Cognitive Social Evaluations for Multi-Context BDI Agents

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Abstract. Since electronic and open environments became a reality, computational trust and reputation models have attracted increasing interest in the field of multi-agent systems (MAS). Some of them are based on cognitive theories and require cognitive agents to display all their potential. However, none of them have yet shown a full integration with real cognitive agents. In this paper we propose a specification to partially integrate Repage, a cognitive reputation model, into a multi-context *Belief, Desire, Intention* (BDI) architecture with graded attitudes.

1 Introduction

Computational trust and reputation models have been recognized as one of the key technologies required to design and implement agent systems [1]. In recent years, many models have been developed [2, 3], but two main approaches currently exist in literature. On the one hand, centralized approaches consider reputation and trust to be a global and public property of the agent. They are widely used in online web sites such as eBay, Amazon etc. On the other hand, distributed approaches consider reputation and trust to be a subjective property of each agent. In this case, this system becomes an important part of the agents architecture. Nevertheless, the integration of this system with the remaining elements of the agent architecture is still something that ought to be improved.

Indeed, the trust and reputation system is primarily considered a black box that reacts to queries from the agents' reasoner by returning a simple value (a real number, a boolean, a probability distribution etc.), representing the trust or reputation of the given target agent. To truly exploit the potential of some of the trust and reputation systems, a tight integration between this system and the other elements of the agent architecture is necessary. This will allow the agent to reason not only about the final value of trust or reputation but also about all the individual elements that contribute to that value; in other words, the process followed to arrive at that value. Because of that, the use of cognitive models for both the trust and reputation system and the agent architecture is a good option, since trust and reputation have a cognitive nature, but their integration (partial or total) has never been faced before.

This article is a first step in this direction. Working with a cognitive reputation system and a cognitive agent architecture (in our case a BDI architecture) as a foundation, we present a possible specification regarding the integration of the concept of

Image (the own evaluation of a target) into a BDI architecture. The framework we use is multi-context systems [4]. This framework provides us a formal environment where the specification of cognitive processes is convenient and natural and which also provides nice properties from the software engineering and logical point of view.

2 The Repage Model

Repage [5] is a computational reputation model based on a cognitive theory about REPutation, imAGE and their interplay [6]. Although *image* and *reputation* are social evaluations, they are also distinct objects. *Image* is a belief on the evaluation of a target agent playing a certain role, while *reputation* is a nested evaluation or meta-evaluation: a belief about how a given target is commonly said to be. In this sense, an *image* is what the agent believes about how good or bad is a target agent respect to a specific role. A *reputation* is what the agent believes that is being said (by other agents) about how good or bad is the target agent with respect to a specific role.

The Repage architecture is designed to reflect this distinction. We will not describe in detail the internals of the Repage architecture here, because it is not the focus of the paper (for a more detailed description we refer to [5] or the APPENDIX of this paper). For the moment, it suffices to say that internally, the Repage model has a memory composed of a set of predicates that are interconnected and conceptually organized into different levels of abstraction. Interconnection relations show dependency between predicates. Each predicate, including *image* and *reputation*, contains a probabilistic evaluation that refers to a certain agent playing a specific role. For instance, an agent may have an *image* of agent T (target) as a seller (role), and a distinct *image* of the same agent T playing the role of informant. The probabilistic evaluation consists of a probability distribution over the discrete sorted set of labels: {Very Bad, Bad, Normal, Good, Very Good} (from now on {VB, B, N, G, VG}). This probabilistic distribution is given by a vector of five positions where the first value corresponds to the probability of *being* Very Bad, and the fifth value of *being* Very Good. For instance, an agent A can have the following predicate: $Img(John : seller, [0.2, 0.1, 0.3, 0.1, 0.3])$, representing the image that he has of $John$ as a $seller$, and meaning that agent A believes that with a probability of 0.2, $John$ will act Very Bad, 0.1 that will act Bad, and so on. Notice that the meaning of the labels {VB, B, N, G, VG} has to be contextualized. It depends on the role being evaluated (see [5] and Section 4.2 of this paper).

At the bottom level of the Repage memory we find a set of predicates not evaluated yet by the agent (that is, objective values that have not been influenced by the mental state of the agent). *Contracts* are agreements on the future interaction between two agents. The result of a contract is represented by its *Fulfillment*. Finally, the *Communications* are pieces of information that other agents may convey, and may be related to three different aspects: (1) the image that the informant has about a target; (2) the image that, according to the informant, a third party agent has on the target, and (3) the reputation that the informant believes about the target. From these bottom predicates, the system generates new predicates and builds up a hierarchy that ends up with the generation of *image* and *reputation* predicates.

The cognitive aspect of the Repage model relies on that every predicate has associated a cognitive meaning (in terms of beliefs), and that final values of the predicates are as important as the previous steps to calculate them. For instance, the final probabilistic distribution obtained in an image predicate may come from the aggregation between several *communicated images* and an *outcome* predicate that comes from a contract and an fulfillment predicate. Because different network dependences could produce the same final value at the top of the hierarchy, this information may be very valuable, for instance when thinking about argumentation issues.

