** is hidden. Afterwards, the open machine becomes **Inactive**.

As said previously, equality of open machines is parametrised by the **OperationDefinitions** for the operations that can be called in these machines. Formally, $OM_1 =_{Op} OM_2$ is defined as follows. Here, $\llbracket _ \rrbracket_{\mathcal{OSM}}^{\text{nops}}$ is the semantic function for **OpenStateMachines**, which is defined in terms of those for **BasicOpenStateMachines** and for **CompOpenStateMachines**, and like those, takes a parameter that defines the semantics of operations. Below, that parameter is the set defined by **nops**, including the semantics of the operations other than **Op**, and the set containing just the pair **Op.name** → $\llbracket \text{Op} \rrbracket_{\mathcal{OSM}}^{\text{nops}}$ that gives the semantics of **Op** as defined by $\llbracket _ \rrbracket_{\mathcal{OSM}}^{\text{nops}}$.

$$OM_1 =_{Op} OM_2 \iff \left(\frac{\llbracket OM_1 \rrbracket_{\mathcal{OSM}}^{\text{nops} \cup \{\text{Op.name} \mapsto \llbracket \text{Op} \rrbracket_{\mathcal{OSM}}^{\text{nops}}\}}}{\llbracket OM_2 \rrbracket_{\mathcal{OSM}}^{\text{nops} \cup \{\text{Op.name} \mapsto \llbracket \text{Op} \rrbracket_{\mathcal{OSM}}^{\text{nops}}\}}} = \right)$$

The open machines OM_1 and OM_2 are related by $=_{Op}$ exactly when their semantics are equal, as given by $\llbracket _ \rrbracket_{\mathcal{OSM}}^{\text{nops}}$ with the parameter as defined above.

This concludes the discussion of the semantics of open machines. Next, we use the semantics to justify the soundness of the normalization laws.

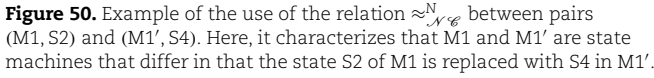
6.2. Proofs of soundness

In what follows, we justify the soundness of selected Laws 2 and 6. First we formalize them, and then sketch our proofs of soundness using the semantics. Results obtained as part of proving Law 2 are useful to prove soundness of Laws 3, 15, and 16 following a similar proof strategy. Similarly, results established for Law 6 are relevant to justify that Laws 11 and 17 are sound. Complete proofs can be found in [37].

6.2.1. Law 2 (intro-call-for-act-state)

Before presenting the formalization of Law 2, we first define a relation that allows comparing state machines.

Relating structurally similar NodeContainers We recall that both state machines and states are **NodeContainers**. The relation $(nc1, nc2) \approx_{\mathcal{N}}^{\mathcal{N}} (nc3, nc4)$ allows us to compare a machine *nc1* with a substate, at any level, *nc2*, to another machine *nc3*, whose



For the simple case, in which we want to replace a whole machine with another, we do not require this relation. Equally, if $nc2$ is a direct state of $nc1$, then $(nc1, nc2) \approx_{\mathcal{N}, \mathcal{C}}^N (nc3, nc4)$ holds when

Below, ϕ is applied to **NodeContainers** $nc5$ and $nc6$ to define a function from transitions to transitions. Here $\phi(nc5, nc6)$ is a lambda function that applies to a transition t ; if the *source* or *target* of t is $nc5$, then it is replaced by $nc6$. Otherwise, no pairs are added to the overriding set. Transitions may have a *condition* that depends on the time since a state has been entered, so we apply ϕ_{exp} , whose definition is omitted, to replace occurrences of $nc5$ by $nc6$ also in that *condition*.

$$\lambda t. \bullet t \oplus \left\{ \begin{array}{l} \text{if } t.\text{source} = \text{nc5} \text{ then } \text{source} \mapsto \text{nc6}, \\ \text{if } t.\text{target} = \text{nc5} \text{ then } \text{target} \mapsto \text{nc6}, \\ \text{cond} \mapsto \phi_{\text{exp}}(t.\text{cond}, \text{nc5}, \text{nc6}) \end{array} \right\}$$

Following the declarations, a list of numbered properties restrict the values of the metavariables to capture the assumptions in

the diagram for Law 2. First, in A1, we record the fact that Law 2 uses action_s as an Action of a State S and that s is the statement of action_s . We recall that the statement of an action is recorded via an attribute named action according to the metamodel in Fig. 5. A2 formalizes the definition of OpS using a metafunction $\text{actionOperation}(s)$, defined in [37]; as the name suggests, it defines an action operation for the given statement s , using interfaces $\text{req}'s$ and $\text{defEvents}'s$ of Law 2. [A3] records the Call's target as the operation OpS and that there are no arguments. [A4] formalizes the definition of the interface IOpS : its component operations maps to the singleton set containing the signature of OpS , obtained by a projection function opSig . [A5] states that the parameter nops_2 is defined by extending nops_1 with the semantics of OpS . Finally, A6 captures how the machine \underline{m} is defined in terms of \underline{m} , after it is enriched with the required interface IOpS : the only difference in \underline{m}' is that S has the original action_s removed and a new action added, so that the action attribute is replaced by call_{Ops} .

Law 2 and all the other laws for RoboChart machines apply to both StateMachineDefs and OperationDefs ; in other words, they are laws of StateMachineBody . The formalization of Law 2 when \underline{m} and \underline{m}' are OperationDefs is very similar to that presented above. There are only two differences: the equality is for the semantics defined by the function $\llbracket _ \rrbracket_{\mathcal{O} \mathcal{P} \mathcal{Q}}$, instead of $\llbracket _ \rrbracket_{\mathcal{S} \mathcal{M} \mathcal{Q}}$, and [A3] records that the arguments to be passed in the Call are given by a function $\text{usedArgs}(s)$, which, as explained before, if \underline{m} is an OperationDef , captures the parameters of \underline{m} used in s , if any.

Accordingly, the proof of Law 2 has two cases: one for StateMachineDefs and another for OperationDefs . We sketch below the proof for StateMachineDefs . For OperationDefs , the proof strategy is similar and simpler.

