# Formal Verification of a Map Merging Protocol in the Multi-Agent Programming Contest\*

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#### Abstract

Communication is a critical part of enabling multi-agent systems to cooperate. This means that applying formal methods to protocols governing communication within multi-agent systems provides useful confidence in its reliability. In this paper, we describe the formal verification of a complex communication protocol that coordinates agents merging maps of their environment. The protocol was used by the LFC team in the 2019 edition of the Multi-Agent Programming Contest (MAPC). Our specification of the protocol is written in Communicating Sequential Processes (CSP), which is a well-suited approach to specifying agent communication protocols due to its focus on concurrent communicating systems. We validate the specification's behaviour using scenarios where the correct behaviour is known, and verify that eventually all the maps have merged.

# 1 Introduction

The Multi-Agent Programming Contest<sup>1</sup> (MAPC) is an annual challenge to foster the development and research in multi-agent programming. Every couple of years a new challenge scenario is proposed, otherwise, some additions and extensions are made to make the scenario from the previous year more challenging.

The 2019 edition of MAPC [1] introduced the Agents Assemble scenario, where two teams of multiple agents compete to assemble complex block structures. Agents have incomplete information about their grid map environment. They are only able to perceive what is inside their limited range of vision. Therefore, building a map of the team's environment must be done individually at the start; each agent believes its starting position is (0,0), and the agents merge their maps when they meet, adjusting the coordinates accordingly.

This paper describes the formal specification and verification of the map merge protocol that was used by the winning team from MAPC 2019, the Liverpool Formidable Constructors (LFC) [8]. One of the major challenges in the MAPC is making sure all critical parts of the team work reliably. Without a coherent map, the agents cannot coordinate to assemble the block structures, so the map merge protocol is critical to the team's mission. The complexity of the different challenges in the scenario, as well as the presence of another interfering team, can cause unforeseen problems. Before MAPC 2019 the LFC team had limited time to perform tests to validate the code, which due to its complexity meant that it was very hard to efficiently prevent or detect bugs.

In this paper we build a formal specification of the map merge protocol from its implementation and previous description in [8], and formally verify the specification to provide evidence of the protocol's reliability. Our specification is written in the process algebra Communicating Sequential Processes (CSP) [16], which is designed for specifying concurrent communicating systems. We view each agent

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<sup>&</sup>lt;sup>1</sup>https://multiagentcontest.org/.

in the system as a process, which is communicating with the other agents (processes) to achieve the system's overall behaviour.

To verify properties about our specification we use model checking, which can automatically and exhaustive check the state space for a formal model for satisfaction of a given property. If a property is violated, a model checker usually gives a counterexample, which can aid debugging. In CSP, model checking uses the idea of refinement. If we have two specifications P and Q, then P is refined by Q ( $P \subseteq Q$ ) if every behaviour of Q is also a behaviour of P. This can be thought of as Q implementing P, like a software component implementing an interface. We use the CSP model checker Failures-Divergences Refinement (FDR) [14] to show that the system behaves according to some required properties. This can be thought of as checking that the system correctly implements an interface.

The work presented in this paper is motivated in two directions. First, the verification provides extra confidence that the protocol works. The protocol was difficult to test because of the dynamic environment and the amount of agent communication, but model checking is a useful approach to finding corner cases. Second, the MAPC provides an interesting example application to explore the utility of CSP for modelling this kind of problem. This is of lesser importance than the first motivation, but useful nonetheless.

The rest of this paper is organised as follows. A brief background on JaCaMo (the language the agent system is developed in) and CSP is presented in the next section, Sect. 2. Section 3 describes how we used CSP to specify and verify the map merge protocol used by the LFC team in the MAPC 2019. It contains a detailed description of how the protocol works (Sect. 3.1), the CSP specification of the protocol (Sect. 3.2), and how the specification was validated and verified (Sect. 3.3). The related work is discussed in Sect. 4, with a variety of similar approaches that have been applied to the specification and verification of multi-agent systems. Finally, Sect. 5 presents our concluding remarks.

# 2 Background

The LFC team uses the JaCaMo multi-agent programming platform to develop their agents for the MAPC 2019. In this section we briefly explain JaCaMo and highlight the relevant parts that were used in the map merging protocol (Sect. 2.1). We also give an overview of CSP and the notation used throughout the paper, and introduce model checking (Sect. 2.2).

#### 2.1 JaCaMo

JaCaMo<sup>2</sup> [4,5] is a multi-agent development platform that combines three dimensions that are often found in agent systems (agent, environment, and organisation), and provides first-class abstractions that enable a developer to program these dimensions in unison. JaCaMo is a combination of three different technologies that were developed separately and then linked together: the Jason [6] Belief-Desire-Intention (BDI) [25] agent programming language for the agent dimension, CArtAgO [26] for programming environments using artefacts, and Moise [19] for the specification of organisation of agents. An additional first-class abstraction has been developed that provides an interaction dimension for JaCaMo in [32], but this is not yet fully integrated.

The merge protocol as implemented by LFC [8] is comprised of message passing between agents and updating information. The agent communication is implemented solely in Jason, while some of the information updates are done in a shared artefact (called the *TeamArtifact*). In this paper we focus on the communication, which is the critical part of the protocol.

In Jason, communication between agents is based on speech-act theory, where agents send a performative such as *tell* (sends a belief to an agent, causing a belief addition event) or *achieve* (sends a goal to an agent, causing a goal addition event). The formal semantics of speech-act theory for Jason can be found in [29].

#### 2.2 CSP

CSP is a formal language for specifying the behaviour of concurrent communicating systems. We use the FDR [14] model checker to both manually and automatically check specifications. Manual checks

<sup>&</sup>lt;sup>2</sup>http://jacamo.sourceforge.net/.

Action	Syntax	Description		
Skip	Skip	The terminating process		
Simple Prefix	$a \rightarrow Skip$	Simple synchronisation on $a$ with no data, followed by $Skip$		
Input Event	a?in	Synchronisation that binds a the input value to $in$		
Output Event	b!out	Synchronisation outputting the value of out		
Parameter Event	c.value	Synchronisation matching the given value		
Sequence	P ; Q	Executes processes $P$ then $Q$ in sequence		
External Choice	$P \square Q$	Offers a choice between two processes $P$ and $Q$		
Replicated External Choice	$\square x : Set \bullet P(x)$	Offers an external choice of the process $P(x)$ with every value $x$ in the set $Set$		
Parallelism	$P \mid [chan] \mid Q$	P and $Q$ run in parallel, synchronising on the channels in $chan$		
Parallelism	$P \mid [pChan \mid qChan]  Q$	P and $Q$ run in parallel, synchronising on the channels common to the sets $pChan$ and $qChan$		
Interleaving	$P \mid \mid \mid Q$	P and $Q$ run in parallel with no synchronisation		
Replicated Interleaving	$    x : Set \bullet P(x)$	Interleaves a copy of the process $P(x)$ for every value $x$ in the set $Set$		

Table 1: Summary of CSP operators used in this paper

use FDR's Probe tool, which enables a user to step through the system's behaviour. Automatic checks are written as assertions.