Also notice that we are not talking about *trust*. Following the definition of social cognitive trust given by Castelfranchi and Falcone in [7], *trust* can be seen as a mental state of the agent, so, a set of beliefs, desires and intentions. In this sense, if agent i has an image of certain agent j as a *seller*, this image can be part of the beliefs determining the *trust* of agent i in agent j regarding the role *seller*.

3 Multi-context Systems and BDI Agents

Multi-context systems (MCS) provide a framework to allow several distinct theoretical components to be specified together with the mechanisms in order to relate these components to one another [4]. These systems are composed of a set of contexts (or units), and a set of bridge rules. Each context can be seen as a logic and a set of formulas written in that logic. Bridge rules are the mechanisms to transfer information from one context to another.

Giunchiglia and Serafini [4] proposed the following formalization of MCS: Let I be the set of context names, a MCS is formalized as $\langle \{C_i\}_{i \in I}, \triangle_{br} \rangle$, where

- $C_i = \langle L_i, A_i, \triangle_i \rangle$, where L_i is a formal language with its syntax and semantics, A_i is a set of axioms and $\triangle_i$ the a set of inference rules. So, L_i and A_i define an axiomatic formal system, a logic for the context C_i. Besides axioms, it is possible to include a theory T_i as predefined knowledge. All A_i, $\triangle_i$ and T_i are written in the language L_i.
- $\triangle_{br}$ is a set of bridge rules.

Bridge rules can be seen as inference rules to exchange information between context. Each one has a set of antecedents (or preconditions) and a consequent (or postcondition). A bridge rule is typically represented as follows:

$$\frac{C_{i_1} : \varphi_1, \ldots, C_{i_n} : \varphi_n}{C_{i_x} : \varphi_x}$$

Each φ_i is a formula that belongs to its respective context, and written in its own language. So, when the formulas $\varphi_1, \ldots \varphi_n$ hold in their respective contexts, the formula φ_x is generated in the context C_{i_x}.

The use of MCS offers several advantages when specifying and modeling agent architectures [8]. From a software engineering perspective, MCS supports modular architectures and encapsulation. Each functional component and data structured component can be specified in separated contexts, and the links between them can be written explicitly by using bridge rules.

From a logical modeling perspective, it allows the construction of agents with different and well-defined logics, keeping all formulas of the same logic in their corresponding context. This considerably increases the representation power of logical agents, and at the same time, simplifies their conceptualization. Several works have appeared where MCS are used to specify agents. In our case, the specification of BDI architectures using MCS given in [9] and [10] are specially interesting, and thus they are the base of our theoretical framework.

In their BDI architecture they use one context for each attitude; So they have the believe context (B), the desire context (D) and the intention context (I). Each of them is equipped with a logic that corresponds to the premises that Rao and Georgeff [11] stated. So, belief context has the modal operator B, and the axioms K, D, 4 and 5 of modal logic. The desire context, the modal operator D and the axioms K and D, and the intention context, the modal operator I and the same axioms as D. The bridge rules between these contexts will determine the relationship between the attitudes and the type of agent (like Rao and Georgeff, they define three main types of agent, depending on these relationships: strong realism, realism and weak realism). They also included the communication context (C), which interacts with the exterior of the agent.

4 The Agent Model

In this section, we present our BDI agent model that is specified as a multi-context system. Before starting, we need to introduce some of the nomenclature we use.

4.1 Some Notation

We define the finite set $\mathcal{A} = \{i_1, \ldots, i_n\}$ and $VAgents = \{vi_1, \ldots, vi_n\}$ of agent identifiers and agent variables respectively, and the finite set $R = \{r_1, \ldots, r_p\}$ and $VRoles = \{vr_1, \ldots, vr_p\}$ of role identifiers and role variables respectively, where $n, p \in I\!N \geq 1$. Then, the expression $i : r$ means that agent i plays the role r (in the same way as explained in Section 2). We assume that actions can be seen as speech acts [12], and specified as illocutions. The same approach is taken by Esteva *et al.* in the specification of electronic institutions.

In our case, action expressions will follow the structure $\iota(i_v : r_v)$, where:

- ι is an illocution particle (so, an action descriptor. For instance, *Buy* or *Sell*).
- $i_v \in \mathcal{A}$ or $VAgents$.
- $r_v, \in R$ or $VRoles$.

Let e be an action expression, if i_v or r_v are variables, we say that e is an illocution schema, and it needs to be instantiated. We assume that our agents will have a set IL of illocution schemas. For instance, we can have the illocution schema $e = Buy(i_v? : seller)$, where $i_v \in VAgents$. Then, let $i \in \mathcal{A}$ we write $e[i]$ to indicate the instantiation of e with the agent i. So, $e[i] \equiv Buy(i : seller)$. With this notation, the set of primitive actions can be build as follows: $\{e[i] | e \in IL, \text{ where } i \in \mathcal{A}\}$. It is easy to see that more complex illocutions could be used, and in fact, should be used in more realistic environments. However since this is not the focus of this article and since they capture the current dynamics described in Repage [5], we leave it as future work.