Proof. (Case StateMachineDefs \underline{m} and \underline{m}') We define an action $\underline{a}_0 = \text{action}_s \oplus \{\text{action} \mapsto \text{call}_{\text{Ops}}\}$, a new state $\underline{S}_0 = S \oplus \{\text{actions} \mapsto (S.\text{actions} \setminus \{\text{action}_s\}) \cup \{\underline{a}_0\}\}$ that adds to S the action \underline{a}_0 , and a machine that extends \underline{m} by including IOpS as an additional required interface $\underline{m}_0 = \underline{m} \oplus \{\text{RInterfaces} \mapsto \underline{m}.\text{RInterfaces} \cup \text{IOpS}\}$, for which we can establish the following results.

- R1 $(\underline{m}_0, \underline{S}_0) \approx_{\mathcal{N} \mathcal{C}}^N (\underline{m}', \underline{S}_0)$;
- R2 $\text{vars}(\underline{S}_0) = \text{vars}(S)$, that is, the set of variables used in S and \underline{S}_0 is the same;
- R3 $\text{usedOps}(\underline{a}_0) = \text{usedOps}(\text{action}_s) \cup \{\text{OpS}\}$, since \underline{a}_0 calls OpS , and in the definition of OpS , we have s . So, $\text{usedOps}(\underline{S}_0) = \text{usedOps}(S) \cup \{\text{OpS}\}$, that is, the set of operations used by \underline{S}_0 , those called by actions of \underline{S}_0 , its substates or transitions, is that used by S augmented with OpS , thus we also have that $\text{usedOps}(\underline{m}') = \text{usedOps}(\underline{m}_0) \cup \{\text{OpS}\}$, and $\text{usedOps}(\underline{m}') \cap \text{usedOps}(\underline{m}_0) = \text{usedOps}(\underline{m}_0)$, that is, the operations used by both \underline{m}' and \underline{m}_0 are the same. Therefore, they behave the same:

$$\begin{aligned} & \forall \text{op} : \text{usedOps}(\underline{m}') \cap \text{usedOps}(\underline{m}_0) \bullet \\ & \llbracket \text{nops}_1(\text{op}) \rrbracket_{\mathcal{O} \mathcal{P} \mathcal{Q}}^{\text{nops}_1} = \llbracket \text{nops}_2(\text{op}) \rrbracket_{\mathcal{O} \mathcal{P} \mathcal{Q}}^{\text{nops}_2} \end{aligned}$$

- R4 $\llbracket \underline{S} \rrbracket_{\mathcal{N} \mathcal{C}}^{\text{nops}_1} = \llbracket \underline{S}_0 \rrbracket_{\mathcal{N} \mathcal{C}}^{\text{nops}_2}$, that is, the semantics of the state \underline{S}_0 is the same as that of S .

■

We recall that the proofs of these results and all others omitted here are in [37]. They justify the application of the two key lemmas

below. Lemma 6.1 establishes that requiring additional operations has no impact on the semantics of a state machine.

Lemma 6.1. [Augment required operations]

$$\begin{aligned} & \llbracket \underline{m} : \text{StateMachineDef} \rrbracket_{\mathcal{S} \mathcal{M} \mathcal{Q}}^{\text{nops}_1} \\ & = \\ & \llbracket \underline{m} \oplus \{\text{RInterfaces} \mapsto \underline{m}.\text{RInterfaces} \cup \text{RlopS}\} \rrbracket_{\mathcal{S} \mathcal{M} \mathcal{Q}}^{\text{nops}_1} \end{aligned}$$

Proof. Using the definition of $\llbracket _ \rrbracket_{\mathcal{S} \mathcal{M} \mathcal{Q}}$, which does not rely on the definition of required interfaces to give semantics to operation calls. Instead, we recall, the semantics of operations is passed as a parameter. Here, the argument nops_1 is used on both sides of the equation, thus, augmenting the required interfaces of \underline{m} with RlopS has no impact on the behaviour. ■

Lemma 6.2 below can be seen as a more general account of Law 2 in terms of the semantics of states. It establishes that the semantics of two state machines \underline{m} and \underline{m}' is the same when $(\underline{m}, s) \approx_{\mathcal{N} \mathcal{C}}^N (\underline{m}', s')$ and the semantics of states s and s' is also the same. Similarly to A6 in the formalization of Law 2, here P1 requires that (\underline{m}, s) is related to (\underline{m}', s') by $\approx_{\mathcal{N} \mathcal{C}}^N$, where $s : \text{State}$ constrains the type of s to be a State . Proviso P2 requires that the variables used by s and s' are the same, and P3 requires that operations used by both machines have the same behaviour. Proviso P4, in addition, states that the semantics of s' and s , given by a function $\llbracket _ \rrbracket_{\mathcal{N} \mathcal{C}}$ and parametrised by the semantics of operations nops_1 and nops_2 , respectively, must be equal.

Lemma 6.2.

$$\llbracket \underline{m} : \text{StateMachineDef} \rrbracket_{\mathcal{S} \mathcal{M} \mathcal{Q}}^{\text{nops}_1} = \llbracket \underline{m}' : \text{StateMachineDef} \rrbracket_{\mathcal{S} \mathcal{M} \mathcal{Q}}^{\text{nops}_2}$$

provided:

- P1 $(\underline{m}, s : \text{State}) \approx_{\mathcal{N} \mathcal{C}}^N (\underline{m}', s' : \text{State})$
- P2 $\text{vars}(s) = \text{vars}(s')$
- P3 $\left(\forall \text{op} : \text{usedOps}(\underline{m}') \cap \text{usedOps}(\underline{m}) \bullet \right.$
 $\left. \llbracket \text{nops}_1(\text{op}) \rrbracket_{\mathcal{O} \mathcal{P} \mathcal{Q}}^{\text{nops}_1} = \llbracket \text{nops}_2(\text{op}) \rrbracket_{\mathcal{O} \mathcal{P} \mathcal{Q}}^{\text{nops}_2} \right)$
- P4 $\llbracket s : \text{State} \rrbracket_{\mathcal{N} \mathcal{C}}^{\text{nops}_1} = \llbracket s' : \text{State} \rrbracket_{\mathcal{N} \mathcal{C}}^{\text{nops}_2}$

Proof. There are two cases to consider:

- 1) $s \in \underline{m}.\text{nodes}$ and $s' \in \underline{m}'.\text{nodes}$: so we can infer from Proviso P1 that $\underline{m}.\text{nodes}$ and $\underline{m}'.\text{nodes}$ differ only in that s is replaced by s' in $\underline{m}'.\text{nodes}$. Proviso P4 requires that the behaviour of the states s' and s is the same, so they engage in the same control flow events $\text{enter.id}(s)$, $\text{entered.id}(s)$, and $\text{interrupt.id}(s)$, and so $\text{id}(s) = \text{id}(s')$ holds. Moreover, we can infer that the semantics of Transitions involving these states is the same. We recall that the control flow semantics of NodeContainers is defined by a parallel composition of the semantics of nodes and transitions, taking into account any variables shared between them. Proviso P2 ensures that the variables used by s and s' are the same. From this and Proviso P3 we can infer that the control flow semantics of \underline{m} and \underline{m}' match, as do their NodeContainer semantics given by $\llbracket _ \rrbracket_{\mathcal{N} \mathcal{C}}$. We recall that the semantics of a StateMachineDef , as given by $\llbracket _ \rrbracket_{\mathcal{S} \mathcal{M} \mathcal{Q}}$, is defined in terms of $\llbracket _ \rrbracket_{\mathcal{N} \mathcal{C}}$ in a parallel composition with a model of its variables and clocks. From

Proviso P1 the variables and clocks declared by \underline{m} and \underline{m}' are the same, and so $\llbracket \underline{m} \rrbracket_{\mathcal{S}, \mathcal{M}, \mathcal{Q}}^{\text{nops}_1} = \llbracket \underline{m}' \rrbracket_{\mathcal{S}, \mathcal{M}, \mathcal{Q}}^{\text{nops}_2}$ as required.

- 2) \underline{s} and \underline{s}' are not direct descendants of \underline{m} and \underline{m}' , so from Proviso P1 and the definition of $\approx_{\mathcal{N}, \mathcal{C}}^N$ we can infer that there exist substates \underline{z} and \underline{z}' of \underline{m} and \underline{m}' , respectively, such that $(\underline{z}, \underline{s}) \approx_{\mathcal{N}, \mathcal{C}}^N (\underline{z}', \underline{s}')$. We can show that $\llbracket \underline{z} \rrbracket_{\mathcal{N}}^{\text{nops}_1} = \llbracket \underline{z}' \rrbracket_{\mathcal{N}}^{\text{nops}_2}$. For that, we consider the semantics of composite states, which is defined in terms of their semantics as **NodeContainers**, that is, using $\llbracket _ \rrbracket_{\mathcal{N}, \mathcal{C}}^-$. In addition, in [37], we have a lemma that is similar to Lemma 6.2 itself, but applies to states. Using that lemma, we can establish the equality above concerning \underline{z} and \underline{z}' . Proceeding, with this equality and Proviso P1, a property of $\approx_{\mathcal{N}, \mathcal{C}}^N$ ensures that $(\underline{m}, \underline{z}) \approx_{\mathcal{N}, \mathcal{C}}^N (\underline{m}', \underline{z}')$. Then, by an argument similar to that of case (1), we can lift this result, given that $\llbracket \underline{z} \rrbracket_{\mathcal{N}}^{\text{nops}_1} = \llbracket \underline{z}' \rrbracket_{\mathcal{N}}^{\text{nops}_2}$, to show $\llbracket \underline{m} \rrbracket_{\mathcal{S}, \mathcal{M}, \mathcal{Q}}^{\text{nops}_1} = \llbracket \underline{m}' \rrbracket_{\mathcal{S}, \mathcal{M}, \mathcal{Q}}^{\text{nops}_2}$ as required. ■

Using the lemmas and results above, soundness can be established by a stepwise argument as follows, using Results R1 to R4 and Lemmas 6.1 and 6.2.

$$\begin{aligned} & \llbracket \underline{m} \rrbracket_{\mathcal{S}, \mathcal{M}, \mathcal{Q}}^{\text{nops}_1} && \text{(Definition of } \underline{m}_0 \text{ and lemma 6.1)} \\ &= \llbracket \underline{m}_0 \rrbracket_{\mathcal{S}, \mathcal{M}, \mathcal{Q}}^{\text{nops}_1} && \text{(Lemma 6.2 assuming R1 to R4 hold)} \\ &= \llbracket \underline{m}' \rrbracket_{\mathcal{S}, \mathcal{M}, \mathcal{Q}}^{\text{nops}_2} \end{aligned}$$

In summary, our overall strategy is to consider first an intermediate machine \underline{m}_0 , which includes the required interface, but no extra operation. Lemma 6.1 guarantees that the inclusion of the extra interface has no effect on the semantics. We note that although the new operation is in scope, it is not used, and so we do not need to consider its semantics. We consider the semantics of the new operation in the last step, justified by Lemma 6.2. This is our key result in this section.

6.2.2. Law 6 (elim-deadline-transition)

As proved in the previous section, the processes defined by $\llbracket _ \rrbracket_{\mathcal{S}, \mathcal{M}, \mathcal{Q}}^-$ or $\llbracket _ \rrbracket_{\mathcal{C}, \mathcal{D}, \mathcal{Q}}^-$ for the **StateMachineDefs** or **OperationDefs** \underline{m} and \underline{m}' identified in Law 2 have the same tock-CSP semantics. For Law 6, tock-CSP equality holds for the semantics of the **StateMachineDefs** characterized in the law. For **OperationDefs**, however, Law 6 establishes a weaker notion of equality, captured by a new relation \approx_M^α defined below, where α is a set of required variables. The key point in this case is that, as established below, if the semantics of two **OperationDefs** \underline{m} and \underline{m}' are related by \approx_M^α , then any machines that differ just in that they call \underline{m}' rather than \underline{m} have the same semantics (either equal or related by \approx_M^α). So, the weaker notion of equality is sufficient to justify transformations that replace \underline{m} with \underline{m}' , whether they are **StateMachineDefs** or **OperationDefs**.

OperationDef relation We recall that within the semantics of machines (**StateMachineDefs** or **OperationDefs**), memory is modelled via CSP processes that offer to synchronize on channels to *get_* the current value of a variable or clock, or *set_* a new value. In Law 6, in the semantics for the machine on the left-hand side of the equality, the evaluation of the guard g , for example, occurs before the evaluation of the expression d for the deadline. For the machine on the right-hand side, g and d , used as arguments for *dop*'s, are evaluated in parallel. For **StateMachineDefs**, the *set_* and *get_* channels are all hidden in the semantics, and this kind of difference is not visible. For **OperationDefs**, however, whose

semantics, we recall, is given by $\llbracket _ \rrbracket_{\mathcal{C}, \mathcal{D}, \mathcal{Q}}^-$, both *get_* and *set_* events related to the required variables are exposed (see Fig. 49). So, in the case of Law 6, for example, if g and d involve required variables, the semantics of the **OperationDefs** on the left and right-hand sides are not equal.