A CSP specification is built from (optionally parameterised) processes. A process describes behaviour as a sequence of *events*; for example,  $a \to b \to Skip$  is the process where the events a and b happen sequentially, followed by Skip which is the terminating process. An event<sup>3</sup> is a communication on a *channel*. Channels enable message-passing between processes, but a process can perform an event (communicate the event on the channel) even if there is no other process to receive the event. Where two processes agree to perform a set of events in parallel (*synchronise* on a set of events) both processes must perform the event(s) synchronously.

By convention CSP process names are written in upper-case, and channels or events in lower-case. A CSP process is often composed of several 'subprocesses', which is the term we use to refer to other processes called by a process. Here, a subprocess helps to structure the specification and encapsulate behaviour, similarly to an object and its methods. We adopt the convention of using a double underscore to separate a process name from the 'main' process to which it belongs (e.g., MAIN\_PROCESS\_SUBPROCESS). Below, we describe the CSP operators used in this paper, which are also summarised in Table 1.

Channels may declare typed parameters. If a channel is untyped, then we get 'simple' events like a and b from the above example; the events of a typed channel must contain parameters matching those types. For example, if channel c takes one integer parameter, then an event might be c.42. Parameters may be inputs (c?in), outputs (c!out), or match a given value (c.value). Inputs can be restricted (c?p:set) to only accept a parameter (p) that is the given set (here, a set of integers). Processes can occur in sequence; for example, P; Q describes a process where process P runs, then process Q.

A choice of processes can be offered; for example  $P \square Q$  offers the choice of either P or Q, once one process is picked the other becomes unavailable. Processes can also run in parallel. CSP provides three parallel operators; in  $P \mid [chan] \mid Q$ , processes P and Q run in parallel, and agree to communicate on the channels in the set chan; in  $P \mid [pChan \mid qChan] \mid Q$ , processes P and Q run in parallel, and

 $<sup>^3</sup>$ Note that events in CSP are different from Jason BDI events, the former are communication events while the latter are plan triggering events.

agree to communicate on the channels common to the *pChan* and *qChan* sets; and in  $P \parallel \parallel Q$ , the processes P and Q run at the same time with no synchronisation.

CSP does not have variables, so if a specification needs a variable that will be accessed by several processes, a 'state process' is often used. This is where a process is used to store, and control access to, some values. The values are stored as process parameters and channels are provided to get and set the values. Other processes communicate with the state process using these get and set channels. While this requires more channels and internal communication, it can lead to cleaner communication between the processes that need to use the variable(s).

# 3 Specification and Verification of the Map Merge Protocol

The map merge protocol played a major role in LFC's victory<sup>4</sup> [8] in MAPC 2019. It overcomes one of the main challenges that has to be solved before trying to assemble structures and deliver tasks. Even though LFC won, there were many failures during the matches due to limited testing and no formal verification prior to the contest. Although the origin of most of the failures is still unknown, we aim to provide confidence about the reliability of the map merge protocol.

In this paper we specify and verify the map merge protocol as used by LFC [8]. Section 3.1 describes the protocol, in particular the communication between the agents. Then, Sect. 3.2 presents our CSP specification of the protocol and describes how it models two agents merging their maps. Finally, Sect. 3.3 discusses the validation and verification of the specification using the FDR model checker.

### 3.1 Map Merge Protocol

The communication in the map merge protocol consists of message passing between a group of agents, triggering plans that reason about the message received and send the required reply if applicable. Figure 1 shows an overview of the protocol. At the start of the simulation, every agent has its own map (referred to as being the *leader* of its own map, or being a *map leader*). As the simulation progresses, agents meet each other and merge their maps. Each map leader coordinates a map for itself and any other agents whose maps it has merged with. This means that there can be a minimum of two and a maximum of four agents directly involved in one instance of the merge protocol. For example, only two agents will be involved if both agents are the leaders of their own map.

Each agent has a name, or ID; in Fig. 1 we use A1 and A2. Because of the (intentionally challenging) communications restrictions of the MAPC, when agents meet they do not know each other's ID, so they cannot directly communicate. Therefore, before agents can exchange useful information about their maps, some kind of *identification* process is needed. In LFC's strategy for identification, when one agent sees another it sends a broadcast to all the agents in its team requesting information about what they can see around them. Upon receipt of all of the replies, the agent that sent the request will compare the replies to what it can see, to try to identify the agents that it has met. The specifics of LFC's identification strategy can be found in [8].

The merge protocol starts as part of the identification strategy, after one agent successfully identifies another. The identification process is reflexive but asynchronous. For example, if A1 identifies A2, then A2 will (eventually) identify A1; but they each perform the identification process separately, so they might not both identify each other at the same time. In this example each agent will then start its own merge process, but as we will see later on only one merge will go through. In Fig. 1 the protocol is seen from A1's perspective, but it works exactly the same for all agents.

Once the map merge protocol starts, the agent that is requesting the merge (the requesting agent) sends a message to its map leader (now, the requesting map leader) containing a list of agents that it wants to merge with, that is, all agents that it has successfully identified. Requests are dealt with one at a time, so each request constitutes a new instantiation of the protocol. As previously mentioned, messages in Jason trigger events which will enable plans that match the triggering event to be viable for selection<sup>5</sup>. The requesting agent's map leader will start the plan that handles the request to merge, when it receives the request\_merge message; if the requesting agent is its own map leader it will simply trigger the appropriate plan internally.

<sup>&</sup>lt;sup>4</sup>Source code of the team is available at (the main plans for the map merge protocol are located in "src/agt/strategy/identification.asl"): https://github.com/autonomy-and-verification-uol/mapc2019-liv.

<sup>&</sup>lt;sup>5</sup>A plan still has to succeed its context check (i.e., meet its preconditions) before being selected for execution.