Our cognitive agents evaluate other agents depending on the role they are playing. As we mentioned, in the Repage model the role determines the *action* and the attributes for which an agent doing it can be evaluated for (for the sake of simplicity, we consider that each role determines only one single action). For instance, agents playing the role *buyer* will evaluate agents playing the role *seller* regarding the *quality* of the product obtained after the action *buy*.

More formally, on the one hand the expression $\Phi(r)$ will represent the illocution schema with which the role r is associated. Then, concrete actions will be written with the expression $\Phi(r)[j]$ indicating the action associated with the role r instantiated with the agent j which plays the role r.

On the other hand, letting $q_1 \dots q_k$ be the attributes of role r where $k \in I\!N \geq 1$, and assuming that when an action is executed with a transaction identifier t, we write the result of this transaction t as $\delta_t(r).q_1 \dots \delta_t(r).q_k$. We use this transaction identifier to differentiate outcomes coming from several executions of the same action.

To illustrate this, we can define $\Phi(seller) = Buy(vi? : seller)$, where vi is an agent variable. Then, the expression $\Phi(seller)[j]$ stands for $Buy(j : seller)$. If the role *seller* is evaluated with the attribute *quality*, and the action is performed with a transaction identifier t, the expression $\delta_t(seller).quality = A$ will indicate that the quality obtained in the transaction t is A.

4.2 The Multi-context BDI Model

The specification of our BDI agent as a multi-context system is formalized with the tuple $Ag = \langle\{BC, DC, IC, PC, CC, RC, GrC\}, \triangle_{br}\rangle$, and it is based on the model designed in [10]. The first five contexts $\{BC, DC, IC, PC, CC\}$ correspond to Belief, Desire, Intention, Planner and Communication context respectively. The last two, $\{RC, GrC\}$, correspond to the Repage context and the Grounding context respectively. The set of bridge rules $\triangle_{br}$ incorporates the rules $1, 2, 3$ and 4, in Figure 2, and the bridge rules A, B, C, D and E, in Figure 3. Figure 1 shows a graphical representation of this multi-context specification. In the next sections, we briefly explain the logic of each unit and bridge rules[1].

Belief context(BC): The logic used in this context is based on the logic defined in [10]. The knowledge we are interested in representing are social evaluations that in terms of Repage, represent a probability distribution over a finite set of labels. The cognitive meaning of an Image of agent Ag describes a mental state that represents the expectation of the next interaction with Ag. For instance, an Image predicate with the value $(.5, .5, 0, 0, 0)$ means that the agent believes that it is equally probable $(.5)$ that the next interaction with Ag will produce a Very Bad result or a Bad result. In terms of logical expressions, this description requires a multi-valued logic with actions. Also

[1] The logic in each unit is based on the ones defined in [10], but not the bridge rules connecting Beliefs, Desires and Intentions. So, besides the incorporation of Repage Context and Grounding Context, the underlying BDI model we present is substantially different.

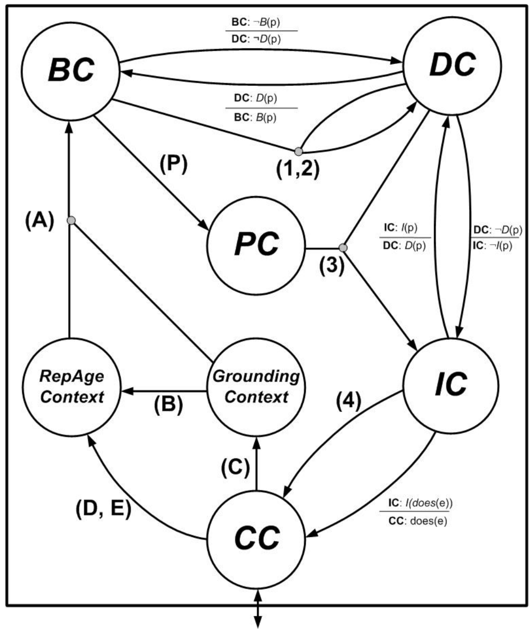

Fig. 1. The Repage context embedded in a strong realism multi-context BDI agent. Circles represent context and arrows represent bridge rules from one or more contexts to another one.

notice that the meaning of each label (*Very Bad*, *Bad* , ...) must be contextualized. The Grounding context is the responsible for this (see Section 4.2).

To define the logic of this unit, we use as a based propositional dynamic logic (PDL) with only simple actions, and it is defined in the classical way: Let Π be a set of primitive actions, all formulas in CP_0 are formulas in PDL. Furthermore, inductively, if $\alpha \in \Pi$ and φ in PDL, then $[\alpha]\varphi$ is also in PDL. Intuitively, the expression $[\alpha]\varphi$ means that after the execution of action α, the formula φ holds. These actions will be instantiations of all possible illocution schemas.

On this logic, we define the multi-valued logic BC by adding the fuzzy modal operator B over PDL formulas, together with a set of truth constants $\overline{z}$ (that we will call the degree of the fuzzy formulas), where $z \in [0,1] \bigcap \mathbb{Q}$, and using connectives from Lukasievick multi-valued logic. The complete syntax and semantics of the BC logic can be found in [10].