In the semantics of any machine that calls such an operation, however, all *get_* events are hidden (see Fig. 49, where *set_* events show on the border of the outer box, but *get_* events do not). So, the semantics of a **StateMachineDef** that calls operations whose semantics are processes that can differ in the order of *get_* events, but nothing else, does not expose these differences. So, our notion of equality $=_s$ for **OperationDefs** does not require the order of *get_* events (for shared variables) to be the same. It is defined in terms of the new relation \approx_M^α over the semantics. To illustrate its role, we consider the following examples.

Example 9.

$$\begin{aligned} P_0 &= \text{get}_g?g \rightarrow \text{get}_d?d \rightarrow \text{get}_g?x \rightarrow e!(d+x) \rightarrow \text{Skip} \\ P_1 &= \text{get}_g?g \rightarrow \text{get}_d?d \rightarrow e!(d+g) \rightarrow \text{Skip} \end{aligned}$$

Initially, process P_0 is prepared to synchronize on *get_g* to receive a value g , followed by similar prefixings on *get_d* and *get_g* again. Afterwards, there is a prefixing on e with a value that is the sum of d and x , followed by termination. When we consider P_0 's behaviour composed with a process modelling its memory, the only visible event is e with a value that depends only on the values communicated between P_0 and the memory, but not on the order of *get_s*. In that context, we can replace P_0 by P_1 , where the second prefixing on *get_g* is removed, and the value of g read first is used in the output. In the context of a memory process, the behaviour is identical, so, we have that P_0 is related to P_1 by $\approx_M^{(d,g)}$. This, however, is only valid because there are no *set* or *share* events in between the *get_s* that could allow changes to values in the memory in between *share* events. We consider the following process P_2 , similar to P_0 , but including a *share* event.

Example 10.

$$\begin{aligned} P_2 &= \text{get}_g?g \rightarrow \text{get}_d?d \rightarrow \text{share} \rightarrow \text{get}_g?x \rightarrow \\ & \quad e!(d+x) \rightarrow \text{Skip} \end{aligned}$$

In this example, in between the two *get_g* events, we have a synchronization on *share*. With this, it means that the value of g could change between the *get_s*, and we cannot disregard the second *get_g*. The same holds, if, instead of *share*, we had a *set_g* event.

The relation $P \approx_M^\alpha Q$ is defined below; it compares processes $L\text{Mem}(P, \alpha)$ and $L\text{Mem}(Q, \alpha)$ instead of P and Q directly. With $L\text{Mem}(P, \alpha)$ (and similarly, $L\text{Mem}(Q, \alpha)$) what we have is P with a copy of its associated memory for required variables, and with the internal communications with that memory hidden. So, the comparison between P and Q defined by $P \approx_M^\alpha Q$ is restricted to its behaviour in context.

Figure 51 shows the process $L\text{Mem}(P, \alpha)$, where we use αv to denote a particular required variable. The memory process $L\text{Mem}V$ defines a context for P and has the following roles. (1) It is always ready to interact with the environment on a *get_αv* channel, whenever the value of v is known (set, as determined by *αvset*). (2) It holds a local value of αv , which is used by P , via *getL_αv* events, instead of *get_αv* events directly. (3) It, therefore, hides any order

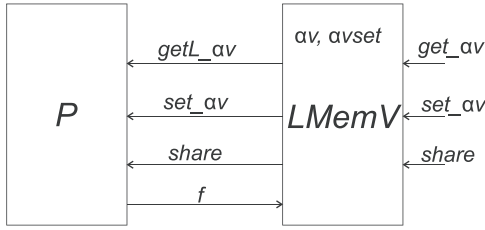


Figure 51. Definition 6.3 – Pictorial representation of $LMem(P, \{\alpha v\})$: the process $LMemV$ records the value of αv and whether its value is initialized using a boolean $\alpha vset$.

on get_av events imposed by P . (4) It passes on any $share$ events, recording that the value of αv is then not known ($\alpha vset$ is false) as it may have been changed by other processes. (5) It passes on set_av events, recording that the value of αv is now set. An extra channel f is used by P to terminate the memory process, if P itself finishes.

For example, if we assume that g and d are required variables, we have the following results. $LMem(P_0, \{g, d\})$ and $LMem(P_1, \{g, d\})$ are the same, because after the initial get_s neither process offers to synchronize in set_s or $share$, and so the following (internal) $getL_s$ happen without further interference. $LMem(P_2, \{g, d\})$, on the other hand, behaves differently. Although its initial behaviour is the same as that of $LMem(P_0, \{d, g\})$ and $LMem(P_1, \{d, g\})$, after synchronizing on $share$ the memory process must refresh its copy of the values of d and g before the next $getL_g$, namely via additional synchronizations on get_d and get_g .

The definition below formalizes $P \approx_M^\alpha Q$ in terms of $LMem$ as suggested by the examples. Formally, in $LMem(P, \alpha)$ we have a parallel composition of P , where, for each variable v in α , $get_id(v)$ is renamed to $getL_id(v)$, with a process $LMemV(\alpha)$, that models the local copy of the state of variables in α by synchronizing with P on events $getL_id$ instead of get_id (see Fig. 51). P is sequentially composed with a prefixing on f , a fresh event, to terminate the parallel composition with $LMemV(\alpha)$ after P terminates. The synchronization set includes events $getL_id(v)$ and $set_id(v)$ for all variables v in α , f , and $share$. The hiding of events $getL_id$ and f completes the definition. $LMemV(\alpha)$ is defined in [37].

Definition 6.3.

$$P \approx_M^\alpha Q \iff LMem(P, \alpha) = LMem(Q, \alpha)$$

where

$$LMem(P, \alpha) = \left(\begin{array}{l} (P \parallel v : \alpha \bullet get_id(v) \leftarrow getL_id(v) \parallel ; f \rightarrow Skip) \\ \parallel \{v : \alpha \bullet getL_id(v), set_id(v)\} \cup \{f, share\} \\ LMemV(\alpha) \end{array} \right) \setminus \{v : \alpha \bullet getL_id(v)\} \cup \{f\}$$

Using \approx_M^α we can then define another relation $=_s$ for comparing $OperationDefs$ that differ in their get_s .

