

From Formal Modelling to Agent Simulation Execution and Testing

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Abstract: This work presents an approach to agent-based simulation development using formal modelling, i.e. stream X-Machines, that combines the power of executable specifications and test case generation. In that respect, a domain specific language is presented for effortlessly encoding agent behaviour as a stream X-Machine in a well known simulation platform. The main benefits in using the specific formal approach in such a practical setting, apart from the fact that it offers a clear, intuitive way for specifying agent behaviour, is the existence of tools for test case generation, that allow to systematically generate “agent simulation test scenarios”, i.e. sequences of agent inputs that can be used for validation.

1 INTRODUCTION

In the past years the research community has experienced an explosive interest in the area of agent based simulations, the latter being applied to wide range of scientific fields, such as biology, pedestrian simulations, economics to mention a few (Davidsson et al., 2007). Thus, the number of agent simulation platforms (Nikolai and Madey, 2009) (Allan, 2010), and development methodologies proposed in the literature is quite large.

However, there is little work in approaches that combine various aspects of the standard software engineering process in building simulations. One important issue when developing any system is systematic testing, i.e. the generation of an (ideally) exhaustive set of test cases, that will allow checking the conformance of a system to its specification. Another important aspect is validation, i.e. checking whether the system exhibits the intended behaviour. Validation could be performed by executing the system with some representative scenarios, thus allowing the developer to investigate the simulation system behaviour.

Towards this direction, this paper advocates the use of *Stream X-Machines* (SXM), a formal method extending the finite state machines, i.e. a class of state machines augmented with memory and partial func-

tions labelling transitions, to develop agent simulations. One of the main benefits using the specific formalism is that SXMs offer a testing method that under certain design-for-test conditions ensures the conformance of a system to its specification (Ipate and Holcombe, 1997). Furthermore, there exist tools that allow encoding of executable SXM specifications of agents in simulation environments, and most importantly, in the current context, tools that allow automated test case generation.

Thus, this paper presents TXStates, a domain specific language (DSL) that acts as a layer for specifying and executing agents represented as SXMs in NetLogo (Wilensky, 1999), one of the most widely known multi agent simulation platforms. The TXStates DSL has evolved for a number of years and earlier versions of it have been used to develop medium to large scale simulations in NetLogo, including some agent simulations that include behaviour under the influence of emotions (Sakellariou et al., 2014). The model developed in TXStates can then be transformed to a JSXM model. JSXM (Dranidis et al., 2012) is a tool, supporting modelling and execution of SXMs and most importantly automated test case generation, based on the SXM testing theory.

The approach (and not yet a methodology) this work proposes, is to use TXStates to develop a simulation based on a SXM model through the usual it-

erative development process, and then use JSXM to produce test cases for the same model. The generated test case scenarios can a) be used to show that the JSXM and the TXStates model are equivalent and b) act as input scenarios to the simulation environment, providing visual output that the user can use in order to visually validate the modelled agents. The latter presents a complete set of “simulation scenarios” that can assist the user in finding inconsistencies between the system the modeller *intended to represent* and the implemented model, thus performing validation.

The rest of the paper is organised as follows. Section 2 outlines our approach. Section 3 provides an overview of the SXM formal modelling technique, how SXM concepts are mapped to agent concepts and an introduction to SXM testing. The TXStates domain specific language is presented in section 4. Section 5 describes the model used as a working example in the current paper. The process of moving from specification to testing using the JSXM tool is described in 6. Related work is presented in 7. Finally, section 8 concludes the work and presents future work.

2 THE SXM APPROACH

Quite often, building a simulation involving complex agents is a challenging and error-prone task. The challenge relies mainly on the fact that the modeller has to consider all possible interactions between the modelled agent and the environment, and ensure that these are dealt with in the model.

However, in many cases, and especially in simulation environments where execution is usually cheap, discovering the set of interactions and ensuring that the agent behaves correctly relies on developing the simulation in an iterative manner, i.e. an implement—visualise—revise cycle. When the agents become complex, such a cycle demands tools that would facilitate code changes and at the same time provide a clear, intuitive representation of the behaviour. The TXStates DSL aims at exactly that. Offering the ability of encoding agent behaviour as stream X-Machines, maintains clarity and allows users to easily modify the encoded behaviour. The execution layer provided by the DSL allows to “run” the simulation and detect any inconsistencies at an initial level.

To ensure that the simulated agent behaves correctly, testing the model has to be performed in a systematic manner. For this purpose, the modeller expresses in JSXM the *corresponding model* in order to produce test cases. We refer to this as a *corresponding model* since the modeller has to include in

the former various environment conditions in order to compensate for the functionality provided by the simulation environment. The model expressed in JSXM is used to generate test cases that serve two purposes. The first concerns that of ensuring that the two models are equivalent (Ipate and Holcombe, 1997). Secondly, the generated test cases are used as “simulation scenarios” that allow the systematic validation of the agent by visualizing the agent behaviour with TXStates. Thus model developers can confirm that the simulated agent behaves as the modeller expected, i.e. validate the model.

Figure 1, depicts the approach taken by this work. The *intended model* that the user aims at, is modelled in TXStates. This model acts as a guide for developing the JSXM model that is used for generating test cases. The test cases then are executed by the TXStates DSL in order to prove *equivalence* of the two models. When this is achieved, the same test cases act as simulation scenarios, that visualized by TXStates allow the user to observe the behaviour of the developed simulation in a range of situations, and thus validate the model.