Intuitively, the expression $\overline{z} \rightarrow_L B\varphi$, where $\rightarrow_L$ is the implication of the Lukasievicz logic, means the belief that the probability of φ is at least z. We will write this expressions as $(B\varphi, z)$. Then, the expression $(B[\alpha]\varphi, z)$ means that the probability of holding φ after the execution of action α is at least z. These kinds of expressions will allow us to represent the knowledge of image predicates as a set of beliefs.

Desire context (DC): We use a similar logic as BC, but instead of the modal operator B, we introduce the modal operator D. It is also multi-valued. In this logic, we define two kinds of expressions: generic desires (found also in [10]) and realistic desires.

On the one hand, *generic desires* represent the desires that the agent has without taking into account any information on how to achieve them. The expressions $(D^{+}\varphi, z)$ and $(D^{-}\varphi, z)$ indicate that z is the level of satisfaction/disgust if the formula φ holds. Also, z can be seen as the strength As before, z is a normalized value included in the interval $[0, 1]$. On the other hand, *realistic desires* represent agents' desires already containing some information on how to achieve them. In this case, in the expressions $(D^{+}[\alpha]\varphi, z)$ and $(D^{-}[\alpha]\varphi, z)$, z represents the level of expectation of satisfaction/disgust upon achieving φ through the action α.

Generic desires are predefined preferences over possible situations that the agent wants to achieve or avoid, and they are totally independent of the agent's beliefs. Instead, concrete desires incorporate information on how to possibly achieve the desires by doing some action. For this reason, they depend on the current beliefs of the agent and the probability to achieve them. For instance, in human beings, the wish to win the lottery (generic desire), together with the knowledge of the low probability we have to win it by buying a ticket number (realistic desire), makes us realize that our expected level of satisfaction if we buy a number is very low. Maybe so low that we will not buy any.

Intention context (IC): The logic used here defines intentions as the desires that the agent has decided to achieve. To specify intentions we introduce the multi-valued modal operator I. We represent intentions as a trade-off between the expected level of satisfaction and the cost of carrying out the action. In this sense, in the expression $(I[\alpha]\varphi, z)$, z's close to 1 will indicate a good trade-off between the expected level of satisfaction of having φ by way of the action α and the cost of executing α.

Planner context (PC): The logic in the Planner context is a first-order logic restricted to Horn clauses. In this first approach, this context only holds the special predicate $action$, which defines a primitive action together with its cost. For instance, the action of buying from seller $S1$ at cost 0.6 is represented by $action(\lceil Buy(S1 : seller)\rceil, 0.6)$. We look forward to introducing plans as a set of actions in the future. The information in this context is provided by the beliefs of the agent (see bridge rule P). For each possible illocution, there is a predefined knowledge that indicates the cost of actually doing the action. In this paper we will assume that this cost is normalized in the interval $[0, 1]$.

Communication context (CC): This is a functional context whose logic is a first order logic restricted to Horn clauses, with several special predicates, *does*, *done* and *rec*.

When we let α be an action, the predicate $does(\alpha)$ means that the agent will actually execute that action. The predicate $done(\alpha_t)$ will be generated, where t indicates the transaction identifier. Also, this context is in charge of gathering all communications. The special predicate $rec_x(\beta)$ means that communication β has been received from agent x. At the moment, β can be either an expression of some communication language or a fulfillment predicate(*fulFill*), indicating the value of the attributes of a past transaction.

Bridge Rules 1, 2, 3, 4 and P: Bridge rules 1 and 2 transform generic desires, to more concrete and realistic desires. To do this, these bridge rules merge generic desires from DC (with absolute values of satisfaction or disgust) with the information contained in BC, which includes the probability to achieve the desire by executing certain actions. The result is a desire whose gradation has changed, becoming more realistic. This is calculated by the function g. If we define it as the product of both values, we obtain the expected level of satisfaction/disgust.

Bridge rule 3 generates intentions. These take into account both the expected level of satisfaction and the cost of the action. At the same time, executing an action to achieve a certain formula can generate undesirable counter-effects. Thus, bridge rule 3 also takes into account the possible negative desires that can be reached by executing this action. In this bridge rule, for each positive realistic desire (D^+), we must include all negative desires (D^-) that can result from the same action. The difference between the degree of a positive desire and the sum of the degrees of all negative desires that can be accomplished through the same action, can be seen as a measure of the global satisfaction level expectation on executing that concrete action. This value is combined with the cost of the action itself, that comes from the planner context. Notice that the degree of the intention is calculated by the function f. An equilibrate agent could define $f(c, d) = (d + (1 - c))/2$, with a normalized cost in $[0, 1]$ [10].

Bridge rule 4 instantiates a unique intention (the one with maximum degree) and generates the corresponding action in the communication context. The remaining bridge rules will be explained in the following subsections[2].

Finally, Bridge rule P informs to the planner context of the state of the world by generating all belief formulas as first order formulas in the planner context.