Definition 6.4.

$$op_1 =_s^{(\alpha, nops_1, nops_2)} op_2 \iff \llbracket op_1 \rrbracket_{\mathcal{SMD}}^{nops_1} \approx_M^\alpha \llbracket op_2 \rrbracket_{\mathcal{SMD}}^{nops_2}$$

Operations op_1 and op_2 are related by $=_s^{(\alpha, nops_1, nops_2)}$ exactly when their semantics, given by $\llbracket _ \rrbracket_{\mathcal{SMD}}$, is related by \approx_M^α . Here, α is a set of variables and $nops_1$ and $nops_2$ are functions that define the semantics of operations that op_1 and op_2 may call. (We consider in the above definition just the simpler case in which op_1 and op_2 do not have parameters, so that $\llbracket op_1 \rrbracket_{\mathcal{SMD}}^{nops_1}$ and $\llbracket op_2 \rrbracket_{\mathcal{SMD}}^{nops_2}$ are processes, rather than functions from arguments to processes. The generalization to require \approx_M^α to hold for each combination of arguments is simple.) Importantly, Theorem 6.1 presented below establishes that the semantics of **StateMachineDefs** is unaffected by exchanging the definitions of an operation op if they are related by $=_s^{(\alpha, nops_1, nops_2)}$.

Theorem 6.1. Provided $op_1 =_s^{(\alpha, nops, nops)} op_2$, where op_1 and op_2 are **OperationDefinitions** with the same name op , α is the set of variables required by op_1 and op_2 , and $nops$ defines operations other than op , then for any **StateMachineDef** \underline{m} ,

$$\llbracket \underline{m} \rrbracket_{\mathcal{SMD}}^{nops \cup \{op \mapsto \llbracket op_1 \rrbracket_{\mathcal{SMD}}^{nops}\}} = \llbracket \underline{m} \rrbracket_{\mathcal{SMD}}^{nops \cup \{op \mapsto \llbracket op_2 \rrbracket_{\mathcal{SMD}}^{nops}\}}$$

Proof. Let $nops_1 = nops \cup \{op \mapsto \llbracket op_1 \rrbracket_{\mathcal{SMD}}^{nops}\}$ and $nops_2 = nops \cup \{op \mapsto \llbracket op_2 \rrbracket_{\mathcal{SMD}}^{nops}\}$. There are two cases:

- 1) op is not called by \underline{m} : so the semantics of op_1 and op_2 do not affect that of the state machine \underline{m} , and so $\llbracket \underline{m} \rrbracket_{\mathcal{SMD}}^{nops_1} = \llbracket \underline{m} \rrbracket_{\mathcal{SMD}}^{nops_2}$, as required.
- 2) op is called by \underline{m} : because \underline{m} is well-formed, all variables required by op_1 and op_2 are either defined or required by \underline{m} , that is, α is a subset of $localVariables(\underline{m}) \cup requiredVariables(\underline{m})$. So, let $\alpha = \beta \cup \gamma$, where β and γ are disjoint sets, β is a subset of local variables of \underline{m} and γ is a subset of required variables of \underline{m} . Therefore, from the proviso, we have that $op_1 =_s^{(\beta \cup \gamma, nops, nops)} op_2$, and by definition $\llbracket op_1 \rrbracket_{\mathcal{SMD}}^{nops} \approx_M^{\beta \cup \gamma} \llbracket op_2 \rrbracket_{\mathcal{SMD}}^{nops}$. Therefore, the semantics of calls to op_1 and op_2 , given by the copy rule, is likewise related by $\approx_M^{\beta \cup \gamma}$. The result then follows by three lemmas that lift this result (see Fig. 49) to (1) the **NodeContainer** semantics of \underline{m} (to obtain $\llbracket \underline{m} \rrbracket_{\mathcal{NC}}^{nops_1} \approx_M^{\beta \cup \gamma} \llbracket \underline{m} \rrbracket_{\mathcal{NC}}^{nops_2}$), (2) from this to the **StateMachineBody** semantics of \underline{m} , (to obtain $\llbracket \underline{m} \rrbracket_{\mathcal{SMB}}^{nops_1} \approx_M^{\gamma} \llbracket \underline{m} \rrbracket_{\mathcal{SMB}}^{nops_2}$), and finally (3) to the **StateMachineDef** semantics of \underline{m} , obtaining $\llbracket \underline{m} \rrbracket_{\mathcal{SMD}}^{nops_1} = \llbracket \underline{m} \rrbracket_{\mathcal{SMD}}^{nops_2}$ as required. ■

The lemmas used in the above proof are in [37], and we present below the last of these for illustration.

Lemma 6.3. Provided $\llbracket \underline{m} \rrbracket_{\mathcal{SMB}}^{nops_1} \approx_M^\alpha \llbracket \underline{m} \rrbracket_{\mathcal{SMB}}^{nops_2}$, where $\alpha \subseteq requiredVariables(\underline{m})$, then $\llbracket \underline{m} \rrbracket_{\mathcal{SMD}}^{nops_1} = \llbracket \underline{m} \rrbracket_{\mathcal{SMD}}^{nops_2}$.

Proof. We recall that the **StateMachineDef** semantics for \underline{m} is defined by a parallel composition of its **StateMachineBody** semantics and the memory process for required variables, with the get_id events hidden. In that composition (by a lemma in [37]) we can replace $\llbracket \underline{m} \rrbracket_{\mathcal{SMD}}^{nops_1}$ with $LMem(\llbracket \underline{m} \rrbracket_{\mathcal{SMB}}^{nops_1}, \alpha)$ because $LMem(\llbracket \underline{m} \rrbracket_{\mathcal{SMB}}^{nops_1}, \alpha)$ only places, between $\llbracket \underline{m} \rrbracket_{\mathcal{SMB}}^{nops_1}$ and the memory process, an $LMemV$ process (see Fig. 51) that caches a local value for the required variables and passes every other communication on to $\llbracket \underline{m} \rrbracket_{\mathcal{SMB}}^{nops_1}$. From the proviso and the definition of \approx_M we have that $LMem(\llbracket \underline{m} \rrbracket_{\mathcal{SMB}}^{nops_1}, \alpha) = LMem(\llbracket \underline{m} \rrbracket_{\mathcal{SMB}}^{nops_2}, \alpha)$. So, we can make the following argument, where we indicate the parallel composition using \parallel , the memory process as MP , and the set of

channels being hidden as $\llbracket \text{get_}, \dots \rrbracket$.