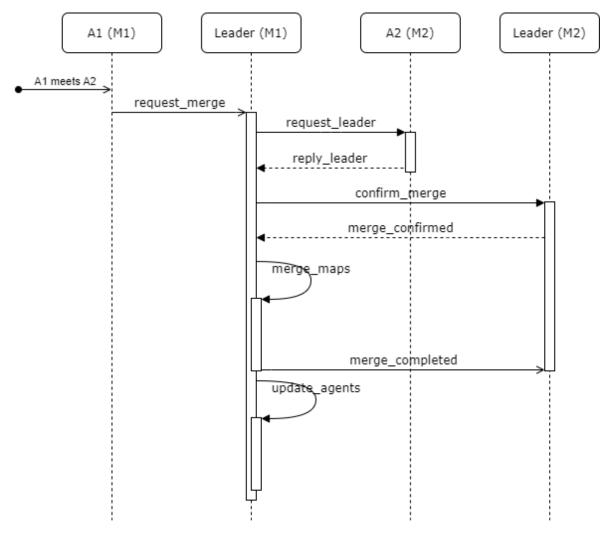


Figure 1: UML Sequence diagram for the map merge protocol. A1 represents Agent1 with a map M1, A2 is Agent2 with a map M2. The solid arrow heads represent synchronous messages, open arrow heads asynchronous messages, dashed lines represent reply messages, and rectangles represent processes [8].

To proceed with the merge the requesting map leader must get the name of the *other* agent's map leader (for example, in Fig. 1 agent A1 wants to merge maps with A2). After receiving the name of the other map leader, the requesting map leader will use a priority order among both map leaders to determine if the merge will continue. This is necessary because the other agent may also have started the map merge process, however, only one of these merges can proceed. The priority is determined using the number in the agent's name, the agent with the lowest number has priority. For example agent A1 has priority over A2.

After the priority check, if the merge is continuing then the requesting map leader sends a message to the other map leader asking it to confirm the merge. This is necessary because it is possible that the other map leader is already in the middle of a merge, which could result in it losing its position as a map leader. If this happens and the original merge continues, then the map information from this merge will be wrong. Thus, if the other map leader is no longer the leader of that map it will send a reply cancelling the merge. Another attempt to merge these two maps can be made in the next step.

The plans for both leaders are atomic, so concurrent intentions are not in effect (normally in Jason agents alternate between their intentions). This means that leaders are not able to start multiple merge processes simultaneously, nor can they enter a deadlock waiting for information indefinitely (we assume that eventually all agents reply).

If the merge is confirmed, then the map information (such as the coordinates of points of interest in the MAPC scenario) is updated. Finally, a message is sent to the other map leader letting it know

that the merge has been completed, and thus releasing the lock from the atomic plan that it was in. A final update is made to the list of agents that are part of the new merged map, which is sent to each agent in the list.

In summary, the main goal and requirements of the map merge protocol are:

GOAL: If agent A1 merges its map with agent A2, A1's map leader will be the map leader for A1, A2, and any agents that either of them shared their map with before the merge.

REQ1: The map leader of A1 has priority over the map leader of A2, otherwise A1 should cancel the merge.

REQ2: If A2's map leader loses control of its map by the time it processes the request to merge from A1's map leader, it will cancel the merge.

In the next section we describe how we model the map merge protocol, while Sect. 3.3 describes how we verify that the protocol preserves these properties.

### 3.2 CSP Specification

Our CSP specification was built by one person, part-time over the course of about 12 months. The specification was built by manually interpreting and translating the English-language description of the protocol [8] and the Jason implementation. The specification is  $\sim$ 440 lines in total, though this includes comments. Despite the small number of lines, the specification contains 1,597,190 states and 6,334,936 transitions 7.

In the specification of the map merge protocol, each agent is modelled by an AGENT process, if the agent is a map leader then it will also be represented by a  $MAP\_LEADER$  process. As mentioned in Sect. 3.1, at the start of a match each agent is also its own map leader, so each agent will begin as a cooperating pair of AGENT and  $MAP\_LEADER$  processes. The 'main' processes, AGENT and  $MAP\_LEADER$ , are decomposed into subprocesses that structure the specification and encapsulate behaviour. We remind the reader that we use a double underscore to separate a subprocess name from the 'main' process to which it belongs. For example, the subprocess named  $MAP\_LEADER\_REQUEST\_MERGE$  is the  $REQUEST\_MERGE$  processes which belongs to the  $MAP\_LEADER$  process.

Our specification only uses three agents. This was a conscious choice to keep the specification's state space small, while still enabling us to check that a pair of agents can merge their maps in the presence of an interfering agent. We define AgentName, the set of all the agent IDs as:  $datatype\ AgentName = A1 \mid A2 \mid A3$ 

The top-level of our specification is a parallel (|[chan]|)process composition  $MAP\_LEADER$ This all the AGENTprocesses. takes the form:  $LFC = AGENTS \mid [interface] \mid MAP\_LEADERS$ 

where AGENTS is an interleaving (|||) of an AGENT process for each ID in AgentName; and  $MAP\_LEADERS$  is a parallel composition of a  $MAP\_LEADER$  process for each ID in AgentName, so the map leaders can communicate. In this top-level process, the AGENT and  $MAP\_LEADER$  processes agree to synchronise (cooperate) on any events in the set of events interface.

 $MAP\_LEADERS$  composes the  $MAP\_LEADER$  processes in a way that allows them to synchronise on some events, because they communicate to control the map merge. But AGENTS simply interleaves the AGENT processes because they do not need to communicate for the merge protocol. Other behaviours require agents to communicate, but this is abstracted away in our specification.

The IDs in AgentName (for example A1) are used to synchronise communications between a  $MAP\_LEADER$  and the AGENT processes that it coordinates, and between it and other  $MAP\_LEADER$  processes. The messages in Fig. 1 are represented in our specification by CSP channels. The processes in the specification also make use of other internal channels to describe the required behaviour.

<sup>&</sup>lt;sup>6</sup>The CSP files are available at: https://doi.org/10.5281/zenodo.4624507.

 $<sup>^7\</sup>mathrm{Reported}$  states from a check for freedom from non-determinism using FDR 4.2.7.

```
MAP\_LEADER\_REQUEST\_MERGE(Me, AgentSet) = \\ MAP\_LEADER\_HANDLE\_REQUEST\_MERGE(Me, AgentSet) \\ |[\{|beginMerge|\}]| \\ MAP\_LEADER\_BEGIN\_MERGE(Me, AgentSet)
```

Figure 2: Excerpt from  $MAP\_LEADER\_REQUEST\_MERGE$  showing the parallel composition of  $MAP\_LEADER\_HANDLE\_REQUEST\_MERGE$ , which handles requests to merge; and  $MAP\_LEADER\_BEGIN\_MERGE$ , which allows the map leader to begin a merge. The processes synchronise on the beginMerge event. Me is the ID of the  $MAP\_LEADER$  process, and AgentSet is the set of agents this map leader is coordinating.