Grounding context & Rules B and C: This context is the responsible for the contextualization of the Repage labels, $\{VB, B, N, G, VG\}$, taking into account the role and the action that they refer to. So, it is context-dependent. For instance, the *meaning* of a VG (very good) transaction when buying fish is different from sending letters. The first one could imply a good quality on the fish, or a good price (or possibly a combination of the two), while the second one could imply a short delivery time.

Different attributes are valued in different transactions. Given that a transaction of a basic role r is evaluated through an attribute q, we define the predicate $\delta_t(r).q = C$ in the Grounding context which means that the attribute q of role r has had a value of C in the transaction whose identifier is t. The bridge rule C (see Figure 3) connecting the Communication context (CC) and the Grounding context (GrC) is responsible for generating these predicates in the Grounding context.

The Grounding context manages the discretization of attribute values into one of the five categories that Repage uses: $L = \{VB, B, N, G, VG\}$. To do so, we define for

[2] We assume that a bridge rule from CC to BC generates one belief for each action that is executed: $CC : done(e) \rightarrow BC : B(done(e))$

$$\textbf{1:}\quad \frac{DC : (D^+\varphi, d_\varphi), BC : (B([\alpha]\varphi), p_\varphi)}{DC : (D^+[\alpha]\varphi, g(d_\varphi, p_\varphi))}$$

$$\textbf{2:}\quad \frac{DC : (D^-\varphi, d_\psi), BC : (B([\alpha]\psi), p_\psi)}{DC : (D^-[\alpha]\varphi, g(d_\varphi, p_\varphi))}$$

$$\textbf{3:}\quad \frac{\begin{array}{c} DC : (D^+[\alpha]\varphi, \delta), PC : action(\alpha, c) \\ DC : (D^-[\alpha]\psi_1, \delta_{\psi_1}), \ldots, (D^-[\alpha]\psi_n, \delta_{\psi_n}) \\ \delta - \sum_{i=1}^{n} \delta_{\psi_i} \geq 0 \end{array}}{IC : (I[\alpha]\varphi, f(\delta - \sum_{i=1}^{n} \delta_{\psi_i}, c))}$$

$$\textbf{4:}\quad \frac{IC : (I[\alpha]\varphi, i_{max})}{CC : does(\alpha)}$$

$$\textbf{P:}\quad \frac{BC : B_i\varphi}{PL : \lceil B_i\varphi \rceil}$$

Fig. 2. The bridge rules 1,2, 3, 4 and P respectively (see Figure 1). The notation $\lceil \cdot \rceil$ used in rule P indicates a first-order formula.

each role r and attribute q five boolean functions $\varphi^q_{VB}(r), \ldots, \varphi^q_{VG}(r)$ that must ensure that for each possible value of the domain, one and only one of these functions returns *true*. The description of Repage [5] states that some predefined internal functions must generate an outcome (evaluation of a direct interaction) in terms of one of the elements of the set L, from a contract and a fulfillment received. We translate this idea to these five discretization functions for each role and attribute. The fact of externalizing this process carries an important advantage: it allows the possibility to change at run-time the functions, modifying then the concepts of Very Good or Very Bad of the agent, for instance.

We use these functions to feed the Repage context, by categorizing the values into the labels of the set Val. These functions will be defined by the initial theory of the grounding context, but have the possibility to be changed at run-time. The bridge rule B is used to feed the Repage context (RC) in terms of outcome predicates from GrC.

Repage context(RC): This context deals with social evaluations and therefore the creation of Image predicates. As we mentioned before, Repage generates Image predicates from direct experiences and communications. They are written as follows:

- $Img(A_1 : r, [V_{VB}, V_B, V_N, V_G, V_{VG}])$: Corresponds to the Image of agent A_1 playing role r. Here, vector $[V_{VB}, V_B, V_N, V_G, V_{VG}]$ is the value of the evaluation, that in Repage is a probability distribution over the set $\{VB, B, N, G, VG\}$. Each V_D indicates the probabilistic value of the element D belonging to this set.
- $ComImg(A_1, A_2 : r, [V_{VB}, V_B, V_N, V_G, V_{VG}])$, $ComTPImg(A_1, A_2, A_3 : r, [V_{VB}, V_B, V_N, V_G, V_{VG}])$: These correspond to predicates that come from communications: communicated Image and communicated

$$\textbf{A:}\quad \frac{\begin{array}{c} RC : Img(A_1 : r, [V_{VB}, V_B, V_N, V_G, V_{VG}]), \\ GrC : \varphi^q_{VB}(r), \ldots, \varphi^q_{VG}(r) \end{array}}{\begin{array}{c} BC : (B([\phi(r)[A_1]]\varphi^q_{VB}(r)(X)), V_{VB}) \\ \vdots \\ BC : (B([\phi(r)[A_1]]\varphi^q_{VG}(r)(X)), V_{VG}) \end{array}}$$

$$\textbf{B:}\quad \frac{GrC : \delta_t(r).q = C \wedge \varphi^q_V(r)(C) \wedge done(\phi_t(r)[A_1])}{RC : Outcome(A_1 : r, V)}$$