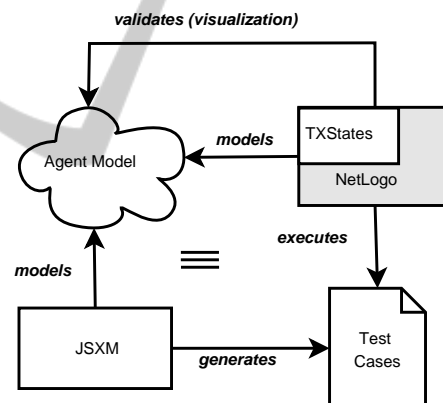


Figure 1: The SXM Approach to Simulation Development.

3 MODELLING AND TESTING AGENTS AS SXMS

State machines have been used extensively to derive agent simulation implementations since they provide a rather intuitive way to model agent behaviour. SXMs extend finite state machines with a memory structure and transitions labelled with functions and thus allow more powerful modelling of a system. For completeness, the definition of SXMs is presented below.

Definition 1. A stream X-machine (Holcombe and Ipate, 1998) is an 8-tuple

$$Z = (\Sigma, \Gamma, Q, M, \Phi, F, q_0, m_0)$$

where:

- Σ and Γ are the input and output alphabets, respectively.
- Q is the finite set of states.
- M is the (possibly) infinite set called memory.
- Φ is a set of partial functions ϕ ; each such function maps an input and a memory value to an output and a possibly different memory value, $\phi : M \times \Sigma \rightarrow \Gamma \times M$.
- F is the next state partial function, $F : Q \times \Phi \rightarrow Q$, which given a state and a function from the type Φ determines the next state. F is often described as a state transition diagram.
- q_0 and m_0 are the initial state and initial memory respectively.

Intuitively, a SXM Z can be thought as a finite automaton with the arcs labelled by functions from the set Φ . The automaton $A_Z = (\Phi, Q, F, q_0)$ over the alphabet Φ is called the associated finite automaton (abbreviated associated FA) of Z and is usually described by a state-transition diagram.

Definition 2. A computation state is defined as the tuple (q, m) , with $q \in Q$ and $m \in M$. The computation step is defined as $(q, m) \xrightarrow{\phi} (q', m')$ with $q, q' \in Q$ and $m, m' \in M$ such that $\phi(m, \sigma) = (\gamma, m')$ and $F(q, \phi) = q'$. The computation is the series of computation steps when all inputs are applied to the initial computation state (q_0, m_0) .

An agent can be considered as an entity that maps its current percepts and state to an action. Thus, in order to model the behaviour of an agent using SXMs, a mapping of the concepts of the former to the latter is necessary. However, due to the structure of SXMs this mapping is rather clear and straightforward:

- The input alphabet Σ forms the agent percepts.
- The agent's internal world representation and all parameters that affect its behaviour are mapped to the SXM memory M and current state. In other words M holds agent beliefs, while with appropriate encoding of states, it can also hold the agent's current goal.
- Agent behaviour is modelled as a set of functions Φ and the transition diagram F .
- Finally, agent actions are mapped to the output Γ .

3.1 Background on Testing with SXM

SXMs have the significant advantage of offering a testing method that under certain design-for-test conditions ensures the conformance of a system under

test (SUT) to a specification. This section provides details regarding test case generation to ensure completeness of the paper.

The goal of the testing method is to devise a finite test set $X \subset \Sigma^*$ of input sequences that produce identical results when applied to the specification and the SUT *only if* they both compute identical functions. The main assumption that needs to be made for the SUT is that it consists of correct elementary components, i.e. the processing functions are correctly implemented. Furthermore, it is estimated that the number of states in the SUT is $n' \geq n$, where n is the number of states of the specification. Let $k = n' - n$.

Input sequences attempt to drive the SUT to all the states, then exercise from those states paths of transitions of length $k + 1$ and finally uniquely identify the reached states. If the output sequences produced by the SUT are different than the ones produced by the specification faults are revealed.

The SXM testing method (Ipate and Holcombe, 1997; Holcombe and Ipate, 1998) relies on the following design-for-test condition:

- **Output-distinguishability.** Processing functions should be distinguishable by their different outputs on some memory-input pair, i.e. for every $\phi_1, \phi_2 \in \Phi$, $m \in M$ and $\sigma \in \Sigma$ such that $(m, \sigma) \in \text{dom } \phi_1$ and $(m, \sigma) \in \text{dom } \phi_2$, if $\phi_1(m, \sigma) = (\gamma, m_1)$ and $\phi_2(m, \sigma) = (\gamma, m_2)$ then $\phi_1 = \phi_2$.

The testing method for SXMs is an extension of the W -method for finite state machines. The test generation is a two stage process: (1) the W method (Chow, 1978) is applied on the associated automaton A_Z to produce a set $T \subseteq \Phi^*$ of sequences of processing functions, which are then (2) translated into sequences of inputs for Z using a so-called test function $t : \Phi^* \rightarrow \Sigma^*$.

T is obtained by constructing a state cover S and a characterization set W of A_Z . $S \subseteq \Phi^*$ contains sequences to reach all states of A_Z , while $W \subseteq \Phi^*$ contains sequences to distinguish between any two distinct states of A_Z . Each sequence $t \in T$ consists of three sub-sequences, i.e., $t = syw$, where $s \in S$ drives the automaton to a specific state, $y \in \Phi^*$ attempts to exercise transition-paths up to length of $k + 1$ and w distinguishes the resulting state from any other state. Thus $T = S\Phi[k + 1]W = S(\bigcup_{0 \leq i \leq k+1} \Phi^i)W$.