As mentioned in Sect. 3.1, a map merge happens between two agents and their respective map leaders (note that an agent may be its own map leader). Unlike the description in Sect. 3.1, there will always be four processes involved in a map merge in our specification: two AGENT processes and two  $MAP\_LEADER$  processes. This is because we model the behaviours common to all agents separately from the behaviours specific to a map leader. As in Sect. 3.1, we refer to the agent that requests the merge and its map leader as the 'requesting agent' and the 'requesting map leader', respectively.

We use the example from Fig. 1 to describe how our model captures the scenario. We have split this into three phases:

- 1. Requesting Merge and Leader: initial communication to obtain information that will be used during the map merge and used to check the viability of the merge;
- 2. **Confirming Merge:** use the information obtained in the previous phase to determine if the merge can proceed or if it should be cancelled;
- 3. Merge and Update: perform the map merge and update all agents involved.

As in Fig. 1, agent A1 is requesting that agent A2 merges maps with it, and both agents are their own map leader. Because we do not include the maps themselves in our specification, we do not use the map IDs (M1 and M2).

#### 3.2.1 Phase 1: Requesting Merge and Leader

In the first phase of the protocol, an agent sends a request to its map leader to merge with one or more other agents, then the map leader requests the name (ID) of the mad leader of each of the agents it has been requested to merge with. When one of the other agents replies, the requesting map leader begins negotiating the map merge with the other map leader.

In our example, A1's AGENT process sends a message to its map leader (which is itself) requesting that it merges with A2. This is represented by an event on the channel  $request\_merge$ , which is sent from the AGENT(A1) process to the  $MAP\_LEADER(A1)$  process and triggers the  $MAP\_LEADER$  to start its map merging process. In the  $requesting\ MAP\_LEADER$ , this is handled by the  $MAP\_LEADER\_REQUEST\_MERGE$  process, part of which is shown in Fig. 2

The MAP\_LEADER\_\_HANDLE\_REQUEST\_MERGE process listens for request\_merge events from any agent it currently coordinates (any agent in its AgentSet). The request\_merge event contains a parameter mergeSet, which is the set of agents that the map leader should try to merge with. In our example, merge\_set only contains A2, but it can contain the IDs of any agents that are not in the AgentSet of the requesting map leader (as explained in Sect. 3.1).

When a request\_merge event is received, the beginMerge event is used to start the merge. This is an event introduced purely for our specification. The MAP\_LEADER\_BEGIN\_MERGE process sends request\_leader events to each agent in the mergeSet and waits for a reply\_leader event from one of these agents, acting on the first of these events to arrive. The reply\_leader event contains a parameter that is the ID of the agent's map leader. In our example, A2 sends the reply that its map leader is A2.

The MAP\_LEADER\_\_BEGIN\_MERGE process, triggered by A1 receiving the reply\_leader event from A2, checks if the map leader for A1 has priority over the map leader for A2. As mentioned in Sect. 3.1, the agent with the lowest ID number takes priority, so A1 has priority over A2, which has priority over A3. If the requesting map leader does not have priority, then the map merge attempt

```
MAP\_LEADER\_\_CONFIRMING\_MERGE \\ (Me, RequestingAgent, OtherAgent, OtherMapLeader, AgentSet) = \\ confirm\_merge.Me.OtherMapLeader \rightarrow \\ (\\ merge\_cancelled.Me.OtherMapLeader \rightarrow \\ remove\_reasoning\_about.RequestingAgent.OtherAgent \rightarrow Skip \\ )\\ \Box\\ (\\ merge\_confirmed.Me.OtherMapLeader?otherAgentSet \rightarrow \\ MAP\_LEADER\_\_MERGE\_MAPS \\ (Me, AgentSet, OtherMapLeader, otherAgentSet);\\ MAP\_LEADER\_\_UPDATE\_AGENTS \\ (Me, AgentSet, OtherMapLeader, otherAgentSet) \\ )\\ )
```

Figure 3: Excerpt from  $MAP\_LEADER\_CONFIRMING\_MERGE$ , which handles the requesting map leader confirming the merge with the other map leader. The parameter Me is the ID of the  $MAP\_LEADER$  process, RequestingAgent is the ID of the agent that requested the merge, OtherAgent is the agent the RequestingAgent wanted to merge with, OtherMapLeader is the ID of the other map leader (the leader of OtherAgent's map), and the AgentSet is the set of agents that this map leader is coordinating.

ends here. In our example, the map leader is the same as the requesting agent, A1, and A1 does have priority over A2 (the other map leader), so it moves on to confirming the merge with the other  $MAP\_LEADER$  process.

#### 3.2.2 Phase 2: Confirming Merge

The requesting map leader asks the other map leader to confirm that the merge can proceed. As explained in Sect. 3.1, this allows a map leader to cancel a merge request if it has completed a (concurrent) merge with a different map leader. In our example, the requesting map leader is A1 and the other map leader is A2.

The requesting  $MAP\_LEADER$  (A1) handles this phase using the process  $MAP\_LEADER\_CONFIRMING\_MERGE$  (excerpt in Fig. 3). The first event in this process,  $confirm\_merge.Me.OtherMapLeader$ , is a request from map leader A1 (here, the value of Me) to map leader A2 (here, the value of OtherMapLeader), to confirm that the merge can go ahead. As we can see from Fig. 3, the other map leader (A2) can reply with either  $merge\_cancelled$  or  $merge\_confirmed$ .

When the map leader A2 receives the  $confirm\_merge$  event, it 'considers' the eligibility of the merge. If it is no longer a map leader, it replies  $merge\_cancelled$ , and the merge process will terminate after replying to any pending  $confirm\_merge$  events. The  $merge\_confirmed$  event signals that the merge can continue. Either of these events passes control back to the requesting map leader (A1), which will: SKIP (terminate) if the reply was  $merge\_cancelled$ ; or move on with the merge and update step if the reply was  $merge\_confirmed$ .