$$\textbf{C:}\quad \frac{CC : rec_{A_1}(fulFill(\phi_t(r)[A_1], q_1 = a_1, \ldots, q_n = a_n))}{GrC : \delta_t(r).q_1 = a_1 \wedge \cdots \wedge \delta_t(r).q_n = a_n}$$

$$\textbf{D:}\quad \frac{CC : rec_{A_1}(Img < A_1, A_2, r, [V_{VB}, V_B, V_N, V_G, V_{VG}] >)}{RC : ComImg(A_1, A_2 : r, [V_{VB}, V_B, V_N, V_G, V_{VG}])}$$

$$\textbf{E:}\quad \frac{CC : rec_{A_1}(Img < A_2, A_3, r, [V_{VB}, V_B, V_N, V_G, V_{VG}] >)}{RC : ComTPImg(A_1, A_2, A_3 : r, [V_{VB}, V_B, V_N, V_G, V_{VG}])}$$

Fig. 3. The bridge rules A,B, C, D and E respectively (see Figure 1). *We assume that* $X \equiv \delta(r).q$, *where* q *is an arbitrary attribute of the role* r. $A_1, A_2, A_3 \in Agents$

Third Party Image (a communicated image which the source of the image is not the same than the sender). The parameters with the addition of x as the source agent are the same as in the previous point. Parameter z is the source agent of the image in the case of third party image.

– $Outcome(A_1 : r, V)$: An outcome predicate is the evaluation of a direct and concrete experience the agent had. Here, V is one of the labels of the sorted set $\{VB, B, N, G, VG\}$.

The internals of Repage can be found in [5].

Bridge Rule A: The generation of an image predicate inside Repage generates five beliefs, one for each category (from VB to VG) while taking into account the functions defined in the Grounding context. Bridge rule A is in charge of this by grounding the abstract level of Repage predicates with their real contextualized meaning stored in the Grounding context. The intuitive idea is the following: Let's assume that an agent holds the following Image predicate: $Img(Ag : r, [V_{VB}, V_B, V_N, V_G, V_{VG}])$. Since Image represents the expected behavior of a certain target agent (in this case Ag) playing a certain role, in this case r, the agent holding it believes that after the execution of the action that defines the role r ($\phi(r)$) instantiated with the target agent Ag ($\phi(r)[Ag]$), with a probability of V_{VB} she will obtain a result that for her is classified as Very Bad, and with probability of V_{VG} that is classified as Very Good. These classifications are defined in the grounding context (φ functions).

Furthermore, because all φ functions of the same role and attribute divide the domain of the attribute in disjoint sets, we can add the appropriate inference rules to the BC to deal with conjunctions and disjunctions. For instance, if we have generated the predicates $(B[\alpha]\varphi^q_{VG}(X), i)$ and $(B[\alpha]\varphi^q_G(X), j)$, then we also have $(B([\alpha]\varphi^q_{VG}(X) \vee \varphi^q_G(X), i+j))$.

Bridge rules D and E: Rules D and E (Figure 3) show the reaction of the communication context once it receives communications of images and third party images from other agents. As we mentioned, Repage processes communicated images and third party images. Then, as soon as the communication context receives some of them, they can be inserted directly inside the Repage Context. Here, expressions like $Img < x, y, r, [V_{VB}, V_B, V_N, V_G, V_{VG}] >$ are part of a communication language (for instance, the one defined in [13] for this purpose). The above refers to the image that agent x has of agent y playing the role r.

5 A Practical Example

To illustrate the reasoning process of our BDI architecture we present a simple example based on the classic market metaphor. Our scenario is populated with buyers and sellers who interact. In this example we focus on the buyer who has to decide who is a good seller. All sellers sell the same products. Each product has associated a quality graded from 0 to 100 (lowest to highest quality). At each turn, buyer agents choose a seller and buy a product from her. To do so, they have to deliberate and pick the *best* seller.

Buyers evaluate sellers in terms of the attribute *quality* (q) of the product they sell. We assume that sellers always offer the same quality. We map this attribute to the sorted set $\{VB, B, N, G, VG\}$ in five equal parts. So, the Grounding context will incorporate the corresponding theory to store this information: for all $i \in \{VB, B, N, G, VG\}$, $\varphi^q_i(seller)$:$(0, 100] \rightarrow \mathcal{B}ool$. In particular, $\varphi^q_{VB}(seller)(X) = 0 < X \leq 20, \ldots,$ $\varphi^q_{VG}(seller)(X) = 80 < X \leq 100$. This mapping means that for an agent with this theory in the Grounding context, a very good seller sells products of quality higher that 80.

In this world buyer agents can only perform one action: *buy*. The general schema is: $buy(s : seller)$ where s is a seller agent.