Based on (Ipate and Holcombe, 1997), the maximum number of test sequences, i.e., $\text{card}(T)$, is less than $n^2 \cdot r^{k+2} / (r - 1)$, where $n = \text{card}(Q)$, $r = \text{card}(\Phi)$. The total length l of the test set is less than $\text{card}(T) \cdot n'$, where $n' = k + n$.

Since SXMs have memory, there may exist sequences of processing functions that are accepted by the associated automaton A_Z but they cannot be driven

by any input sequence. These sequences are called non-realizable.

Definition 3. A sequence $p \in \Phi^*$ is called realizable in q and m if $p \in L_{AZ}(q)$ and $\exists s \in \Sigma^*$ such that $(m, s) \in \text{dom } \|p\|$. The set of realizable sequences of Z in q and m is notated as $LR_Z(q, m)$. Let LR_Z be defined as $LR_Z(q_0, m_0)$.

The definitions of the state cover and the characterization sets are extended to handle realizable sequences of processing functions.

A state is r -reachable if it can be reached by a realizable sequence $p \in LR_Z$.

Definition 4. A set $S_r \subseteq LR_Z$ is called a r -state cover of Z if for every r -reachable state q of Z there exists a unique $p \in S_r$ that reaches the state q .

The set of memory values that can be attained at a state q is notated as $MAtt(q)$ and it consists of all memory values that are the result of realizable sequences that end at state q , i.e. $MAtt(q) = \{m \in M \mid \exists p \in LR_Z \text{ and } \exists s \in \Sigma^*, \|p\|(m_0, s) = (g, m)\}$.

Any two states have to be *separable*, i.e. distinguished by two realizable sequences with *overlapping* domains.

Definition 5. A pair of states (q_1, q_2) is separable if there exists a finite set of sequences Y such that $\forall m_1 \in MAtt(q_1), m_2 \in MAtt(q_2)$, there exists $p_1 \in LR(q_1, m_1) \cap Y$ and $p_2 \in LR(q_2, m_2) \cap Y$ such that $\text{dom } p_1 \cap \text{dom } p_2 \neq \emptyset$.

Essentially, at each state the same sequence of inputs will trigger one of the two sequences of processing functions. By the observed outputs we can tell which sequence of processing functions has been triggered and thus identify the state.

Definition 6. A set $W_s \subseteq \Phi^*$ is called a separating set of Z if it separates (distinguishes) between every pair of separable states of Z .

If S_r reaches all states of Z and W_s separates all pairs of states in Z . the testing method reduces to a variant of the W -method:

$$T = UW_s = ((S_r \Phi[k+1]) \cap L_{AZ})W_s$$

Furthermore, the testing method requires that all sequences of $U = (S_r \Phi[k+1]) \cap L_{AZ}$ are realizable, i.e. it is required that $U \subseteq LR_Z$. Note that the sequences of processing functions of maximum length $k+1$ that follow the r -state cover are limited to those that are accepted by the associated automaton.

The final test suite for checking functional equivalence is:

$$X = t(T) = t(UW_s)$$

The sequences of inputs in $X \subset \Sigma^*$ are fed to the SXM in order to produce the corresponding expected sequences of outputs $Y \subset \Gamma^*$.

4 MAS SIMULATION WITH TXStates

TXStates is an internal DSL for the NetLogo Agent Simulation environment, that allows encoding SXM agent specifications in a natural manner. Before presenting TXStates a brief presentation of NetLogo is provided in order to clarify the terminology provided in the rest of the paper and place the present work in context.

NetLogo is “a cross-platform multi-agent programmable modelling environment” (Wilensky, 1999) aiming at MAS simulation. In NetLogo, the environment consists of a static grid of *patches*, useful for describing the environment, since they are capable of interacting with other entities. This “world” is inhabited by *turtles* that are entities that “live” and interact within it. They are organised in groups called *breeds*, i.e. user defined teams sharing some characteristics. Finally, *links* are entities that “connect” two turtles representing usually a spatial/logical relation between them.

Patches, turtles and links carry their own *internal state*, stored in a set of system and user-defined variables local to each agent. By the introduction of an adequate set of patch variables, a sufficient description of complex environments can be achieved. The definition of turtle specific variables allows the former to carry their own state and facilitates encoding of complex behaviour.

Agent behaviour can be specified by the domain specific NetLogo programming language, supports two main programming constructs: functions (called *reporters*) and *procedures*. The language includes a large set of primitives for turtles motion, environment inspection, classic program control (ex. branching), etc. NetLogo v5 introduced *tasks*, the version of anonymous functions or closures of NetLogo. Reasoning about time is supported through *ticks*, each tick corresponding to a discrete execution step. Finally, the programming environment offers simple GUI creation facilities that minimize the time required to develop a simulation.

Although a powerful modelling tool, as indicated by the constantly increasing number of publications that use NetLogo as the platform of choice, NetLogo has been criticised for not providing modelling constructs that allow encoding of more complex agents. The TXStates DSL provides an answer to this and contributes to the list of tools to support complex agent behaviour encoding, such as BOD (Bryson, 2003) and IODA (Kubera et al., 2011), adding the dimension of automatic test case generation for agents.

