

# A Three-Dimensional Abstraction Framework to Compare Multi-Agent System Models

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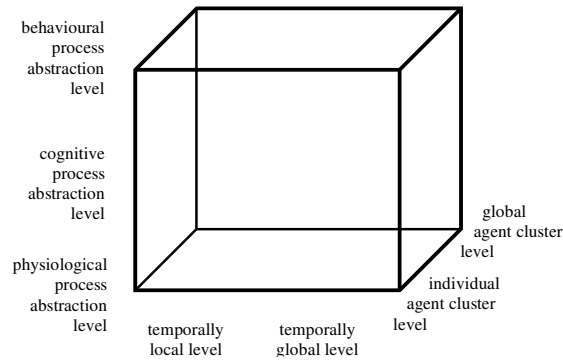
**Abstract** Models of agents or multiagent systems in a certain application area can be made at different levels of abstraction. The aim of this paper is to clarify different dimensions of abstraction. The three dimensions of considered are: the process abstraction dimension, the temporal dimension, and the agent cluster dimension. Thus a three-dimensional framework is obtained in which different types of multi-agent system models can be classified. For a number of multiagent system models in different application areas from the literature it is discussed how they fit in the framework.

## 1 Introduction

One of the important choices made in (multi)agent system modelling in a certain application area is the grain-size or abstraction level of the model being developed. Models which are too coarse-grained (too abstract) may miss details of the domain modelled that are essential to the aim of the model, and models which are too fine-grained (too detailed) for the aim of the model may become difficult to handle because they are too complex and/or intransparent. Therefore choosing the right level of abstraction may be crucial. However, upon further consideration the notion of abstraction level itself is not so self-evident. For example, does more abstract mean that the models for the internal processes within agents are described at a more abstract level (abstracting from internal physiological, cognitive and affective detail)? Or should it be interpreted such that the models describe relationships over larger time intervals (abstracting from the smaller time steps)? Or does more abstract mean that within the multiagent system model higher level structures are used that aggregate individual agents (considering groups or clusters of agents as entities, as in organisation models)? In this paper the viewpoint is taken that to clarify the notion of abstraction level the point of departure should be that different dimensions of abstraction have to be considered.

The focus of the paper is on the following dimensions of abstraction: the *process abstraction*, *temporal*, and *agent cluster dimension*. For each of these dimensions a multiagent system application can be modeled from a more local-level perspective and from a more global-level perspective. Thus a framework is obtained to distinguish abstraction levels for different types of models (see the cube in Figure 1). It will be shown that this framework is able to distinguish and position different types

of multi-agent system models known from the literature, including, for example, population-based vs agent-based models, behavioural vs cognitive agent models, and executable models vs requirements models. Note that the distinctions made by the framework are purely semantic, independent of any representation format of a model. In the paper, first the three dimensions are introduced in Sections 2, 3 and 4. Next, in Section 5 it is shown how the three-dimensional framework can be used to position models and approaches available in the literature. Finally, Section 6 is a discussion.



**Fig.1.** Process abstraction, temporal and agent cluster dimension

## 2 The Process Abstraction Dimension

For the process abstraction level dimension, a multi-agent process can be conceptualised (from more abstract, higher to less abstract, lower levels) at the behavioural level, the cognitive level, or the physiological level; see Fig. 1.

**Behavioural Level** At the *behavioural level* relations are described between input and output states of agents, for example:

- direct reactive behaviour relating received input to an immediate response
- an avoidance reaction after three times a negative experience with something or somebody
- spread of information over a population by gossiping

At the behavioural process abstraction level, models abstract from internal (e.g., cognitive or physiological) concepts, such as beliefs, desires, intentions or activation states, and subprocesses involving them. Behavioural specifications only make use of concepts related to input states or output states (e.g., observations, actions, outgoing and incoming communication) of an agent.

The different dimensions will be illustrated by a toy case study involving an instant dating service: an Internet agent ID that can be contacted when somebody wants a date. This is to be considered a fictitious example just for the purpose of illustration. In principle many activities during a date are possible, such as hiking, going out for a dance club, attending a concert, et cetera. For the case study three characteristics make up a type of an activity: active or not, involving eating or not, and romantic or not. Moreover, it is assumed that dating is steered by an identity described by specific body states: blood sugar level, adrenaline level, testosterone level, and dopamine lack. Each person involved has interaction in three phases:

- Based on a chosen identity the person requests ID for a date
- After a candidate has been proposed by ID the person proposes ID a desired activity type
- When a received activity type is desired, a date with this candidate is performed

These have been specified in the form of temporally local behavioural properties LBP1, LBP2, and LBP3, as follows. Here  $\rightarrow$  is used to denote a causal relation.