5.1 Setting the state of the world

The scenario has a single buyer and three sellers named $S1, S2$ and $S3$. Suppose that the Repage context of the buyer agent has generated the following image predicates (how they have been generated is not relevant to our discussion).

$$Image(S1 : seller, [.1, .1, .1, .3, .4])$$
$$Image(S2 : seller, [.2, .2, .2, .2, .2])$$
$$Image(S3 : seller, [.4, .3, .1, .1, .1])$$

Due to bridge rule A, several beliefs are generated in the Belief context. For instance, for seller $S1$, the following instances of the bridge rule A are executed: (Let X be $\delta(seller).q$)

$$\frac{RC : Image(S1 : seller, [.1, .1, .1, .3, .4]), GrC : \varphi^q_{VB}(seller)}{BC : (B([buy(S1 : seller,)]0 < X \leq 20), .1)}$$
$$\vdots$$
$$\frac{RC : Image(S1 : seller, [.1, .1, .1, .3, .4]), GrC : \varphi^q_{VG}(seller)}{BC : (B([buy(S1 : seller)]80 < X \leq 100), .4)}$$

The generated beliefs describe the probabilities of achieving a certain quality depending on the seller if an interaction is produced. For example, $(B([buy(S1 : seller)] 0 < X \leq 20), .1)$ means that when buying at seller $S1$ there is a probability of 0.1 to obtain a product whose quality is below 20, meanwhile $(B([buy(S1 : seller)]80 < X \leq 100), .4)$ means that there is a probability of 0.4 that we obtain a product whose quality is higher than 80.

As a result of the new predicates in the Belief context, some inference rules in the same Belief context theory are fired. For instance, with the appropriate inference rule the predicate $(B([buy(S1 : seller)]40 < X \leq 100), .9)$, that is not directly generated by the rule A, would be generated from the predicates $(B([buy(S1 : seller)]40 < X \leq 60), .2)$, $(B([buy(S1 : seller)]60 < X \leq 80), .3)$ and $(B([buy(S1 : seller)]80 < X \leq 100), .4)$ by simply adding their fuzzy value, since they are completely disjoint and we are dealing with probabilities. This inference rule is totally context-dependent. We placed it ad-hoc for this example to show how other information may be deduced from predicates generated by the bridge rules.

On the other hand, the Planner context has the predicates describing the elementary actions with their cost. For the sake of simplicity, we suppose in this example that the cost is unitary and equal for all elementary actions[3]. In our case, because we have only three sellers, elementary actions refer to the action *buy* with each of the possible sellers:

$$action(buy(S1 : seller), 1)$$
$$action(buy(S2 : seller), 1)$$
$$action(buy(S3 : seller), 1)$$

5.2 Desire context

The desire to be satisfied leads the reasoning process. In this example, the buyer agent is more interested in buying a product whose quality is higher than 80. But if it were not possible, she would be satisfied with one rated between 60 and 80. At the same time, a product with a quality between 20 and 60 is not desirable, but the agent would prefer that to one whose quality is equal or less than 20. One way to model this situation inside

[3] We assume that bridge rule P has been activated. Also we omit the notation $\lceil\cdot\rceil$

the Desire context in terms of desire predicates is as follows (let X be $\delta(seller).q$):

$$\begin{gathered}(D^+(80 < X \leq 100), 1)\\(D^+(60 < X \leq 80), .8)\\(D^-(0 < X \leq 20), 1)\\(D^-(20 < X \leq 60), 0.6)\end{gathered}$$

Given that theory in the Desire context, generic desires, by means of bridge rules 1 and 2, become more concrete (and realistic) as soon as we add the information about the probability of success when executing the corresponding action. For instance, for the first positive desire and belief about seller $S1$ on the same interval, bridge rule 1 instantiates to:

$$\frac{\begin{gathered}DC : (D^+(80 < X \leq 100), 1),\\ BC : (B([buy(S1 : seller)]80 < X \leq 100), 0.4)\end{gathered}}{DC : (D^+([buy(S1 : seller)]80 < X \leq 100), g(1, 0.4))}$$

As a mater of example, we define function g as $g(d, p) = d \cdot p$. The product offers an intuitive view of an expected level of satisfaction/disgust since it combines a level of satisfaction/disgust with a probability. After the application of the bridge rules 1 and 2, the desire predicates involving seller $S1$ are:

$$\begin{gathered}(D^+([buy(S1 : seller)]80 < X \leq 100), 0.4)\\(D^+([buy(S1 : seller)]60 < X \leq 80), 0.24)\\(D^-([buy(S1 : seller)]0 < X \leq 20), 0.1)\\(D^-([buy(S1 : seller)]20 < X \leq 60), 0.12)\end{gathered}$$

5.3 Intention context

Intentions consider the cost and benefit of trying to accomplish a desire both in terms of its cost and its expected level of satisfaction. This expected level of satisfaction is calculated taking into account positive and negative expectations, since aforesaid the same action can generate both desirable and undesirable effects. Bridge rule 3 generates graded Intentions. For the predicates related to $S1$ and the first desire the bridge rule 3 is instantiated as follows:

$$\frac{\begin{gathered}DC : (D^+([buy(S1 : seller)]80 < X \leq 100), 0.4)\\ DC : (D^-([buy(S1 : seller)]0 < X \leq 20), 0.1)\\ DC : (D^-([buy(S1 : seller)]20 < X \leq 60), 0.12)\\ PL : action(buy(S1 : seller), 1)\end{gathered}}{IC : I([buy(S1 : seller)]80 < X \leq 100, f(0.18, 1))}$$

Each positive desire fires bridge rule 3 together with all instances of negative desires that can result from the same action.