## 3.2.3 Phase 3: Merge and Update

This phase is split into two stages: merging the maps, and updating the agents. First, the requesting map leader uses the  $MAP\_LEADER\_MERGE\_MAPS$  process, shown in Fig. 4, to merge the maps. The process is triggered by the  $merge\_confirmed$  event, as shown in Fig. 3.

```
\begin{split} MAP\_LEADER\_MERGE\_MAPS(Me, MyAgentSet, otherMap, OtherAgentSet) = \\ merge\_maps.Me.otherMap \rightarrow \\ update\_agentSet.Me!OtherAgentSet \rightarrow \\ merge\_completed.Me.otherMap.union(MyAgentSet, OtherAgentSet) \rightarrow \\ SKIP \end{split}
```

Figure 4: The  $MAP\_LEADER\_MERGE\_MAPS$ , which controls the merging of maps between two map leaders (abstracted to the  $merge\_maps$  event. Me is the ID of the  $MAP\_LEADER$  process and MyAgentSet is its agent set. Similarly, otherMap is the ID of the other  $MAP\_LEADER$  process and OtherAgentSet is its agent set.

Since the map is not captured in our specification, merging the maps is abstracted to the event  $merge\_maps$ . The requesting  $MAP\_LEADER$  updates the AgentSet (the set of agents it coordinates). It then tells the other map leader that the merge is completed, using the  $merge\_completed$  event, which also sends the union of the two agent sets.

After  $merge\_completed$ , control returns to the  $MAP\_LEADER\_CONFIRMING\_MERGE$  process (Fig. 3), which calls the  $MAP\_LEADER\_UPDATE\_AGENTS$  process to update all the agents in its new AgentSet. This involves a sequence of communications between the requesting map leader and each AGENT in the new AgentSet.

This phase closely corresponds to the description in [8], summarised as follows:

- 1. **Build new list of identified agents:** in our specification, this is simply the union of the requesting and other map leader's *AgentSets*.
- 2. Send update to the leader of M2 (A2): as shown in Fig.4, the merge\_completed.Me.otherMap.union(MyAgentSet, OtherAgentSet) event sends the new (merged) AgentSet to the other map leader.
- 3. Send update to all agents of M1 (A1): here a recursive process sends update\_identified\_same\_group to each agent in the agent set of the requesting map leader (A1). This event passes the new AgentSet to each of these agents.
- 4. Send update to all agents of M2 (A2): here a recursive process sends update\_identified to each agent in the AgentSet of the other map leader. This event passes the new agent set to each of these agents and is also used to update each agent's map leader to the requesting map leader, A1.

After the updates are completed, the requesting map leader recurses back to the  $MAP\_LEADER\_REQUEST\_MERGE$  process (Fig. 2) ready to begin another merge. If there are no more agents to merge with from this request, it waits for the next merge request. The other map leader process no longer represents an agent that is a map leader, so it will only reply  $merge\_cancelled$  if it is asked to merge. This handles requests to merge that may already be in progress.

#### 3.3 Specification Validation and Verification

After specifying the map merge protocol, we validate that it performs the protocol's required behaviour and then verify that all the maps are eventually merged. The validation step is used to check that the specification conforms with the protocol's implementation. The verification step is used to check that the specification is correct. For both of these steps, we use the assertions and in-built tools of the CSP model checker, FDR. The assertions are described in Table 2 and the time that FDR took to check the assertions is summarised in Table 3.

#### Validation

For the validation step, first we used FDR's Probe tool to manually step through the model one event at a time. This was useful when debugging the specification, especially after adding or updating behaviour. For more substantial verification, we also checked how the agents behaviour in six different scenarios (see Table 2). These scenarios were based on the implementation's behaviour in LFC's

Name	Type	Description		
Scenario 1	has trace	A1 merging with A2, A1 has priority, A2 merges into A1		
(REQ1)				
Scenario 2	has trace	A1 merging with A2, but A2 cancels the merge		
(REQ2)				
Scenario 3	has trace	A2 merging with A1, denied because A2 does not have priority		
(REQ1)				
Scenario 4a	has trace	A2 requests a merge with A3, then A1 requests a merge with A3. A1		
(REQ1)		merges with $A3$ first, then $A3$ replies that its Map Leader is now $A1$ .		
		A2 now tries to merge with $A1$ , which is denied because $A2$ does not		
		have priority		
Scenario 4b	has trace	A2 requests a merge with A3, then A1 requests a merge with A3. A1		
(REQ2)		merges with A3 first, then A3 replies that its Map Leader is still A3.		
		A2 tries to merge with A3, which is cancelled because A3 is not a Map		
		Leader any more		
Scenario 5	has trace	A1 merges with $A2$ , then $A3$ tries to merge with $A2$ , which replies that		
(REQ1)		its Map Leader is now A1. A2 tries to merge with A1, which is denied		
		because A3 does not have priority		
done	refinement	Can the <i>LFC</i> process reach the state where any of the agents can call		
Reachable		done (showing that it is coordinating all the agents).		
(GOAL)				

Table 2: Summary of the verification (Scenarios 1–5) and validation (done reachable) assertions applied to the map merge protocol. The requirement, or goal, that each assertion covers is presented in brackets.

matches during MAPC 2019, so the correct behaviour is known. The specification was checked to see that it would perform each of the scenarios correctly, showing that it corresponds to the implemented protocol.

The scenarios were developed alongside the specification, and were useful for checking that it continued to meet the requirements while behaviour was being added. Hence, Scenarios 1 to 3 describe the requirements of a pair of agents; while Scenarios 4a, 4b, and 5 check the requirements with the interference of a third agent; mirroring the specification's development. Scenario 1 is the example in Fig. 1, where agent A1 meets agent A2 and requests they merge maps, A1 has priority so A2's map is merged into A1's; and Scenario 2 shows A2 cancelling the merge instead. Scenario 3 is A2 trying to merge with A1 and not having the priority to do so. Scenarios 4a and 4b check the two situations that can occur when an agent stops being a Map Leader after a third agents has started merging with it. Finally, Scenario 5 checks the combination of an agent that stops being a Map Leader and an agent that doesn't have priority for a merge.

While the six scenarios are not an exhaustive list, they cover both of the protocol's requirements (Sect.3.1). REQ1, that the merge will be denied if the requesting map leader does not have priority, is checked by Scenarios 1 and 3 (for two agents) and Scenarios 4a and 5 (for three agents). REQ2, that an agent will cancel a merge if it loses control if its map, is checked by Scenario 2 (for two agents) and Scenario 4b (for three agents). The GOAL is checked by the *done* reachable assertion, described below alongside the other verification checks.

Each scenario is described as a trace of the relevant events in the scenario. We used FDR's in-built [has trace] check, to explore the model's state space to see if it can perform the scenario trace (though this does not show that it will always perform the scenario trace). In the assertion check we hide all the events that are not in the scenario trace. This takes the form:

assert  $LFC \setminus (diff(Events, trace\_events)) : [has trace]; < trace\_events >$  where LFC is the specification's top-level process, Events is the set of all events, and  $trace\_events$  is a sequence of events. The diff() function in the hiding operator  $\setminus (diff(Events, trace\_events))$  hides only

the events not in *trace\_events*.