#### **LBP1 Requesting for a date**

If  $P$  observed that the dopamine lack is high, the adrenaline level is  $X1$ , the blood sugar lack is  $X2$ , and the testosterone level is  $X3$ ,

then  $P$  will request  $ID$  to look for a date with identity  $id(X1, X2, X3)$

observed( $P$ , dopaminelack, high) & observed( $P$ , adrenaline,  $X1$ ) &  
 observed( $P$ , bloodsugarlack,  $X2$ ) & observed( $P$ , testosterone,  $X3$ )  
 $\rightarrow$  communication( $P$ , date\_with\_id( $id(X1, X2, X3)$ ),  $ID$ )

#### **LBP2 Proposing an activity**

If it was communicated by  $ID$  to  $P$  that  $Q$  with identity  $id(X1, X2, X3)$  agrees to have a date, and  $P$  observed for adrenaline  $X1$ , blood sugar lack  $X2$ , testosterone  $X3$ ,

then  $P$  will propose  $ID$  to perform activity  $act(X1, X2, X3)$ .

communication( $ID$ , agrees( $Q$ ,  $id(X1, X2, X3)$ ),  $P$ ) &  
 observed( $P$ , adrenaline,  $X1$ ) & observed( $P$ , bloodsugarlack,  $X2$ ) & observed( $P$ , testosterone,  $X3$ )  
 $\rightarrow$  communication( $P$ , wants( $P$ ,  $act(X1, X2, X3)$ ),  $ID$ )

#### **LBP3 Performing an agreed activity**

If it was communicated by  $ID$  to  $P$  that  $Q$  with identity  $id(X1, X2, X3)$  agrees to have a date, and  $P$  observed for adrenaline  $X1$ , blood sugar lack  $X2$ , testosterone  $X3$ ,

and it was communicated that  $Q$  wants to do activity  $act(X1, X2, X3)$ ,

then  $P$  will perform  $act(X1, X2, X3)$  with  $Q$ .

communication( $ID$ , agrees( $Q$ ,  $id(X1, X2, X3)$ ),  $P$ ) & observed( $P$ , adrenaline,  $X1$ ) &  
 observed( $P$ , bloodsugar,  $X2$ ) & observed( $P$ , testosterone,  $X3$ ) &  
 communication( $ID$ , wants( $Q$ ,  $act(X1, X2, X3)$ ),  $P$ )  
 $\rightarrow$  performed( $P$ , date( $act(X1, X2, X3)$ ,  $Q$ ))

**Cognitive Level** At the *cognitive level*, both informational concepts (e.g., observations, communications, beliefs), and affective or motivational concepts (e.g., emotions, feelings, desires) are considered. For the case study it is assumed that persons aim at maintaining homeostasis for the specific body states. By monitoring the body, specific desires are generated which motivate actions to fulfill them (e.g., communicating a request for a date or a proposal for an activity). For these actions, first intentions are generated, and from an intention, the actual performance of the action is generated. As an example, a desire to find a date is directly related to the state of the body, in particular the dopamine, adrenaline, blood sugar and testosterone levels. For the sake of simplicity it is assumed that the desire leads to a corresponding intention, and in turn this leads to the related communication.

#### **LCP1 Generating a desire to date using some identity**

If  $P$  observed that the dopamine lack is high, adrenaline level is  $X1$ , blood sugar lack level  $X2$ , and testosterone level  $X3$

then  $P$  will have the desire to obtain a date with identity  $id(X1, X2, X3)$

observed( $P$ , dopaminelack, high) & observed( $P$ , adrenaline,  $X1$ ) &  
 observed( $P$ , bloodsugarlack,  $X2$ ) & observed( $P$ , testosterone,  $X3$ )  
 $\rightarrow$  desire( $P$ , date\_with\_id( $id(X1, X2, X3)$ ))

#### **LCP2 Generating an intention to date based on a desire**

If  $P$  has the desire to obtain a date with identity  $I$ ,

then  $P$  will have the intention to obtain a date with identity  $I$ .