There is a continuous debate whether one mod-

elling tool is better than another. We have invested considerable time to develop a good number of models in NetLogo and we found it appropriate for the applications we have encountered, that is, biological or biology-inspired agents with spatial characteristics and their emergent behaviour. Notwithstanding the simulation tool, this work can be immediately adopted since it refers to the general concept of testing through a formal specification.

4.1 TXStates Models SXMs

The TXStates provides support for encoding all modelling constructs of SXM definition presented in section 3. Ease of encoding was a very important requirement, since in most cases in multi-agent simulations, the development is iterative, since the emergent phenomena that manifest in such as setting demand a trial and error approach and constant changes in the model.

In essence, TXStates extends the NetLogo programming language, with the necessary constructs to build executable SXM models. The DSL is *internal* since it relies on the syntax of NetLogo and all the code is implemented using the NetLogo language, possibly at the cost of execution speed, but offering tight coupling with the underlying language and without interrupting the normal development cycle a modeller follows in the specific platform. In essence, we decided not to implement an external DSL, since apart from the SXM model the developer has to provide to specify agent behaviour, in order to arrive to an executable simulation, other parts of the simulation, such as environment setup, visualization, agent perception mechanisms, have to be defined as well, thus having an external DSL would mean that the developer would have to work on two different platforms simultaneously.

The implementation relies on storing agent specific information on turtle-own variables, since each agent must carry its own agent (execution) state. Thus, memory M is mapped to a data structure stored in a turtle-own variable called *memory* that consists of attribute - value pairs. The DSL provides special care for its management to facilitate model development. For instance, in Figure 2 the procedure `x-mem-set <V> <Val>` is a destructive update with value `<Val>` for attribute (or memory element) `<V>`.

In a similar manner, percepts that correspond to SXM input Σ are stored in a variable *percept* and although *percepts* is a relatively simple data structure, the library provides a set of programming constructs (Figure 2) to access/add percepts depending on environment changes. Please note that it is the model developer's responsibility to update the former in each

```
(1) MEMORY PRIMITIVES
x-init-memory
x-mem-initial-var <V> <Val>
x-mem-set <V> <Val>
x-mem-value <V>
(2) PERCEPT PRIMITIVES
x-add-percept <P>
x-percept-add-value <P> <Val>
x-has-percept? <P>
x-percept-value <P>
x-oneof-percept-value <P>
x-all-percept-values <P>
```

Figure 2: TXStates primitives for X-Machine memory handling and percept updates.

simulation cycle.

Finally, there is a class of turtle variables that the library uses *internally* and should not be changed in any way by the developer of the model, since they store information relevant to state invocation and the corresponding code (in fact function calls as NetLogo tasks) of each state. Examples include *active-states* turtle variable that holds the active X-Machine state.

Probably the most interesting features of the DSL are encoding the set of functions Φ , output Γ , states Q and the transition diagram F . These are described in the sections that follow.

4.2 Encoding Agent Actions

Functions of the set Φ (referred as X-Function) are encoded as NetLogo reporters (NetLogo jargon for functions), that return results in a specific format, the latter being handled by the TXStates meta-interpreter. There are no arguments to these reporters since by X-Machine definition, functions operate on input and memory and produce output and memory updates and thus all these functions are assumed to work on the memory structures described in the previous section.

Since X-functions are *partial functions*, they must return (report in NetLogo terms) either output and memory updates, prefixed by a special *success token* or a special *failure token*. These special tokens are employed by the TXStates meta-interpreter to determine possible transitions. Thus, each such NetLogo reporter should return either:

- `x-false`, a keyword handled by the meta-interpreter, indicating that the function is not applicable (*failure token*),
- `x-true <xmOutput> <xmMemUpdates>`, indicating that the function is applicable *success token* and will produce `<xmOutput>` output and change memory according to the `<xmMemUpdates>`.

The `<xmOutput>` corresponds to the X-Machine output Γ and in the simulation context represents the list of actions that the agent has to perform. These actions are specified as NetLogo tasks, annotated by the keyword `x-action`, that get to be executed if the function is selected by the interpreter for a state transition. Delimiters `#<` and `>#` mark the start and the end of the list of actions. Thus `<xmOutput>` has the form:

```
#< x-action task [...]
  x-action task [...] >#
```

The second “argument” `<xmMemUpdates>` is a list of memory updates, i.e. invocations of `x-mem-set` commands described in 2, again delimited by `#<` and `>#`. Thus, `<xmMemUpdates>` has the following form:

```
#< x-mem-set ...
  x-mem-set ... >#
```

Empty `<xmOutput>` and `<xmMemUpdates>` are denoted as `#< >#`. It should be mentioned that the above are *lists*, and not sets, i.e. the changes described either as environment effects or memory updates will be performed in the order they appear.

There are no limitations regarding the code that a X-function can include, as long (a) it returns results of the type indicated above (b) does not include side-effects, i.e. changes in the simulation environment and agent state, apart from those explicitly encoded as return values of an `x-true` function result. Since the meta-interpreter evaluates all functions, producing possible memory and output results and then decides which function to apply, the presence of side-effects outside return values of the function would produce unexpected behaviour. Allowing arbitrary NetLogo code in an X-function contributes towards the tight integration to the TXStates DSL to the underlying platform.