After the activation of bridge rule 3 for each positive desire and considering, for instance, that $f(d, c) = (d + (1 - c))/2$ (so, supposing an equilibrate agent who gives the same importance to the cost and the satisfaction level), in IC we get:

$$\begin{gathered}(I[buy(S1 : seller)]80 < X \leq 100, 0.09)\\(I[buy(S1 : seller)]60 < X \leq 80, 0.01)\end{gathered}$$

Intentions with negative grades are filtered. We assume that an agent will never intend to do something that would bring overall negative consequences.

5.4 Communication context and Grounding context

Finally, bridge rule 4 generates the action to be performed in this context. Bridge rule 4 will be instantiated only one time with the intention of a maximum degree (that is, the one with the best trade off between expected level of satisfaction and the cost of the action). In the example, the bridge rule instantiates as follows:

$$\frac{IC : (I[buy(S1 : seller)]80 < X \leq 100, 0.09)}{CC : does(buy(S1 : seller))}$$

As a consequence of this action the predicate $done(buy(S1 : seller)_t)$ is generated (with the transaction identifier t) . Also, the agent receives a fulfillment predicate through its CC. Let's suppose that $S1$ offers products of quality 70, the communication $rec_{S1}(fulFill(buy(S1 : seller)_t, q = 70))$ is received, firing the bridge rule C as follows:

$$\frac{CC : rec_{S1}(fulFill(buy(S1 : seller)_t, q = 70))}{GrC : \delta_t(seller).quality = 70}$$

The new predicate inside GrC will fire the bridge rule B:

$$\frac{\begin{array}{c} GrC : \delta_t(seller).q = 70, \\ \varphi^q_G(70), done(buy(S1 : seller)_t) \end{array}}{RC : Outcome(S1 : seller, G)}$$

The outcome predicate indicates that the agent has had a direct experience with agent $S1$ as a $seller$ and that the transaction was good (G). Of course, this new information will affect the agent's image of $S1$ and the Repage context will modify the image predicate starting again the generation of new beliefs and so on.

6 Conclusions and future work

We have presented the first step towards the integration of a cognitive reputation model and a BDI agent architecture. The agent has been specified using multi-context systems and we have used an extended BDI architecture that allows for graded attitudes. These two characteristics facilitate a smooth integration of the reputation model and the rest of the elements of the agent architecture. In this first step we have integrated only the Image concept. In the future, we plan to do the same with the concept of Reputation. This is a challenging issue since the cognitive implications of reputation (as we understand it) in terms of beliefs, desires and intentions is not clear yet and requires further work. Our most ambitious work so far is related to giving the cognitive agent the necessary tools to reason about trust and reputation. One of these tools is the capability to communicate social evaluations in a structured way that includes some kind of justification about the main information communicated.

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A APPENDIX: The Repage Architecture

In this appendix we briefly explain the internal elements of Repage model that contribute to the generation of Image and Reputation predicates.

In the Repage architecture we find three main elements, a memory, a set of *detectors* and the *analyzer* (see figure 4). We focus on the memory. In there, predicates are conceptually organized in levels of abstraction and inter-connected. Each predicate that belongs to one of the main types (image, reputation, shared voice, shared evaluation, valued communication and outcome) contains an evaluation that refers to a certain agent in a specific role. As we mentioned, it maintains the value associated to a predicate as a tuple of five numbers (summing to one). Each number has an associated label in the rating scale: VB, B, N, G and VG. The network of dependences indicates which predicates contribute to the values of others. The aggregation of evaluations is done through a simple aggregation function (see [5]).

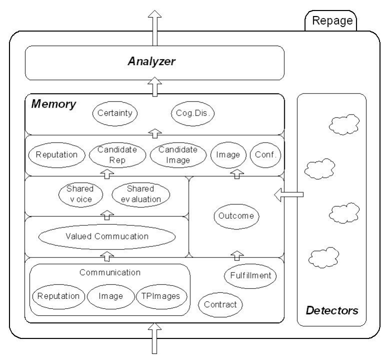

Fig. 4. The Repage Architecture.

At the first level of the Repage memory we find a set of predicates not evaluated yet. *Contract/Fulfillment* are agreements of the future interaction between two agents and the result respectively. *Communications* can be related to three different aspects: the image that the informer has about a target, the image that according to the informer a third party agent has, and the reputation that the informer has about the target.

In level two we have two kinds of predicates. A *Valued communication* is the subjective evaluation of the communication received that takes into account, for instance, the image the agent may have of the informer as informant. An *Outcome* is the agent's subjective evaluation of the direct interaction. From a fulfillment and a contract a *detector* builds up an outcome predicate that evaluates the particular transaction.

In the third level we find, on the one hand, a shared voice holding the information received about the same target and same role coming from communicated reputations. On the other hand, shared evaluation is the equivalent for communicated images and third party images. Shared voice predicates will generate candidate reputation, and share evaluation together with outcomes, candidate image. I they are strong enough they become reputation and image respectively. For details on the reminding elements we refer to [5].