$$\begin{aligned}
& \llbracket \underline{m} \rrbracket_{\mathcal{SMD}}^{\text{nops}_1} \\
&= (\llbracket \underline{m} \rrbracket_{\mathcal{SMD}}^{\text{nops}_1} \parallel \text{MP}) \setminus \llbracket \text{get_}, \dots \rrbracket \\
&= (\text{LMem}(\llbracket \underline{m} \rrbracket_{\mathcal{SMD}}^{\text{nops}_1}, \underline{\alpha}) \parallel \text{MP}) \setminus \llbracket \text{get_}, \dots \rrbracket \\
&= (\text{LMem}(\llbracket \underline{m} \rrbracket_{\mathcal{SMD}}^{\text{nops}_2}, \underline{\alpha}) \parallel \text{MP}) \setminus \llbracket \text{get_}, \dots \rrbracket \\
&= (\llbracket \underline{m} \rrbracket_{\mathcal{SMD}}^{\text{nops}_2} \parallel \text{MP}) \setminus \llbracket \text{get_}, \dots \rrbracket \\
&= \llbracket \underline{m} \rrbracket_{\mathcal{SMD}}^{\text{nops}_2}
\end{aligned}$$

With Theorem 6.1, we ensure that application of Law 6 to operations called in **StateMachineDefs** is sound, because, as shown below, Law 6 establishes $=_S$.

Law 6, stated diagrammatically in Section 4.1, is formalized and proved sound below. As mentioned, the equality holds for **StateMachineDefs**, while for **OperationDefs** we have the relation \approx_M^{rv} , where rv is the subset of variables required by \underline{m} and used in the guard or deadline of a transition whose deadline is removed by application of Law 6 (from left to right).

Formalisation 2 (Law 6).

$$\llbracket \underline{m} : \text{StateMachineDef} \rrbracket_{\mathcal{SMD}}^{\text{nops}_1} = \llbracket \underline{m}' : \text{StateMachineDef} \rrbracket_{\mathcal{SMD}}^{\text{nops}_2}$$

where

- $\underline{S}, \underline{S}' : \text{State}, \underline{ds} : \text{Statement}, \text{Idop_ds} : \text{Interface},$
- $\text{action_ds} : \text{During}, \underline{td} : \text{Transition},$
- $\underline{nc} : \text{NodeContainer},$
- $\text{dop_ds} : \text{OperationDef}, \text{call_dop_ds} : \text{Call}$

$$\begin{aligned}
& \text{A1. } \text{action_ds} \in \underline{S}.\text{actions} \wedge \underline{ds} = \text{action_ds}.\text{action} \\
& \text{A2. } \underline{S} \in \underline{nc}.\text{nodes} \\
& \text{A3. } \left(\begin{array}{l} \underline{td} \in \underline{nc}.\text{transitions} \wedge \underline{td}.\text{deadline} \neq \text{null} \wedge \\ \underline{td}.\text{source} = \underline{S} \end{array} \right) \\
& \text{A4. } \text{dop_ds} = \text{dop_dsOperation}(\underline{ds}, \underline{td}) \\
& \text{A5. } \text{Idop_ds} = \{\text{operations} \mapsto \{\text{opSig}(\text{dop_ds})\}\} \\
& \text{A6. } \left(\begin{array}{l} \text{call_dop_ds}.\text{op} = \text{opSig}(\text{dop_ds}) \wedge \\ \text{call_dop_ds}.\text{args} = \text{usedArgs}(\underline{d}, \underline{td}.\text{condition}, \underline{ds}) \end{array} \right) \\
& \text{A7. } \text{nops}_2 = \text{nops}_1 \cup \{\text{dop_ds}.\text{name} \mapsto \llbracket \text{dop_ds} \rrbracket_{\mathcal{SMD}}\} \\
& \text{A8. } \underline{S}' = \underline{S} \oplus \left\{ \begin{array}{l} \text{actions} \mapsto \\ (\underline{S}.\text{actions} \setminus \{\text{action_ds}\}) \\ \cup \{\text{action_ds} \oplus \{\text{action} \mapsto \text{call_dop_ds}\}\} \end{array} \right\} \\
& \text{A9. } (\underline{m} \oplus \{\text{RInterfaces} \mapsto \underline{m}.\text{RInterfaces} \cup \text{Idop_ds}\}, \underline{nc}) \\
& \quad \approx_M^{\text{N}} \left(\begin{array}{l} \underline{m}', \underline{nc} \oplus \left\{ \begin{array}{l} \text{nodes} \mapsto (\underline{nc}.\text{nodes} \setminus \{\underline{S}\}) \cup \{\underline{S}'\} \\ \text{trans} \mapsto \\ (\underline{nc}.\text{trans} \setminus \{\underline{td}\}) \cup \\ \{\phi(\underline{S}, \underline{S}')(\underline{td} \oplus \{\text{deadline} \mapsto \text{null}\})\} \end{array} \right\} \end{array} \right)
\end{aligned}$$

Similarly to the formalization of Law 2, we have the declaration of metavariables used in Law 6. Namely, we declare \underline{S} , \underline{ds} , Idop_ds , action_ds and \underline{td} , which capture model elements of the state machines. We use \underline{S}' to refer to the state on the right-hand side of Law 6. The **NodeContainer** \underline{nc} is used to capture the **State**, **StateMachineDef** or **OperationDef** that contains the state \underline{S} and its outgoing transition \underline{td} . As before, in the diagram for Law 6 we use $\text{dop_s}(\dots)$ to refer both to a call to an operation and to

the signature used in its definition. Here we declare call_dop_s to represent the call, and dop_s to represent the operation itself.