A X-function encoded as a NetLogo reporter is given in Figure 3. The function checks whether the agent has certain percepts, executes the NetLogo procedure `bee-move` and updates the memory variable “position” to reflect the change in the “beliefs” of the agent that it has moved. The condition that appears in the `ifelse` is known as a “guard” and defines the domain of the partial function.

4.3 State and Transition Diagram Specification

Probably the most important aspect of the TXStates DSL is the ease by which states Q and the transition diagram F are encoded, since the latter allows directly encoding X-Machines in NetLogo.

A single transition labelled by an X-function is represented as:

```
# x-func <XMFunc> goto <StateName>
```

where `<XMFunc>` is a NetLogo X-Function as described in 4.2 and `<StateName>` is the name of a state, i.e. a simple string. An SXM that consists of multiple states each state being a set of transitions and can be defined as follows:

```
x-diagram
state <StateNameA>
# x-func <XMFunc A1> goto <StateName A1>
...
# x-func <XMFunc An> goto <StateName An>
end-state

state <StateNameK>
# x-func <XMFunc K1> goto <StateName K1>
...
# x-func <XMFunc Kn> goto <StateName Kn>
end-state
end-x-diagram
```

In such a specification, the first state that appears in the definition of the `x-diagram` is considered to be the *initial state* q_0 .

In order to relate an X-Machine definition to a specific breed of turtles to the execution environment, the list of state definitions given above, is placed inside a NetLogo reporter the name of which is formed by appending the string “state-def-of-” to the breed name of the turtles. For instance, if the breed is called “bees” the X-Machine controlling the behaviour of persons will be given by a reporter named “state-def-of-bees”.

4.4 Executing the Agent Specification

Executing the agent specifications presented in the previous section is the responsibility of the TXStates *meta-interpreter*. The latter is invoked by calling the `execute-state-machines` command, usually in each simulation cycle. Before invocation, the user must ensure that the agent percepts been updated, through appropriate calls of the corresponding primitives in Figure 2.

The *meta-interpreter* is responsible for handling state transitions and action execution and implements the computation described in Definition 2, with each invocation of the `execute-state-machines` command corresponding to a single *computation step* of Definition 2. Thus at each cycle, the meta-interpreter:

1. Forms the list of functions Φ_{state} , that label transitions in the current SXM state q , i.e. $\Phi_{state} = \phi \in \Phi : (q, \phi, q'') \in F$, in the order they appear in the agent specification.

```

to-report moveTowardsAttackFormation
  ifelse
    x-percept-value "hornet" and x-mem-value "alert" = "hiveInDanger" and
    patch-distance x-percept-value "hornetPos" x-mem-value "position"
      > patch-distance x-percept-value "hornetPos" x-percept-value "closerToHornet"
    [report x-true
     #< x-action task [bee-move x-percept-value "closerToHornet"] >#
     #< x-mem-set "position" x-percept-value "closerToHornet"
     ># ]
    [report x-false]
  end
end

```

Figure 3: Example of a X-Function demonstrating use of TXStates Primitives.

2. Form the list Φ_{trig} that contains all functions from Φ_{state} whose guards are satisfied. In the case that the trigger list is empty, execution ends with an error message.
3. Select the *first* function ϕ_i from the list Φ_{trig} .
4. Execute actions specified by ϕ_i .
5. Apply memory updates specified by ϕ_i .
6. Perform a transition to state q' that corresponds to function $(q, \phi_i, q') \in F$.

In order to simplify the encoding of guards an ordering is imposed to the function application; currently the selection function chooses the *first function* in the state definition that triggers in step 3. This imposes a *priority ordering* on the transitions in a state, with the transitions that appear higher in the state definition having a larger priority. Imposing a priority ordering ensures that the model is always deterministic, i.e. it is always clear which state transition will occur, an issue that is very important when dealing with simulation environments, since it maintains reproducibility. In the *corresponding* JSXM model, the same behaviour is achieved by having a richer set of guards in the functions.

The TXStates DSL¹ is provided as a NetLogo library that users can include in their models and specify behaviour. The major advantage of using TXStates is that developers can develop models in an iterative fashion, modifying the X-Machine model quite easily and viewing directly the results of their changes. Thus, complex model development can be greatly facilitated.

5 CASE STUDY: MODELLING THE JAPANESE BEE

The working example we selected in the present work concerns the behaviour of Japanese bees under the presence of a giant Asian Hornet scout in the

hive (Ono et al., 1995). The phenomenon is an excellent example of collective behaviour under attack in insects, since bees form the so called “bee ball” around the scout hornet, and by doing so increase the temperature inside the ball to a level non tolerable by the hornet, but tolerable by the bee itself.

We have implemented a simulation using SXMs that mimic the behaviour of both the hornet and the bees during this phenomenon. Rather informally, bees that do not perceive any danger, are in a non-alert state, i.e. they keep working as usual. Upon perception of a hornet in the hive, bees start moving towards the hornet in order to form the attack assemblage. However, since the perception radius of bees is limited and in order to engage as large a population as possible, bees become aware (“inAlert”) when perceiving another bee approaching the hornet, or another bee alerted. Bees in alert that do not directly perceive the hornet try to follow an approaching bee or move randomly. While approaching, the bee has to detect when it reached the attack formation: this case occurs either when it is close to the bee, or when there is a bee in its adjacent patches (neighbourhood) is an attacking bee. Upon reaching the attack formation, the bee starts the attack, i.e. produces heat if the environment temperature is below 49 °C, and does nothing otherwise. Obviously, since the hornet moves and possibly kills other bees, bees attacking have to understand whether the hornet has been relocated, in order to adjust their position.