desire( $P$ , date\_with\_id( $I$ ))  $\rightarrow$  intention( $P$ , date\_with\_id( $I$ ))

### LCP3 Requesting to look for a date based on the intention

If  $P$  has an intention for a date with identity  $I$ ,  
then  $P$  will request  $ID$  to look for a date with identity  $I$   
intention( $P$ , date\_with\_id( $I$ ))  $\rightarrow$  communication( $P$ , date\_with\_id( $I$ ),  $ID$ )

**Physiological Level** At the physiological level, processes are described in terms of body and brain states and relationships between them. For example, this may concern muscle activity, levels of (bio)chemical substances in the blood, sensor and effector states, or activation states of neurons, or groups of neurons. Within the case study the four body aspects are considered as before, and in addition sensor and effector states, and activations of (groups of) neurons. For the physiological process abstraction level, a neural network structure was specified, together with connection strengths and threshold values. Threshold functions were used, defined as  $th(\sigma, \tau, V) = 1/(1+e^{-\sigma(V-\tau)})$  with steepness  $\sigma$  and threshold  $\tau$ . This specification assumes that specific values are given for each of the occurrences of connection weight  $\omega$ , steepness  $\sigma$ , and threshold  $\tau$ , in dependence of variables such as  $B$ ,  $I$  and  $A$ . The assumed sensor system for body states maintains so-called *neural body maps* using sensory neurons (e.g., [22], [23]).

### LPP1 Generating a sensor state for a body state

If body state property  $B$  occurs for person  $P$  with level  $V$   
and the connection strength from body state property  $B$  to a sensor state for  $B$  is  $\omega$   
and the steepness and threshold value for this sensor state are  $\sigma$  and  $\tau$   
then the sensor state for  $B$  will have activation level  $th(\sigma, \tau, \omega V)$ .  
activation( $BS(P, B), V$ ) & connection\_strength( $BS(P, B), S(P, B), \omega$ ) &  
steepness( $S(P, B), \sigma$ ) & threshold( $S(P, B), \tau$ )  
 $\rightarrow$  activation( $S(P, B), th(\sigma, \tau, \omega V)$ )

### LPP2 Activating sensory neurons for a body map

If the sensor state for body state  $B$  has activation level  $V$   
and the connection strength from sensor state for  $B$  to the sensory neuron for  $B$  is  $\omega$   
and the steepness and threshold value for this sensor state are  $\sigma$  and  $\tau$   
then the sensory neuron for  $B$  will have activation level  $th(\sigma, \tau, \omega V)$ .  
activation( $S(P, B), V$ ) & connection\_strength( $S(P, B), SN(P, B), \omega$ ) &  
steepness( $SN(P, B), \sigma$ ) & threshold( $SN(P, B), \tau$ )  
 $\rightarrow$  activation( $SN(P, B), th(\sigma, \tau, \omega V)$ )

Depending on these neural body maps certain preparation neurons become activated. In particular, the sensory neurons for lack of dopamine (indicating ‘being bored’) have a positive effect on the activation for preparing to request a date; here the body maps for adrenaline, blood sugar lack and testosterone have effect on which identity is chosen for such a date. How the effects of the activation levels of the four connected sensory neurons that provide input for the preparation neurons are combined, depends on the respective connection strengths and on the threshold value of the preparation neuron, using a threshold function as described above. It is configured in a way so that for each combination of the other three body states (adrenaline, blood sugar lack and testosterone level) a suitable identity is available, (specified by strengths of  $-1$  or  $1$  of the connections  $\omega$  to the preparation for this identity). This determines how a preparation neuron for an initiative to get a date fitting to the body map is activated.

### 3 The Temporal Dimension

For the temporal dimension a process can be conceptualised by descriptions over longer time periods (e.g., *emerging patterns*), or by descriptions relating states over smaller time steps (e.g., *mechanisms*). Temporal perspectives on the dynamics of processes are addressed in a wide variety of literature, from different disciplines, including Cognitive Science, [3], [42], [56], and Artificial Intelligence and Computer Science [5], [12], [40], [13], [21], [31], [50], [59], [4]. Temporally local properties were used in Section 2 to describe the (physiological, cognitive, or behavioural) mechanisms of a process considered in a step-by-step manner. Usually descriptions specified as difference or differential equations, transition systems, or immediate causal relationships, are examples of temporally local descriptions. Patterns that occur as emergent phenomena over time can be described in a temporally more global manner, by relations over longer time periods. For specification of emerging patterns a more expressive temporal modelling language is needed, for example, linear time or branching time modal temporal logics (such as LTL or CTL), or temporal predicate logics (such as the Temporal Trace Language TTL; cf. [12], [40]). Below, different types of often considered global temporal properties are described.