The [has trace] checks act like tests of the specification. They are run automatically by FDR, so they are easily repeatable They also provide useful regression tests, which ensures that a change to the specification during this validation and debugging step has not introduced a bug somewhere else.

```
\begin{split} \textit{get\_agentSet.Me? gotAgentSet} \rightarrow \\ \textit{if gotAgentSet} &== AgentNamethen \\ \textit{done.Me} \rightarrow \textit{terminate.Me} \rightarrow \textit{SKIP} \\ \textit{else} \\ \textit{MAP\_LEADER\_REQUEST\_MERGE(Me, gotAgentSet)} \end{split}
```

Figure 5: Excerpt from  $MAP\_LEADER\_\_REQUEST\_MERGE$ , checking that all the maps have merged. This follows on from the excerpt in Fig. 2.

#### Verification

For verification, we use FDR's in-built assertions to show (by exhaustive model checking) that our specification of the merge protocol is free from divergence and non-determinism. Divergence (livelock) is where the specification performs infinity many internal events, refusing to offer events to the environment. Non-determinism is where the specification may perform several different events, after a given prefix.

Finally, we check that the specification can reach a state where all the maps have merged. To get to this state shows that the specification performs the correct behaviour and that it does not deadlock before reaching the 'done' state. If the specification reaches this state, it shows that the GOAL and requirements REQ1 and REQ2 are obeyed by the specification. This check required the addition of the if ... else... construct to the MAP\_LEADER process (shown in Fig. 5) which is not part of the map merge protocol. The check happens inside the MAP\_LEADER\_REQUEST\_MERGE subprocess, after a merge has been either confirmed or cancelled. The event get\_agentSet retrieves the agent set (the set of agents that this Map Leader is coordinating) from the map leader's internal state process; which is named gotAgentSet here, to avoid a name clash.

The gotAgentSet is compared to the set of all agent IDs (AgentName), using an if...then...else... construction that is not part of CSP but is available in the input language of FDR. If the sets are equal (meaning that this  $MAP\_LEADER$  is now coordinating all the agents) then the process synchronises on the done event. In our specification, the done event can happen after a minimum of two successful map merges (agent A1 merging with agents A2 and A3 in either order) but there could be more, depending on the interleaving of events. This means that the done event represents several successful instances of the protocol, each of which must have obeyed the GOAL and requirements REQ1 and REQ2. We can also see in Fig. 5 that after done, the  $MAP\_LEADER$  waits for the terminate event, which tells it to terminate. This is also only part of our specification, not a part of the merge protocol.

To check if the state where a  $MAP\_LEADER$  can call done is reachable, we use the following assertion:

```
assert\ LFC \setminus (diff(Events, \{|\ done\ |\}))[FD = \\ \square\ agent: AgentName \bullet\ done.agent \to SKIP
```

which checks if the specification (LFC) is refined by ([FD=) the process that offers the external choice  $(\Box)$  of any  $MAP\_LEADER$  calling done. Again, we use  $(diff(Events, \{ | done | \}))$  to hide all the events in LFC other than done, because it is the only event pertinent to this check. Here, the replicated external choice (see Table. 1) offers the done event with each ID agent in the set of all agent IDs, AgentName. The particular refinement check used here (in CSP's failures-divergences model) means that the LFC processes cannot refuse the done event (as this would be a failure) and it cannot diverge. As previously mentioned, this shows that LFC does not deadlock before the done event occurs.

#### Discussion

Table 3 shows a summary of the times (in seconds) taken to complete the *has trace* checks on each scenario trace, the divergence and non-determinism checks, and the check that the *done* event is reachable. These results are from using FDR 4.2.7, on a PC using Ubuntu 20.04.2, with an Intel Core i5-3470 3.20 GHz  $\times$  4 CPU, and 8 GB of RAM. The table reports the compilation time, which is how long it took FDR to build its internal representation of the specification; checking time, which is how

Name	Compiled (s)	Checked (s)	Total (s)
Scenario 1	0.84	0.15	0.99
Scenario 2	0.89	0.10	0.99
Scenario 3	0.89	0.10	0.99
Scenario 4a	0.94	0.08	1.02
Scenario 4b	0.95	0.06	1.01
Scenario 5	0.86	0.10	0.96
Divergence	0.71	2.41	3.12
Non-Determinism	6.19	2.69	8.88
done Reachable	4.72	0.02	4.74

Table 3: Summary of times (in seconds) taken to check each scenario trace (has trace), divergence, non-determinism, and that the *Done* event is reachable. The times shown are for a single run using FDR 4.2.7, showing how long it took to compile and check each assertion, the total time is the sum of the compilation and checking time.

long it took FDR to actually check the assertion; and the total time, which is simply the sum of the previous two times.

The total times for these verification and validation checks were small enough to not be a barrier to quick re-checking of the properties after updates to the specification. The scenario traces provided quick regression tests, each being checked in  $\sim 1s$ . Even the longest of the three exhaustive checks (non-determinism) was still relatively fast, at only 8.88s in total.

As mentioned in Sect. 3.2, our model only uses three agents, which helps keep the state space of the specification small. To provide a comparison, we added a fourth agent to *AgentName* (the set of all agent IDs, mentioned in Sect.3.2):

$$datatypeAgentName = A1 \mid A2 \mid A3 \mid A4$$

The model was not specifically designed for more than three agents, but it adapts to the number of agent IDs (for example, it runs one AGENT process for each ID in AgentName). Then, we rechecked the scenario traces in FDR. For three agents they each took  $\sim$ 1s (Table 3); for four agents they took between 89s and  $\sim$ 107s longer, an average increase of 9788.94% (97.20s). We did not compare the times for the exhaustive checks because they used used all the RAM on the test PC, which will artificially increase the checking time. If we add more agents to the model, other elements may need to be altered to reduce the state space. However, this is left for future work.

# 4 Related Work

A recent survey [3] identified that the main validation and verification approaches being applied to agent systems are: model checking, theorem proving, runtime verification, and testing. Testing has been shown to be less effective in the validation and verification of BDI-based agent systems when compared to traditional procedural programs, encouraging the use of formal methods [30].

Various other approaches for model checking multi-agent systems exist in the literature. MC-MAS [22] and MCK [18] are two symbolic model checkers for agent systems, and AJPF [10] is a *program* model checker for agents written in the Gwendolen [9] language. Runtime verification has also been used to verify agent interaction protocols specified as trace expressions in [13].