Modelling such a phenomenon in an agent based simulation is rather straightforward, having bees and the scout hornet modelled as a single agent. The model has been studied before in (Kefalas et al., 2009) and we closely follow the approach authors have taken in that paper, although providing a different implementation and a modified state diagram.

The behaviour of the bee is modelled as a set of states, as for example *workInHive*, *inAlert*, *attacking*, etc. reflecting the state of the bee under the presence of a hornet in the hive, or other bees in alert. The state transition diagram is shown in Figure 4. This diagram was encoded in the TXStates DSL quite naturally as

¹<http://users.uom.gr/~iliass/projects/TXStates/>

expected. Due to space limitations, part of this encoding is shown below.

```
to-report state-def-of-bees
report
x-diagram
state "workInHive"
# x-func "attackedByHornet" goto "killed"
# x-func "seeHornet"
    goto "approachingHornet"
# x-func "perceiveDanger" goto "inAlert"
# x-func "keepWorking" goto "workInHive"
end-state
... (more states)
state "killed"
# x-func "beeDying" goto "killed"
end-state
end-diagram
end
```

As shown in the diagram of Figure 4, state transitions are labelled by functions. For instance the function in Figure 3 implemented in TXStates labels the self transition of the state “approachingHornet”. Input reflects information the agent perceives from the environment. For example when the agent perceives a hornet, the tuple (*hornet, true*) is member of the input of the agent and this becomes true when the hornet is positioned inside the radius of perception of the bee.

The NetLogo implementation of the Bee model using TXStates is approximately 290 lines of code including the state diagram and the SXM functions, while the code for the hornet and the set up of the environment is approximately 170 lines.

6 CASE STUDY: GENERATING THE TEST CASES

JSXM (Dranidis et al., 2012) is a tool, developed in Java, that allows the specification of SXM models, their animation and most importantly automated test case generation. The test cases that are generated by JSXM are in XML format and they are independent of the technology or programming language of the implementation.

In the following sections we briefly describe the JSXM modelling language and the associated tool suite.²

6.1 The Model in JSXM

The JSXM modelling language is an XML-based language with Java in-line code. The states and the tran-

²The tool can be downloaded from <http://www.jsxm.org>

sitions are described in XML. An extract of the JSXM code for representing the state transition diagram of Figure 4 is provided below:

```
<states>
  <state name="workInHive" />
  <state name="inAlert" />
  <state name="approachingHornet" />
  <state name="attacking" />
  <state name="killed" />
</states>

<initialState state="workInHive" />
<transitions>
  <transition from="workInHive"
    function="attackedByHornet"
    to="killed" />
  <transition from="workInHive"
    function="seeHornet"
    to="approachingHornet" />
  ...
</transitions>
```

The input and the output symbols are also described in XML code.

```
<input name="percept">
  <arg name="temperature" type="xs:byte"/>
  <arg name="freePosX" type="xs:byte"/>
  <arg name="freePosY" type="xs:byte"/>
  <arg name="deadHornet" type="xs:boolean"/>
  <arg name="hornet" type="xs:boolean"/>
  <arg name="hornetPosX" type="xs:byte"/>
  <arg name="hornetPosY" type="xs:byte"/>
  <arg name="closerToHornetX" type="xs:byte"/>
  <arg name="closerToHornetY" type="xs:byte"/>
  ...
  <arg name="lethalBite" type="xs:boolean"/>
</input>
```

The memory and the body of the processing functions are written in in-line Java code. This allows the definition of any complex Java data structure as the memory of the system.

```
<memory>
  <declaration>
    byte positionX;
    byte positionY;
    byte hornet_posX;
    byte hornet_posY;
  </declaration>
  <initial >
    positionX = 0;
    positionY = 0;
    hornet_posX = -1;
    hornet_posY = -1;
  </initial>
</memory>
```

Processing functions are specified by defining their inputs, outputs, preconditions (specifying the domain of the function) and effects on the memory. Due to space limitations only one processing function is shown.