**Achievement properties** express that *eventually a certain state is reached* in which some (desired) state property holds. They relate to what in the literature in Computer Science are sometimes called *liveness* properties, and what in agent literature is referred to as *achievement goals* (in contrast to, for example, maintenance goals). An example of an achievement property expresses that whenever the dopamine lack of a person is high, eventually the dopamine lack will be low, and, the adrenaline, testosterone level and the blood sugar lack will be low:

**GBP1 Body state achieved with low levels**

If at some point in time  $T$  the dopamine lack in the body is high then at a later time point  $T1$  in the body the dopamine lack, adrenaline, blood sugar lack, and testosterone all will be low.

$$\begin{aligned} \forall T, P, V \ [ [ \text{state}(\gamma, T) \models \text{body\_state}(P, \text{dopaminelack}, V) \ \& \ V \geq 0.5 ] \\ \Rightarrow \exists T1, V1, V2, V3, V4 \ [ T1 \geq T \ \& \\ \text{state}(\gamma, T1) \models \text{body\_state}(P, \text{adrenaline}, V1) \ \& \ V1 < 0.5 \ \& \\ \text{state}(\gamma, T1) \models \text{body\_state}(P, \text{bloodsugarlack}, V2) \ \& \ V2 < 0.5 \ \& \\ \text{state}(\gamma, T1) \models \text{body\_state}(P, \text{testosterone}, V3) \ \& \ V3 < 0.5 \ \& \\ \text{state}(\gamma, T1) \models \text{body\_state}(P, \text{dopaminelack}, V4) \ \& \ V4 < 0.5 ] ] \end{aligned}$$

Here  $\text{state}(\gamma, T) \models \text{body\_state}(P, \text{dopaminelack}, V)$  denotes that within the state  $\text{state}(\gamma, T)$  at time point  $T$  in trace  $\gamma$  the state property  $\text{body\_state}(P, \text{dopaminelack}, V)$  holds, denoted by the (infix) predicate  $\models$  for the satisfaction relation. A specific type of achievement properties are *equilibrium properties*, expressing that after some time an equilibrium state is reached; for example:

**GBP6 Reaching an equilibrium while ID functions properly**

Eventually, after some point in time  $T$  person  $P$ 's body states are constant with dopamine lack  $< 0.5$ , and no dates or communications with ID occur.

$$\begin{aligned} \forall P \exists T \forall T1 \geq T \ [ \text{state}(\gamma, T1) \models \exists V1 \ [ \text{body\_state}(P, \text{dopaminelack}, V1) \ \& \ V1 < 0.5 ] \ \& \\ \forall B, V \ [ \text{state}(\gamma, T) \models \text{body\_state}(P, B, V) \Rightarrow \text{state}(\gamma, T1) \models \text{body\_state}(P, B, V) ] \ \& \\ \text{state}(\gamma, T1) \models \neg \exists A, Q \text{ performed}(P, \text{date}(A, Q)) \ \& \\ \text{state}(\gamma, T1) \models \neg \exists C \text{ communication}(C, P, \text{ID}) \ \& \ \neg \exists C \text{ communication}(C, \text{ID}, P) ] \end{aligned}$$

**Milestone properties** express that under certain conditions some *intermediate state* will be reached. These properties can be used, for example, to decompose the overall process into a number of subprocesses that, possibly depending on other milestones already achieved, each result in the achievement of some intermediate state (milestone). For the case study, to achieve GBP1, a person has interaction in three phases, specified as behavioural properties GBP2, GBP3, and GBP4:

**GBP2 Requesting for a date**

If  $P$  observed that the dopamine lack is high, the adrenaline level is  $X1$ ,  
the blood sugar lack is  $X2$ , and the testosterone level is  $X3$   
then  $P$  will request  $ID$  to look for a date with identity  $id(X1, X2, X3)$

$$\begin{aligned} & \forall T, P, X1, X2, X3 \\ & [ [ \text{state}(\gamma, T) \models \text{observed}(P, \text{dopaminelack}, \text{high}) \ \& \ \text{state}(\gamma, T) \models \text{observed}(P, \text{adrenaline}, X1) \ \& \\ & \quad \text{state}(\gamma, T) \models \text{observed}(P, \text{bloodsugarlack}, X2) \ \& \ \text{state}(\gamma, T) \models \text{observed}(P, \text{testosterone}, X3) ] \\ & \Rightarrow \exists T1 [ T1 \geq T \ \& \ \text{state}(\gamma, T1) \models \text{communication}(P, \text{date\_with\_id}(id(X1, X2, X3)), ID) ] \end{aligned}$$

**GBP3 Proposing an activity**

If it was communicated by  $ID$  to  $P$  that  $Q$  with identity  $id(X1, X2, X3)$  agrees to have a date,  
and  $P$  observed for adrenaline  $X1$ , blood sugar lack  $X2$ , testosterone  $X3$ ,  
then  $P$  will propose  $ID$  to perform activity  $act(X1, X2, X3)$ .

$$\begin{aligned} & \forall T, P, X1, X2, X3 \\ & [ [ \text{state}(\gamma, T) \models \text{communication}(ID, \text{agrees}(Q, id(X1, X2, X3)), P) \ \& \ \text{state}(\gamma, T) \models \text{observed}(P, \text{adrenaline}, X1) \ \& \\ & \quad \text{state}(\gamma, T) \models \text{observed}(P, \text{bloodsugarlack}, X2) \ \& \ \text{state}(\gamma, T) \models \text{observed}(P, \text{testosterone}, X3) ] \\ & \Rightarrow \exists T1 [ T1 \geq T \ \& \ \text{state}(\gamma, T1) \models \text{communication}(P, \text{wants}(P, \text{act}(X1, X2, X3)), ID) ] \end{aligned}$$

**GBP4 Performing an agreed activity**

If it was communicated by  $ID$  to  $P$  that  $Q$  with identity  $id(X1, X2, X3)$  agrees to have a date,  
and  $P$  observed for adrenaline  $X1$ , blood sugar lack  $X2$ , testosterone  $X3$ ,  
and it was communicated that  $Q$  wants to do activity  $act(X1, X2, X3)$ ,  
then  $P$  will will perform  $act(X1, X2, X3)$  with  $Q$ .

$$\begin{aligned} & \forall T, P, X1, X2, X3 \\ & [ [ \text{state}(\gamma, T) \models \text{communication}(ID, \text{agrees}(Q, id(X1, X2, X3)), P) \ \& \\ & \quad \text{state}(\gamma, T) \models \text{observed}(P, \text{adrenaline}, X1) \ \& \ \text{state}(\gamma, T) \models \text{observed}(P, \text{bloodsugarlack}, X2) \ \& \\ & \quad \text{state}(\gamma, T) \models \text{observed}(P, \text{testosterone}, X3) \ \& \ \text{state}(\gamma, T) \models \text{communication}(ID, \text{wants}(Q, \text{act}(X1, X2, X3)), P) \\ & \Rightarrow \exists T1 [ T1 \geq T \ \& \ \text{state}(\gamma, T1) \models \text{performed}(P, \text{date}(\text{act}(X1, X2, X3), Q)) ] \end{aligned}$$

**Maintenance properties** express that certain state properties do not (or not much) change during a certain time period: *maintenance properties*. For example, specifying that a form of homeostasis is maintained: a state in which variables stay within certain fixed bounds. This class of properties relates to *safety* properties in computer science and what in agent literature is referred to as *maintenance goals*.

**Representation properties** express how an internal state relates to external states (or input and/or output states) in past (*backward*) or future times (*forward*); e.g., [8], [44], [15], [16], [39]. For example, when a sensory neuron has a high activation level when a stimulus occurred (or has been sensed) before, this is a backward representation relation for this neuron. Moreover, if a high activation level of some preparation neuron later on leads to the effect of the corresponding action, this is an example of a forward representation relation for this neuron. A forward representation property for desires describes, for example, the behaviours or actions that are driven or motivated by these desires, under certain conditions. For the behaviour of a person to make sense, these actions are not arbitrary, but are usually assumed to achieve fulfillment of the desires. The following example of a temporally

global property at the cognitive process abstraction level is a forward representation property for a desire to have a date with a certain identity.