However, these approaches work best when applied top-down, and to the whole system. The LFC system was already implemented in JaCaMo, which has been used by several winning teams in past editions of the contest. Our goal in this work was to verify a specific part of the system; the map merge protocol. Both of these things contributed to our exploration of using a CSP specification of the protocol. However, this does not preclude its integration with other types of formal methods applied to the LFC system, which can provide greater confidence in the correctness of the system (as well as guiding the development of new functions) [12].

CSP has been used in other approaches for multi-agent systems. Examples include an approach that combines a CSP encoding of agent communications with a first-order logic framework [20]; a CSP framework for a Java-based "cognitive agent architecture" called Cougar [15], where the model is used to verify properties about the code generated from the Cougar system; and a timed CSP model of a

multi-agent manufacturing system [31]. However, each of these approaches is (like ours) specific to its example application.

Another approach [21] for multi-agent systems that involves CSP presents a translation from CSP-Z (a combination of CSP and Z [27]) to Promela, the input language of the SPIN [17] model checker. This translation appears to be needed to side-step some inadequacy with a previous version of FDR. They demonstrate their approach using a CSP-Z specification of an air traffic control system. Our work makes use of 'pure' CSP, and doesn't require the specification to be translated into a different language for model checking, so we can be more confident of our results. However, updating this approach for the current versions of FDR and SPIN could be useful if the protocol had specification temporal properties that needed checking.

Finally, there is work on the Agent Communication Programming Language (ACPL) [11], which is a process algebra that takes some inspiration from CSP's approach to concurrency to model the basics of agent communication. ACPL was also used as the basis for a formal compositional verification framework for agent communication [28]. While the map merge protocol tackled in our work does use agent communication, we are verifying the protocol not the communication itself.

Other process algebras have been used to specify and verify multi-agent systems [23]. For example, in [2] the process algebra Finite State Processes (FSP) and  $\pi$  calculus combined with ADL ( $\pi$ ADL) are used to specify safety and liveness properties for a multi-agent system, The multi-agent program is checked for satisfaction of these properties, as is the agent architecture (which is written in  $\pi$ ADL). Looking further afield, process algebras have been applied to similarly distributed, cooperative systems. For example, the Bio-PEPA process algebra has been used to model robot swarms [24], specifying behaviour that enables the swarm to perform a foraging task. They found that their approach enabled a wider range of analysis methods, when compared to other modelling approaches.

## 5 Conclusion

This paper describes the application of formal specification and verification techniques (in CSP) to an existing communication protocol used to merge maps in a multi-agent system. The protocol was used by the LFC team in the MAPC 2019. This work provides extra confidence that the LFC team's map merging protocol works correctly, which was difficult to check using testing alone. The work also explores the utility of CSP for modelling multi-agent systems.

The merge protocol is critical to the performance of the multi-agent system, all of the information needed for the agents to participate effectively in the competition is stored in the agent's maps. Without a coherent map, the agents would not have been able to cooperate to achieve their mission.

Using the model checker FDR, our CSP specification of the protocol was validated (through checking that it could perform traces representing scenarios drawn from the MAPC 2019) and verified to be free of divergences, and non-determinism, and that it could eventually merge all the maps without deadlocking. We conclude that CSP's focus on concurrent communicating systems makes it well suited to specifying this kind of communications protocol.

Although the merge protocol is the most complex communication protocol used in the LFC system, other behaviours also require some form of validation and verification. The identification process (mentioned in Sect. 3.1) could be specified in CSP either as an addition to the specification presented in this paper, or separately. CSP is useful for modelling concurrent communication, but there may be other formal method techniques that are more appropriate for the remaining behaviours. As indicated by the results in [7], different parts of the system may require distinct verification techniques. The use of CSP for modelling agent interaction protocols that make use of the interaction dimension in JaCaMo also requires further investigation. These are left for future work.

# References

[1] Ahlbrecht, T., Dix, J., Fiekas, N., Krausburg, T.: The multi-agent programming contest: A résumé. In: Ahlbrecht, T., Dix, J., Fiekas, N., Krausburg, T. (eds.) The Multi-Agent Programming Contest 2019. pp. 3–27. Springer International Publishing, Cham (2020). https://doi.org/10.1007/978-3-030-59299-8\_1

- [2] Akhtar, N., Missen, M.M.S.: Contribution to the Formal Specification and Verification of a Multi-Agent Robotic System. Eur. J. Sci. Res. 117(1), 35-55 (2014), http://www.europeanjournalofscientificresearch.com
- [3] Bakar, N.A., Selamat, A.: Agent systems verification: Systematic literature review and mapping. Applied Intelligence 48(5), 1251–1274 (may 2018). https://doi.org/10.1007/s10489-017-1112-z
- [4] Boissier, O., Bordini, R., Hubner, J., Ricci, A.: Multi-Agent Oriented Programming: Programming Multi-Agent Systems Using JaCaMo. Intelligent Robotics and Autonomous Agents series, MIT Press (2020)
- Boissier, O., Bordini, R.H., Hübner, J.F., Ricci, A., Santi, A.: Multi-agent oriented programming with JaCaMo. Science of Computer Programming 78(6), 747–761 (Jun 2013). https://doi.org/10.1016/j.scico.2011.10.004
- [6] Bordini, R.H., Wooldridge, M., Hübner, J.F.: Programming Multi-Agent Systems in AgentSpeak using Jason. John Wiley & Sons (2007)
- [7] Cardoso, R.C., Farrell, M., Luckcuck, M., Ferrando, A., Fisher, M.: Heterogeneous verification of an autonomous curiosity rover. In: Lee, R., Jha, S., Mavridou, A., Giannakopoulou, D. (eds.) NASA Formal Methods. pp. 353–360. Springer International Publishing, Cham (2020). https://doi.org/10.1007/978-3-030-55754-6\_20
- [8] Cardoso, R.C., Ferrando, A., Papacchini, F.: LFC: Combining autonomous agents and automated planning in the multi-agent programming contest. In: The Multi-Agent Programming Contest 2019. pp. 31–58. Springer International Publishing, Cham (2020). https://doi.org/10.1007/978-3-030-59299-8\_2
- [9] Dennis, L.A., Farwer, B.: Gwendolen: A BDI language for verifiable agents. In: Workshop on Logic and the Simulation of Interaction and Reasoning. AISB (2008)
- [10] Dennis, L.A., Fisher, M., Webster, M., Bordini, R.H.: Model Checking Agent Programming Languages. Automated Software Engineering 19(1), 5–63 (2012). https://doi.org/10.1007/s10515-011-0088-x
- [11] van Eijk, R.M., de Boer, F.S., van der Hoek, W., Meyer, J.J.C.: Process algebra for agent communication: A general semantic approach. In: Huget, M.P. (ed.) Communication in Multiagent Systems: Agent Communication Languages and Conversation Policies, pp. 113–128. Springer Berlin Heidelberg, Berlin, Heidelberg (2003). https://doi.org/10.1007/978-3-540-44972-0\_5
- [12] Farrell, M., Luckcuck, M., Fisher, M.: Robotics and integrated formal methods: Necessity meets opportunity. In: Furia, C.A., Winter, K. (eds.) Proc. 14th International Conference on Integrated Formal Methods (iFM). Lecture Notes in Computer Science, vol. 11023, pp. 161–171. Springer (2018). https://doi.org/10.1007/978-3-319-98938-9\_10
- [13] Ferrando, A., Ancona, D., Mascardi, V.: Decentralizing MAS monitoring with decamon. In: Larson, K., Winikoff, M., Das, S., Durfee, E.H. (eds.) Proceedings of the 16th Conference on Autonomous Agents and MultiAgent Systems, AAMAS 2017, São Paulo, Brazil, May 8-12, 2017. pp. 239-248. ACM (2017), http://dl.acm.org/citation.cfm?id=3091164
- [14] Gibson-Robinson, T., Armstrong, P., Boulgakov, A., Roscoe, A.: FDR3 A Modern Model Checker for CSP. In: Tools and Algorithms for the Construction and Analysis of Systems. LNCS, vol. 8413, pp. 187–201. Springer (2014). https://doi.org/10.1007/978-3-642-54862-8\_13
- [15] Gracanin, D., Singh, H.L., Hinchey, M.G., Eltoweissy, M., Bohner, S.A.: A CSP-based agent modeling framework for the Cougaar agent-based architecture. In: 12th IEEE International Conference and Workshops on the Engineering of Computer-Based Systems (ECBS'05). pp. 255–262. IEEE (2005). https://doi.org/10.1109/ECBS.2005.6
- [16] Hoare, C.A.R.: Communicating sequential processes. Comms. of the ACM **21**(8), 666–677 (1978). https://doi.org/10.1145/359576.359585