Following the declarations, there is a list of numbered properties restricting the values of the metavariables. First, in A1, we record the fact that Law 6 uses action_ds as a **during** action of \underline{S} and that \underline{ds} is the statement of action_ds . The case where \underline{S} has no **during** action is omitted for simplicity, but can be accounted, for example, by considering \underline{ds} as **skip**, which terminates immediately. A2 requires \underline{S} to be one of \underline{nc} 's states. A3 states that \underline{td} is one of \underline{nc} 's transitions with a deadline and whose source is **State** \underline{S} . A4 formalizes the definition of dop_ds using a metafunction $\text{dop_dsOperation}(\underline{ds}, \underline{td})$, defined in [37]; it defines an operation for the given statement \underline{ds} and transition \underline{td} , using interfaces req'd'g's , defEvents's and Idop's and IddeadlineCheck . A5 formalizes the definition of the interface Idop's , where its component **operations** maps to the singleton set containing the signature of dop's . A6 records the **Call**'s target as the operation call_dop_s and that the arguments to be passed, if any, are given by a function $\text{usedArgs}(\dots)$. A7 states that the parameter nops_2 is defined by extending nops_1 with the semantics of dop's . A8 captures how \underline{S}' is defined in terms of \underline{S} , where the original action action_ds is replaced by call_dop_s . Finally, A9 captures how the machine \underline{m}' is defined in terms of \underline{m} , after it is enriched with the required interface Idop's . The difference in \underline{m}' is that the **NodeContainer** \underline{nc} , a descendant state of \underline{m} or itself \underline{m} , has \underline{S} removed and a new state \underline{S}' added; and \underline{td} removed and replaced by a transition where the **deadline** is set to **null** and any use of \underline{S} is replaced by \underline{S}' using ϕ , defined previously in Section 6.2.1. The proof of soundness for Law 6 in [37] is sketched below.

Proof. There are two cases to consider: \underline{m} and \underline{m}' are **StateMachineDefs** or **OperationDefs**. We focus on the latter given that equality for **StateMachineDefs** can be established by a further application of Lemma 6.3. For

- $\underline{m}_0 = \underline{m} \oplus \{\text{RInterfaces} \mapsto \underline{m}.\text{RInterfaces} \cup \text{Idop_ds}\},$
- $\underline{td}_0 = \phi(\underline{S}, \underline{S}')(\underline{td} \oplus \{\text{deadline} \mapsto \text{null}\}),$
- $\underline{a}_0 = \{\text{action_ds} \oplus \{\text{action} \mapsto \text{call_dop_ds}\}\},$
- $\underline{nc}_0 = \underline{nc} \oplus \left\{ \begin{array}{l} \text{nodes} \mapsto (\underline{nc}.\text{nodes} \setminus \{\underline{S}\}) \cup \{\underline{S}'\}, \\ \text{trans} \mapsto (\underline{nc}.\text{trans} \setminus \{\underline{td}\}) \cup \{\underline{td}_0\} \end{array} \right\}$
- $\underline{uv} = \left(\begin{array}{l} \text{usedVariables}(\underline{td}.\text{condition}) \\ \cup \text{usedVariables}(\underline{td}.\text{deadline}) \end{array} \right)$

we can establish the following results.

- R1. $(\underline{m}_0, \underline{nc}) \approx_M^{\text{N}} (\underline{m}', \underline{nc}_0);$
- R2. $\text{vars}(\underline{nc}) = \text{vars}(\underline{nc}_0);$
- R3. $\text{usedOps}(\underline{S}') = \text{usedOps}(\underline{S}) \cup \{\text{dop_ds}\}$, that is, the set of operations used by \underline{S}' , those called by actions of \underline{S} , its substates or transitions, is that used by \underline{S} augmented with dop_ds , thus we also have that $\text{usedOps}(\underline{m}') = \text{usedOps}(\underline{m}_0) \cup \{\text{dop_ds}\}$, and $\text{usedOps}(\underline{m}') \cap \text{usedOps}(\underline{m}_0) = \text{usedOps}(\underline{m}_0)$, that is, the operations used by both \underline{m}' and \underline{m}_0 are the same. Therefore, they behave the same:

$$\forall \text{op} : \text{usedOps}(\underline{m}') \cap \text{usedOps}(\underline{m}_0) \bullet$$

$$\llbracket \text{nops}_1(\text{op}) \rrbracket_{\mathcal{SMD}}^{\text{nops}_1} = \llbracket \text{nops}_2(\text{op}) \rrbracket_{\mathcal{SMD}}^{\text{nops}_2}$$

- R3. $\llbracket \underline{nc} \rrbracket_{\mathcal{SMD}}^{\text{nops}_1} \approx_M^{\underline{uv}} \llbracket \underline{nc}_0 \rrbracket_{\mathcal{SMD}}^{\text{nops}_2}$, that is, the semantics of the **NodeContainers** \underline{nc}_0 and \underline{nc} is related by $\approx_M^{\underline{uv}}$, where \underline{uv} are variables used in the condition or deadline of \underline{td} , and $\underline{rv} \subseteq \text{requiredVars}(\underline{m}) \cap \underline{uv}$, the subset of \underline{uv} that is required by

m. Proving this result requires showing that the parallel composition of the semantics of \underline{S} with its transition (\underline{td}) deadline semantics is equivalent to that of \underline{S}' , where there is no deadline on transition \underline{td}_0 and instead the during action is replaced by a call to $\text{dop} \cdot \text{ds}$.

They justify the application of the following key lemma.

Lemma 6.4

$$\llbracket \underline{m} : \text{NodeContainer} \rrbracket_{\mathcal{N}'\mathcal{E}}^{\text{nops}_1} \approx_M^\alpha \llbracket \underline{m}' : \text{NodeContainer} \rrbracket_{\mathcal{N}'\mathcal{E}}^{\text{nops}_2}$$

provided:

- P1. $(\underline{m}, \underline{nc}) \approx_{\mathcal{N}'\mathcal{E}}^N (\underline{m}', \underline{nc}')$
- P2. $\text{vars}(\underline{nc}) = \text{vars}(\underline{nc}')$
- P3. $\left(\forall \text{op} : \text{usedOps}(\underline{m}') \cap \text{usedOps}(\underline{m}) \bullet \right.$
 $\left. \llbracket \text{nops}_1(\text{op}) \rrbracket_{\mathcal{E}\mathcal{P}\mathcal{D}}^{\text{nops}_1} = \llbracket \text{nops}_2(\text{op}) \rrbracket_{\mathcal{E}\mathcal{P}\mathcal{D}}^{\text{nops}_2} \right)$
- P4. $\llbracket \underline{nc} \rrbracket_{\mathcal{N}'\mathcal{E}}^{\text{nops}_1} \approx_M^\alpha \llbracket \underline{nc}' \rrbracket_{\mathcal{N}'\mathcal{E}}^{\text{nops}_2}$