**GCP5 Forward representation relation for a desire to date**

If at some point in time  $T$  person  $P$  desires to have a date with identity  $I$   
then at a time point  $T1$  within time duration  $D$  after  $T$  person  $P$  will  
communicate to ID a date request with identity  $I$ .

$$\forall T, P, I \text{ state}(\gamma, T) \models \text{desire}(P, \text{date\_with\_id}(I)) \ \& \\ \Rightarrow \exists T1 [ T \leq T1 \ \& \ T1 \leq T + D \ \& \ \text{state}(\gamma, T1) \models \text{communication}(\text{date\_with\_id}(I), P, ID) ]$$

Looking forward in time some steps further, desires can be viewed as representing a future state in which they are satisfied. As after a desire has been satisfied, in principle it is not there anymore, this may sound a bit circular and paradoxal: desires that exist in the present represent their own future nonexistence:

**GCP6 Fulfillment of a desire to date**

If at some point in time  $T$  person  $P$  desires to have a date with identity  $I$   
then at a time  $T1$  within duration  $D$  after  $T$  person  $P$  will not desire this anymore for any  $I1$ .

$$\forall T, P, I \text{ state}(\gamma, T) \models \text{desire}(P, \text{date\_with\_id}(I)) \ \& \\ \Rightarrow \exists T1 [ T \leq T1 \ \& \ T1 \leq T + D \ \& \ \neg \exists I1 \text{ state}(\gamma, T1) \models \text{desire}(P, \text{date\_with\_id}(I1)) ]$$

**Comparison properties** describe how certain state properties at different time points are compared, and properties in which certain state properties in different traces are compared. *Time comparison properties* are properties expressing, for example, that under certain conditions (e.g., after some time point) the value of a variable is *monotonically increasing* or *decreasing* over time. *Trace comparison properties* express, for example, that if in one trace the values of certain variables are *lower* than in a second trace, then the value of some other variable will also be *lower* in that trace. In the case study dates have an effect on body states in that they decrease the values. As there are no other effects on body states described in the model, this implies that over time the values can never become higher, only lower. This holds for the body states themselves, but also for the related sensor states and sensory neurons. Such monotonic patterns can be expressed by time comparison properties, in particular monotonicity properties, such as the following:

**GPP5 Monotonically decreasing values in body maps**

If at some point in time  $T1$  in the body map  $B$  has value  $V1$   
and at some point in time  $T2$  in the body map  $B$  has value  $V2$   
and  $T1 \leq T2$ , then  $V1 \geq V2$ .

$$\forall T1, T2, P, B, V1, V2 [ \text{state}(\gamma, T1) \models \text{activation}(\text{SN}(P, B), V1) \ \& \ \text{state}(\gamma, T2) \models \text{activation}(\text{SN}(P, B), V2) \ \& \\ T1 \leq T2 \Rightarrow V1 \geq V2 ]$$

An example of a trace comparison property describes traces where at some point in time the dopamine lack is high in comparison to other traces. In the former type of traces eventually the values of all body states will be lower than or equal to their values in the latter type of traces:

**GBP5 Trace comparison for body states**

When in trace  $\gamma1$  at some time  $T$  dopamine lack  $\geq 0.5$  occurs, and trace  $\gamma2$  is any trace, then there is a point in time  $T1 \geq T$  such that at each time point  $T2 \geq T1$  all body state values in trace  $\gamma1$  are at most as high as the body state values in trace  $\gamma2$  at  $T2$ .

$$\forall \gamma1, \gamma2 \forall T, P, V [ \text{state}(\gamma1, T) \models \text{body\_state}(P, \text{dopaminelack}, V) \ \& \ V \geq 0.5 \Rightarrow \\ \exists T1 \geq T \forall T2 \geq T1 [ \forall B, V1, V2 [ \text{state}(\gamma1, T2) \models \text{body\_state}(P, B, V1) \ \& \ \text{state}(\gamma2, T2) \models \text{body\_state}(P, B, V2) ] \\ \Rightarrow V1 \leq V2 ] ]$$

## 4 The Agent Cluster Dimension

Domains where numbers of agents are quite large can be modelled in a more manageable manner by not introducing conceptual entities for each individual agent separately, but by taking *groups*, (*sub*)*populations* or *clusters* of agents as basic conceptual entities. Examples of such clusters are: divisions or departments within an organisation, age-related groups in a population, subcommunities within a society, or sports teams in a competition. The agent cluster dimension describes how a process can be conceptualised from an individual agent perspective to a more global perspective where a number of clusters, each consisting of multiple agents, are considered as basic entities. For the dating case, the following clusters are considered:

- persons in the process of obtaining a date: who requested but did not yet start a date (R)
- persons performing a date (D)
- persons not in a process of dating: not in a date nor in a process of obtaining a date (N)

By temporally local descriptions it can be specified how the states of the clusters (e.g., numbers of agents  $N(t)$  in cluster N) at a given time point relate to the states at a next time point. For example, within the time interval from  $t$  to  $t + \Delta t$  a number of agents  $NtoR(t)$  per time unit will leave cluster N to join cluster R (entering the process to obtain a date), and a number of agents  $DtoN(t)$  per time unit will leave cluster D to join cluster N (after finishing a date). The following equation results:

$$N(t+\Delta t) = N(t) + DtoN(t) \Delta t - NtoR(t) \Delta t$$

This temporally local dynamic property (difference equation) can be used to perform simulations by calculating the values at the next time point from the values at the current time point. Here,  $DtoN(t)$  and  $NtoR(t)$  are expressed in the values of the states at time  $t$  as follows. For a date an average time duration is assumed:  $dd$ . By approximation from the cluster D at each time unit a fraction  $\alpha = 1/dd$  will finish the date. Therefore per time unit the number making the transition from cluster D to cluster N is  $DtoN(t) = \alpha D(t)$ . Similarly it is estimated which part of cluster N per time unit makes the transition to cluster R. Here the number  $N(do, t)$  within cluster N with high dopamine lack is used:  $NtoR(t) = \beta N(do, t)$ . Parameter  $\beta$  indicates how fast the date request will be done. If this duration is on average  $rd$  time units, then  $\beta = 1/rd$  can be taken. The following difference equation is obtained:

$$N(t+\Delta t) = N(t) + \alpha D(t) \Delta t - \beta N(do, t) \Delta t$$

It can also be written as

$$\Delta N(t)/\Delta t = \alpha D(t) - \beta N(do, t)$$

where by definition  $\Delta N(t) = N(t+\Delta t) - N(t)$ . In a continuous form this temporally local dynamic property can be represented by a *differential equation* as follows:

$$dN(t)/dt = \alpha D(t) - \beta N(do, t)$$

In a similar way temporally local dynamic properties can be obtained for the other clusters, which results in the following set of temporally *local* properties (in difference equation format) for the clusters:

$$\Delta N(t)/\Delta t = \alpha D(t) - \beta N(do, t)$$

$$\Delta R(t)/\Delta t = \beta N(do, t) - \gamma R(t)$$

$$\Delta D(t)/\Delta t = \gamma R(t) - \alpha D(t)$$

$$\Delta N(do, t)/\Delta t = \eta N(t) - \beta N(do, t)$$

Here  $\gamma$  is the fraction (per time unit) of the cluster R that starts a date. It is assumed that the transition from cluster D to cluster N only contributes to agents in cluster N with body states dopamine lack low. Moreover, it is assumed that always (by other processes) a certain fraction  $\eta$  (per time unit) of cluster N gets a high dopamine lack; this explains the fourth equation above.

For temporally *global* descriptions at the *behavioural* level an example achievement property indicates that the size of the cluster describing the persons with high body state for  $x$  in N is near 0 (using a small margin  $\epsilon$ ).

#### **GCBP1 Achieving low body states**

Eventually a state is reached in which there are no high body states  $B \neq do$

$$\exists T \forall T_1 \geq T \forall B, V [ B \neq do \ \& \ state(\gamma, T_1) \models has\_size(N(B), V) \Rightarrow V < \epsilon ]$$

Descriptions of clusters at the *cognitive* process abstraction level address the internal cognitive structures of persons within a cluster. For example, it is expressed that a certain fraction of a cluster or population has a desire for a certain type of activity or to date, or has the intention to perform a certain activity or to request a date. In such a way mental states can be aggregated to *collective mental states* of a cluster, which occur with a certain strength. For instance, statements such as ‘it is commonly believed that the climate change is caused by human activities’ refers to *collective beliefs* present in the population with a certain strength. Yet another mental concept that can take an aggregated form, is *collective trust*, for example, in the world wide financial system. It is also possible to describe temporal relationships between collective cognitive states, for example, the collective belief that the climate change is caused by human activities, leads after some time to the collective intention to take measures. Descriptions of clusters at the *physiological* process abstraction level involve collective neural activation states. This can be addressed in a manner similar to how the cognitive level was addressed.