- [17] Holzmann, G.: The model checker SPIN. IEEE Transactions on Software Engineering 23(5), 279–295 (May 1997). https://doi.org/10/d7wqxt, http://ieeexplore.ieee.org/document/588521/
- [18] Huang, X., van der Meyden, R.: Symbolic model checking epistemic strategy logic. In: Proceedings of the Twenty-Eighth AAAI Conference on Artificial Intelligence. pp. 1426–1432. AAAI Press (2014), https://ojs.aaai.org/index.php/AAAI/article/view/8894
- [19] Hübner, J.F., Sichman, J.S., Boissier, O.: Developing organised multiagent systems using the MOISE+, model: programming issues at the system and agent levels. Int. J. Agent-Oriented Software Engineering 1(3/4), 370–395 (2007). https://doi.org/10.1504/IJAOSE.2007.016266
- [20] Izumi, N., Takamatsu, S., Kise, K., Fukunaga, K.: CSP-based formulation of multi-agent communication for a first-order agent theory. commitment 42, 213–261 (1990)
- [21] Kacem, A.H., Kacem, N.H.: From formal specification to model checking of MAS using CSP-Z and SPIN. International Journal of Computing & Information Sciences 5(1) (2007), http://www.ijcis.info/Vol5N1.htm
- [22] Lomuscio, A., Raimondi, F.: MCMAS: A Model Checker for Multi-agent Systems. In: Proc. 12th Int. Conf. Tools and Algorithms for the Construction and Analysis of Systems (TACAS). LNCS, vol. 3920, pp. 450–454. Springer (2006). https://doi.org/10.1007/11691372\_31
- [23] Luckcuck, M., Farrell, M., Dennis, L.A., Dixon, C., Fisher, M.: Formal Specification and Verification of Autonomous Robotic Systems: A Survey. ACM Computing Surveys **52**(5), 1–41 (Sep 2019). https://doi.org/10.1145/3342355, http://dl.acm.org/citation.cfm?doid=3362097.3342355
- [24] Massink, M., Brambilla, M., Latella, D., Dorigo, M., Birattari, M.: On the use of Bio-PEPA for modelling and analysing collective behaviours in swarm robotics. Swarm Intell. 7(2-3), 201–228 (2013). https://doi.org/10.1007/s11721-013-0079-6, http://link.springer.com/10.1007/s11721-013-0079-6
- [25] Rao, A.S., Georgeff, M.: BDI Agents: From Theory to Practice. In: Proc. 1st Int. Conf. Multi-Agent Systems (ICMAS). pp. 312–319. San Francisco, USA (jun 1995)
- [26] Ricci, A., Piunti, M., Viroli, M., Omicini, A.: Environment programming in CArtAgO. In: Multi-Agent Programming: Languages, Tools and Applications, chap. 8, pp. 259–288. Multiagent Systems, Artificial Societies, and Simulated Organizations, Springer (2009). https://doi.org/10.1007/978-0-387-89299-3\_8
- [27] Spivey, J.M.: The Z Notation: A Reference Manual. International Series in Computer Science. Prentice-Hall, New York, NY, (1992)
- [28] Van Eijk, R.M., De Boer, F.S., Van Der Hoek, W., Meyer, J.J.C.: A Verification Framework for Agent Communication. Autonomous Agents and Multi-Agent Systems 6(2), 185–219 (2003). https://doi.org/10/dzcsw4, http://link.springer.com/10.1023/A:1021836202093
- [29] Vieira, R., Moreira, Á.F., Wooldridge, M., Bordini, R.H.: On the Formal Semantics of Speech-Act Based Communication in an Agent-Oriented Programming Language. Journal of Artificial Intelligence Research (JAIR) 29, 221–267 (2007). https://doi.org/10.1613/jair.2221
- [30] Winikoff, M.: BDI agent testability revisited. Autonomous Agents and MultiAgent Systems **31**(5), 1094–1132 (2017). https://doi.org/10.1007/s10458-016-9356-2
- [31] Yeung, W.L.: Behavioral modeling and verification of multi-agent systems for manufacturing control. Expert Systems with applications **38**(11), 13555–13562 (2011). https://doi.org/10.1016/j.eswa.2011.04.067
- [32] Zatelli, M.R., Ricci, A., Hübner, J.F.: Integrating interaction with agents, environment, and organisation in JaCaMo. Int. J. Agent-Oriented Softw. Eng. 5(2/3), 266–302 (Jan 2016). https://doi.org/10.1504/IJAOSE.2016.080889