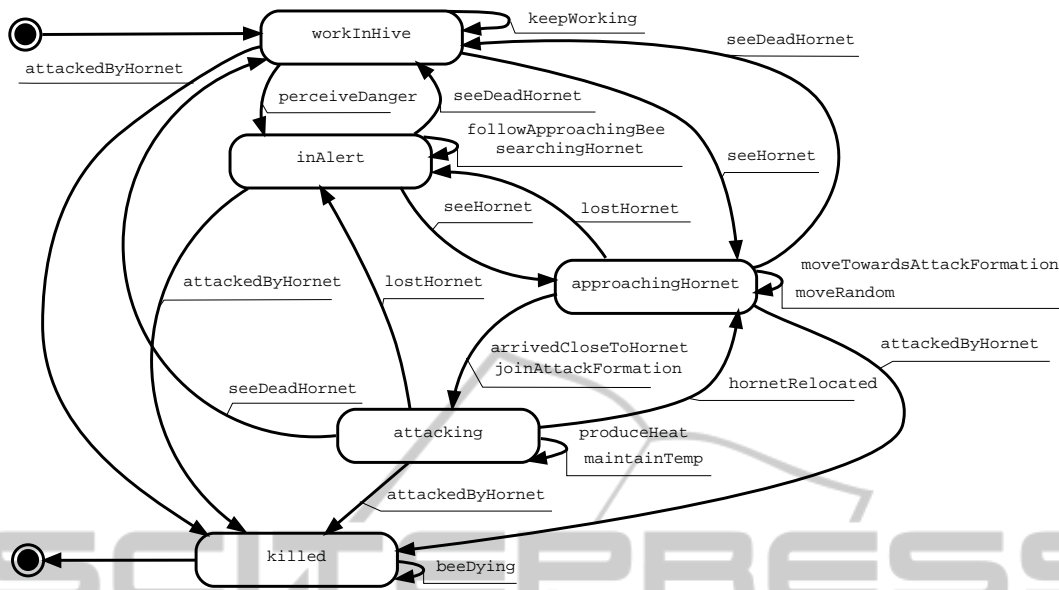


Figure 4: The state diagram representing the Japanese bee. Labels in transitions represent X-functions that based on percepts and memory are triggered to alter the environment and the agent’s internal memory.

```

<function name="seeHornet" input="percept"
  output="action" xsi:type="OutputFunction">
  <precondition>
    !percept.get_lethalBite()
    && percept.get_hornet()
    && !percept.get_deadHornet()
    && abs(positionX-percept.get_hornetPosX())
    +abs(positionY-percept.get_hornetPosY())<10
  </precondition>
  <effect>
    hornet_posX = percept.get_hornetPosX();
    hornet_posY = percept.get_hornetPosY();
    action.msg = "saw_Hornet";
  </effect>
</function>
    
```

6.2 Test Generation

The JSXM tool implements the SXM testing method (extended W -method) for the generation of the test set. For the test generation process the modeller needs to provide:

- a JSXM specification of the SXM model Z .
- an r -state cover S_r and a separating set W_s
- the estimated difference k of states between the SUT and the specification.

The r -state cover for the specific case study consists of the following sequences of processing functions: $\langle \rangle$, $\langle attackedByHornet \rangle$, $\langle perceiveDanger \rangle$, $\langle seeHornet \rangle$, $\langle seeHornet, arrivedCloseToHornet \rangle$. All states of the state diagram are reached by these sequences.

The separating set W_s consists of the following sequences: $\langle attackedByHornet \rangle$, $\langle beeDying \rangle$, $\langle keepWorking \rangle$, $\langle seeDeadHornet \rangle$, $\langle lostHornet \rangle$, $\langle searchingHornet \rangle$, $\langle followApproachingBee \rangle$, $\langle moveTowardsAttackFormation \rangle$, $\langle hornetRelocated \rangle$, $\langle produceHeat \rangle$, $\langle maintainTemp \rangle$. At each reached state the execution of these processing functions produces outputs that uniquely separate the reached state by all the other states.

It should be noted that the r -state cover is computed automatically by the JSXM tool. However, automatically computing the separating set W_s is still an open research issue.

For the input-output test cases to be produced, all the input sequences are fed to the JSXM animator, which acts as an oracle, and the resulting output sequences are recorded. The resulting test cases (pairs of input and output sequences) are stored in a XML file in a programming language independent format. For the specific case study the JSXM tool has generated 62 test cases for $k = 0$.

6.3 From Test Cases to Simulation Scenarios

The test cases produced by the JSXM tool, are then processed in order to produce the simulation scenarios used for validation. Since the input to each JSXM function actually describes the state of the environment, appropriate NetLogo code was developed to set up the exact state of the environment described. For instance in the case of the test generated by JSXM

```

<call>
<function name="seeHornet" />
  <input name="percept">
    <temperature type="xs:byte">30
    </temperature>
    <freePosX type="xs:byte"> 0
    </freePosX>
    <freePosY type="xs:byte"> 1
    </freePosY>
    <deadHornet type="xs:boolean">>false
    </deadHornet>
    <hornetPosX type="xs:byte"> 0
    </hornetPosX>
    <hornetPosY type="xs:byte"> -9
    </hornetPosY>
    ...
    <lethalBite type="xs:boolean"> false
    </lethalBite>
    <beeInAlert type="xs:boolean"> false
    </beeInAlert>
  </input>
  <output name="action">
    <msg type="xs:string">saw_Hornet</msg>
  </output>
</call>

```

Figure 5: Part of a test sequence generated by the JSXM tool. In the specific setting, the bee is expected to follow the transition guarded by the “seeHornet” function and output that it perceived a hornet.

shown in Figure 5, execution of the code places the bee in position (0,0), sets the temperature to 30, and places a live hornet at positions (0,-9). Then the agent TXStates implementation is executed and the resulting actions are matched against the output of the test case, while visually providing feedback to the modeller involving the state change of the bee. Thus the modeller can validate that this is the expected behaviour of the bee in the specific scenario.

7 RELATED WORK

From the various Multi-Agent Systems (MAS) design methodologies that exist, relatively few deal explicitly with simulation design, and among these even fewer are applicable for producing NetLogo code. The Behavior Oriented Design (BOD) (Bryson, 2003) and the Interaction-Oriented Design of Agent simulations (IODA) (Kubera et al., 2011) are examples of such methodologies that are also currently supported by corresponding NetLogo tools. Going into the specifics of both these methodologies exceeds the scope of this section work, however, they both lack support for any automated test generation process.

A number of DSL and DMSL approaches to programming MAS have been reported in the literature.