## **5 Discussion and Classification of Existing Models**

As a main contribution this paper aims at clarifying different types of abstraction levels for agent system models by making explicit different dimensions for such abstraction levels. Any multi-agent system model for a certain application area can be positioned in this three-dimensional space by indicating coordinates for each of these dimensions at a scale from a more local-level (less abstract) perspective and from a more global-level (more abstract) perspective. In this section for different areas in the cube it will be indicated which types of models from the literature fit in this area; see Table 1. Here at each of the axes a distinction was made according to local vs nonlocal (or global), which results in eight different areas. For the process abstraction dimension, the internal (physiological or cognitive) level will be taken as local, in contrast to the behavioural level taken as global.

**Temporally local agent-based internal and behavioural models** are physiological, cognitive or behavioural agent models described at an individual agent level in small time steps. Many examples of such executable models are available, described in a logical (temporal rules), numerical (difference or differential equations), or a hybrid manner, or by transition systems, finite automata or Petri nets. For example, in [11] internal cognitive states of the agents concern the attractiveness of locations, in [17]

internal trust states are maintained on which behaviour is based, and in [58] internal states related to motivation and learning are maintained. Models with internal physiological states can also be found in the area of agent-based epidemics modelling, where the internal infection states of agents are considered. Many of the models in the areas of social simulation, self-organisation, ant computing, and swarm intelligence belong to this class, and often are purely behavioural, described in a reactive manner by stimulus-response-like associations; the complexity emerges from the interaction of large numbers of such simple agents, and the environment.

**Table 1** Overview of literature

<i>dimension</i>			<i>examples from the literature</i>
<i>temporal</i>	<i>cluster</i>	<i>process</i>	
temporally local	agent-based	internal	[5] (logical); [3], [42], [56] (numerical); [11], [13], [17], [1], [46], [32], [37], [51], [58], [60], [61], [36] (hybrid); [4], [21], [6], [7], [10] (transitions, automata, Petri nets)
		behavioural	[52], [53], [26], [14] (social simulation, swarm intelligence); [27] (emotion contagion); [54] (analysis)
	cluster-based	internal	[11] (crime); [20] (organisation); [38], [45] (joint goals and intentions); [2], [37], [43] (epidemics)
		behavioural	[34], [29], [41], [35], [28], [9] (organisation); [49], [57], [62] (ecological)
temporally global	agent-based	internal	[47], [24], [25], [64], [63], [48] (requirements); [31], [50], [59], [4], [21], [6], [7], [10], [12], [40] (verification)
		behavioural	
	cluster-based	internal	[24], [25], [34], [29], [30], [41], [36], [18], [55], [64], [65] (requirements, enterprise); [43], [2], [37]
		behavioural	(epidemics); [49], [57], [62] (ecological)

**Temporally local cluster-based internal and behavioural models** involve collective internal agent states or behaviours for clusters of agents, such as joint or shared actions, goals or beliefs. In general, the temporally local descriptions in this class of models can take the form of executable temporal logical rules, or difference or differential equations, or of a combination of both. For instance, [20] analyses the relationship between intentions and collective activity of groups of agents. In [38] problem solving within groups is investigated based upon joint intentions, and in [45] the expression of joint goals for teams.

**Temporally global agent-based internal and behavioural models** describe temporally more complex properties in terms of internal physiological or cognitive states or behaviours for the individual agents involved. Such descriptions, usually expressed in a richer temporal logical format (e.g., LTL, CTL, situation calculus, TTL), play an important role as a formalisation of patterns emerging from the more local mechanisms. They often occur in literature addressing requirements modelling or verification for multiagent systems.

**Temporally global cluster-based internal and behavioural models** concern descriptions of multiagent systems at a temporally global and global clustering level, but involve internal states of agents. Such descriptions are usually modelled as

temporally complex properties expressing emerging patterns in terms of collective internal agent states or behaviours for clusters of agents such as joint actions or shared goals, emotions or beliefs. Such descriptions involve temporally complex properties expressing emerging patterns in terms of collective dynamics for clusters of agents.

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