Proof. The proof strategy is similar to that in the proof of Lemma 6.2. The base case, when $\underline{m} = \underline{nc}$ and $\underline{m}' = \underline{nc}'$ hold directly, with the other cases established by induction using the definitions of $\llbracket \cdot \rrbracket_{\mathcal{N}'\mathcal{E}}$ and $\approx_{\mathcal{N}'\mathcal{E}}^N$, and the semantics of composite states. ■

Using the lemmas and results above, soundness can be established by a stepwise argument as follows, using Results R1 to R4, a version of Lemma 6.1 for **OperationDefs**, and Lemma 6.4. First, we have that $\llbracket \underline{m} \rrbracket_{\mathcal{F}\mathcal{M}\mathcal{B}}^{\text{nops}_1}$ is equal to $\llbracket \underline{m}_0 \rrbracket_{\mathcal{F}\mathcal{M}\mathcal{B}}^{\text{nops}_1}$ using the definition of \underline{m}_0 and Lemma 6.1. So the proof requires showing that $\llbracket \underline{m}_0 \rrbracket_{\mathcal{F}\mathcal{M}\mathcal{B}}^{\text{nops}_1}$ and $\llbracket \underline{m}' \rrbracket_{\mathcal{F}\mathcal{M}\mathcal{B}}^{\text{nops}_2}$ are related by \approx_M . By a Lemma in [37], we have $\llbracket \underline{nc} \rrbracket_{\mathcal{N}'\mathcal{E}}^{\text{nops}_1} \approx_M^{\text{uv}} \llbracket \underline{nc}_0 \rrbracket_{\mathcal{N}'\mathcal{E}}^{\text{nops}_2}$, and so using Lemma 6.4 we have $\llbracket \underline{m}_0 \rrbracket_{\mathcal{N}'\mathcal{E}}^{\text{nops}_1} \approx_M^{\text{uv}} \llbracket \underline{m}' \rrbracket_{\mathcal{N}'\mathcal{E}}^{\text{nops}_2}$. Finally, this result can be lifted to show that $\llbracket \underline{m}_0 \rrbracket_{\mathcal{F}\mathcal{M}\mathcal{B}}^{\text{nops}_1} \approx_M^{\text{fv}} \llbracket \underline{m}' \rrbracket_{\mathcal{F}\mathcal{M}\mathcal{B}}^{\text{nops}_2}$, as required, using a lifting from the **NodeContainer** semantics to the **StateMachineBody** semantics as used in case 2 of Theorem 6.1's proof.

Finally, we note that if \underline{m} and \underline{m}' are **StateMachineDefs**, we can further apply Lemma 6.3 to obtain equality.

7. CONCLUSIONS

This paper presents what is, as far as we know, the first set of transformations for timed UML-like state machines, with accompanying proofs of soundness and notions of completeness based on normal forms. We consider machines in both a closed (RoboChart machines) and an open context. Most importantly, we consider machines that can specify time properties. Moreover, our laws and normalization procedures are implemented to provide practical normalization engines.

RoboChart is unique as a statechart-based notation with support for time modelling and closed components, and a formal semantics. The open state machines are closer to those in traditional Statecharts [49], UML [5] and SysML [50], but also support a rigorous approach to time modelling. This unique approach, with a process algebraic semantics, can be incorporated in other statechart-based notations. In this sense, our results are concerned with a time modelling approach, rather than just RoboChart or even open machines.

On the other hand, our notations do not include the whole repertoire of constructs of UML and SysML, for example. To keep formalization of models tractable, we have eliminated facilities

such as inter-level transitions, which make compositional reasoning difficult, if not impossible. Writing models that require elaborate control flows that are not directly supported is normally possible via an encoding using variables. For example, we can model completion events using boolean variables to guard transitions and ensure they are enabled only when all internal activity of a state has finished.

Our laws embed a reasoning and normalization approach that can inform similar techniques for other notations. Those that offer more restricted facilities to deal with data and states, such as automata, can benefit from simpler versions of the laws. (Timed automata [51] provide extensive support for time modelling, but not for structured modelling, using rich data, state hierarchies and action-based control.) Reliance on our soundness argument requires a process-algebraic semantics, but considering soundness in other semantic contexts is an interesting avenue of further study.

To prove soundness of our laws, it has been beneficial to rework the semantics of RoboChart state machines to provide a compositional formulation. Two aspects have been changed. The semantics of operations is now captured by the copy rule, and the semantics of a composite state is given just in terms of that of its state machine. As a result, the notion of **NodeContainer** is given a semantics in its own right, and this provides a direct connection with the semantics of open machines. All this simplifies the semantics, facilitating proof, and, as it turns out, reducing the number of states of the CSP model and improving efficiency of model checking.

Previous work on refinement laws for state machines has been carried out in the context of SysML [52]. In that approach, a notion of refinement is defined for state machines in the context of block diagrams, which are used to define systems (and their components) in SysML. Similarly, here we define refinement for machines in the context of modules. The objective in [52] is to compare systems at different levels of abstraction. Here, we restrict ourselves to equalities, but do define equality as mutual refinement. To enable refinement reasoning, extensions to SysML are proposed in [52] to support, for example, hiding and a well-defined action language based on CSP. Hiding is already available in RoboChart (via block containment), since RoboChart is a language developed to support formal verification (by refinement). Consequently, some of the laws in [52] potentially have a counterpart as laws of open machines, and vice versa. We note, however, that the SysML machines do not have time constructs.

In [53], the authors propose a set of laws for UML-RT [54], a UML profile with a clear definition for reactive components and component protocols, useful to describe concurrent and distributed domains. The focus of the laws is on the new elements that UML-RT adds to UML: active classes (capsules), protocols, ports and connections. Laws are not concerned with UML-RT statecharts in their own right, but in the context of the decomposition of active classes. The normal form removes parallelism. That work can be considered complementary to our contribution here, as it addresses concurrency, but not time constructs.

To summarize, our work considers a rich state-machine notation in terms of its support to specify time properties. As far as we know, we provide the only set of sound and complete laws for timed state machines.

DATA AVAILABILITY STATEMENT

Supporting material is available in [37] yellow and robostar.cs.york.ac.uk as explicitly indicated in the body of the paper.

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