For instance in (Hahn, 2008) and (Challenger et al., 2014) present approaches to domain specific modelling languages (DSML), for developing multi agent systems. These approaches differ from TXStates since they focus on describing MAS models using high level concepts such as agent roles, interactions, etc. and provide and model transformations to code. The present work addresses mainly and problem of modelling and validating a single agent in a MAS simulation setting, and provide what could be considered as unit testing/validation of that agent model. To the best of our knowledge, these modelling frameworks do not address this problem.

A number of diverse approaches for testing agent based systems are found in the literature. As mentioned, our focus lies mainly on two aspects. On one hand, whilst testing the communication and coordination in a society of agents is of interest when developing MAS, testing a single agent against its specification is of paramount importance. Under this scope, a number of unit testing frameworks have been proposed. However, there is a variety of views as to what constitutes a unit to be tested. On the other hand, tools that offer automated test generation and execution capabilities are limited.

Caire et al. (Caire et al., 2004) presented a testing framework that offers a skeleton code for the developer to build test cases, considering as a testable unit either a single agent or any of its internal behaviours as a black box. The framework was developed as part of the PASSI (Cossentino and Potts, 2002) development methodology. An agent system’s behaviour was initially captured in a Multi-Agent Zoomable Behaviour Description diagram - introduced by the authors - which is in essence an Activity Diagram extended with Agent UML notations. The tool also provides a test agent for automatic test case execution.

SUnit (Tiryaki et al., 2007) is a framework that is built on top of the Seagent (Dikenelli et al., 2005) MAS development platform. The tool allows for testing of agent interactions and plans, which are considered as the units to be tested. SUnit extends the JUnit³ testing framework, and was developed with the purpose of facilitating test driven development of MAS. SUnit provides a mock agent infrastructure, which the developer uses to automatically run the manually written tests.

Coelho et al. (Coelho et al., 2006) suggest that the modular unit in a MAS is a single agent, and thus, propose the notion of a Mock Agent that is built specifically for testing the agent under test. Therefore, each Mock Agent is a manual fake implementation of an actual agent that interacts with the agent (role) under

³<http://junit.org/>

test. Coelho et al. in (Coelho et al., 2007) later proposed JAT (Jade Agent Testing Framework), a test automation framework built on top of the JADE⁴ MAS development platform, and is aimed to facilitate the developer in creating the Mock Agent code and automatically executing the test scenarios.

The above work focuses on automating the execution rather than the generation of test cases. The latter capability is provided in the work of Zhang et al. (Zhang et al., 2007) who proposed a model-based testing framework that allows for automatic test generation and execution. The framework uses the design artefacts produced with the Prometheus (Padgham and Winikoff, 2005) agent development methodology. The framework was integrated (Zhang et al., 2008) in the Prometheus Design Tool (PDT)⁵. In this case, an agent consists of events, plans and belief-sets, and each of these were considered as a unit to be tested by the authors, in contrast to our work that tests the dynamic internal behaviour of a single agent as a whole rather than its individual components.

A different approach on model based test generation was provided by Seo et al. (Seo et al., 2004) and Zheng and Alagar (Zheng and Alagar, 2005). The former used Statecharts extended with roles descriptions, event types and memory to model a MAS. Based on the diagram, all possible transitions to all concrete events were manually calculated, and then fed to a tool developed by Seo et al. that generated the test sequences. The latter used Extended State Machines (ESM) to formally model an agent and then used this model to generate a set of unit test cases. Each test set consisted of a set of state cover sequences and a set of transition cover sequences. However, in both these cases, no further discussion exists on automating the test execution process. More importantly, in our case, the SXM testing theory provides for more coverage than state and transition coverage, additionally allowing for proof of functional equivalence of the models.

Automated test case generation and execution are useful in supporting model verification to some significant extent. Visualization on the other hand is considered as one of the most predominant validation techniques for simulations. A validation framework proposed by (Klügl, 2008) identifies animation assessment as one of the basic methodological elements. To further support a preliminary model validation, Xiang et al. (Xiang et al., 2005) applied a model-to-model comparison technique. They initially built a conceptual model of the Natural Organic Matter (NOM) evolution, and then implemented a corre-

sponding simulation. By using various verification methods and by visualizing 450 simulation runs of their model with different random seeds, they validated their model against the conceptual one. They subsequently compared their results with another existing implementation of the same conceptual model. The authors argue that the good agreement between the results of these two different implementation supports the validity of their implementation. In our case, the generated test cases facilitate the validation via visualization process, by providing the developer with an easy way of selecting specific test scenarios of interest.

8 CONCLUSIONS

This work presents a systematic approach to the problem of developing, testing and validating agent simulations. Towards this direction, the current work:

- describes a DSL that can be used to specify and execute an SXM model, that encodes the behaviour of an agent in the simulation, and
- shows how an existing tool for automated test case generation that employs the same formal modelling approach, can be used for generating a set of “simulation scenarios”.

Thus this paper demonstrates how the SXM formal modelling technique is employed in a practical setting to develop simulations.

One of our immediate aims is to provide a way to semi-automatically translate large parts of the TXStates model to the JSXM modelling language. Additionally, a tool for semi-automatically testing equivalence of the two models, since in the current state manually crafted code had to be written that processes the output files of JSXM and perform the equivalence test with the TXStates agents.

Furthermore, it is our intention to extend this approach to other agents simulation and agent programming platforms. One future direction is to investigate whether BDI agents can be modelled as SXMs and apply the specific testing approach to such systems.

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⁴<http://jade.tilab.com/>

⁵<http://www.cs.rmit.edu.au/agents/pdt/>

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