The Influence of Personalities Upon the Dynamics of Trust and Reputation

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Abstract

When an agent resides in a community, the opinion of other community members concerning whether a particular individual is trustworthy or not influences the trust level of this agent. Hereby, the precise influence depends on the personality of the agent (e.g. whether he lets his opinion be influenced by others a lot). In this paper, a computational trust model which has dedicated parameters for agent personalities is applied to such a social context. A variety of different communities (containing agents with different personalities) have hereby been simulated. The resulting patterns hereof are shown in this paper. Furthermore, the simulation results are formally analyzed to show that certain patterns do occur in all different communities.

1. Introduction

Trust is a widely studied topic in Social Sciences and it is believed that the success of relations, alliances and communities is deeply rooted in the strength of trust among the members of the society [1]. Due to its importance, also in multi-agent systems research, it is considered to be one of the crucial factors in the modeling of societies, and as a result has been a topic of research for many years [2][3].

When looking more specific within trust research, trust dynamics within groups of agents is one of the topics addressed (whereby the overall trust of the group in one individual is referred to as the *reputation* [4]). Hereby, the reputation of an individual changes due to direct interaction of the individual with the members of the group and/or interaction of the members among each other, thereby communicating their experiences with the individual. In some cases, when the individual resides outside the community and the direct interaction with the individual lacks (e.g. historical figures) or is not frequent, the communication between the group members might be the prime factor which determines the reputation of this individual within the group. Furthermore, the personalities of the individuals play a crucial role: certain easily influenced agents in the group might for example be severely effected by feedback of other group members. These aspects make the dynamics of trust of the group members and the reputation of individuals an interesting process.

In this paper, the social dimension of trust and reputation is explored in different agent communities. An existing model for an agent's trust (cf. [5]) is adapted to a setting where agents give feedback about individuals to each other. Every agent has personality specific attributes, namely (1) *the awareness of history*, (2) *openness to the opinion of others*, and (3) *the dependencies between trust levels of individuals*. Variation in these attributes makes different agent personalities that generate different agent behavior, and hence diverse communities. These behaviors of the agents at the local level results in emergent patterns at the global level. The precise relationship between these local level setting and the global level is studied in this paper. Hereby, the trust level of the agents in the society on an individual is based on their initial trust value and communication among themselves, and it is assumed that individuals are not giving direct experience to agents. Besides the reasons given before, this has also been done to purely focus the research on the dynamics of trust given different personalities, and avoid any external influences (e.g. experiences with the individual). A variety of different personality settings are studied, and the patterns that emerge are investigated using formal verification techniques, to show how personality attributes influence the global patterns.

This paper is organized as follows. First, in Section 2 the model for trust and reputation in multi-agent system adopted is explained. Section 3 shows the communication setup used for the agents. Next, in Section 4 the model is used with agent communities based on different personality settings to investigate emergent patterns in trust and reputation. The formal verification of these results is presented in Section 5. Finally, Section 6 is a discussion.

2. Modeling Trust and Reputation in a Multi-Agent System

This section describes the model which is used to represent the trust an agent has on particular individuals.

Hereby, a trust model previously developed [5] is reused and made suitable for the scenario under investigation.

The model of trust of an agent in an individual as introduced in [5] is composed from two models: one for positive and the other for negative trust, accumulating positive and negative experiences from individual respectively. Here, direct experience of the agent with the individual is replaced by the feedback from other agents about the individual. Furthermore, in the model [5] an experience concerning an individual is a discrete value from set [-1, 0, 1] which is not capable of representing magnitude of experience. Hence, in the current model the feedback from agents is modeled as using a continuous value from the interval [-1, 1]. Both positive and negative trusts of an agent are represented by a number in the interval [0, 1]. Also agent *i*'s total trust on an individual *j* (say S_j) at time *t* is $T_{ij}(t)$ is a number in the range [-1, 1] and is calculated as the difference between positive and negative trust of the agent. Hereby, *-1* and *1* represent minimum and maximum values of the trust respectively:

$$T_{ij}(t) = T_{ij}^{+}(t) - T_{ij}^{-}(t)$$

In particular, also agent *i*'s initial trust of S_j at time point *0* is $T_{ij}(0)$ which is the difference of i's initial positive trust $T_{ij}^{+}(0)$ and negative trust $T_{ij}^{-}(0)$ in S_j. The change in positive and negative trust of agent *i* on individual *j* after receiving agent *k*'s feedback about individual *j* is modeled by the following equations:

$$\frac{dT_{ij}^{+}(t)}{dt} = \beta_i * \begin{pmatrix} \eta_i * \left(1 - T_{ij}^{+}(t)\right) + \\ \left(1-\eta_i\right) * \left(\tau_{ij}^{+}(t) - 1\right) \\ * T_{ij}^{+}(t) * \left(1 - T_{ij}^{+}(t)\right) \end{pmatrix} * M_{jk}(t) * \lceil M_{jk}(t) \rceil$$
$$- \gamma_i * T_{ij}^{+}(t) * \left(1 - (\lfloor M_{jk}(t) \rfloor + \lceil M_{jk}(t) \rceil)^2\right)$$

$$\frac{dT_{ij}^{-}(t)}{dt} = -\beta_i * \begin{pmatrix} \eta_i * \left(1 - T_{ij}^{-}(t)\right) + \\ \left(1-\eta_i\right) * \left(\tau_{ij}^{-}(t) - 1\right) \\ * T_{ij}^{-}(t) * \left(1 - T_{ij}^{-}(t)\right) \end{pmatrix} * M_{jk}(t) * \lfloor M_{jk}(t) \rfloor$$
$$- \gamma_i * T_{ij}^{-}(t) * \left(1 - (\lfloor M_{jk}(t) \rfloor + \lceil M_{jk}(t) \rceil)^2\right)$$

In this trust model several personality characteristics of the agents are included, namely *openness to opinions of others (β)*, *awareness of history (γ)* and *dependencies between trust levels of individuals (η)*. These are numbers from the continuous interval [0, 1]. The personality attribute called *openness (β)* represents to which extent the trust level at time point *t* will be adapted when the agent has a (positive or negative) feedback from another agent about some individual. *Awareness of history* (*γ*) represents the rate of trust decay of the agent on the individual over time (in particular when there is no feedback from other agents). *Dependencies between trust levels (η)* indicates in how far the trust of an agent on an individual is determined independent of trust in other individuals.

In the above equations, $M_{jk}(t)$ is the feedback about individual *j* given by agent *k* at time point *t*. This is a real number from the continuous interval [-1, 1] that represents the level of trust of agent *k* on individual *j* at time point *t*.

$$M_{jk}(t) = T_{jk}(t)$$

$\tau_{ij}^{+}(t)$ and $\tau_{ij}^{-}(t)$ represent the relative positive and relative negative trust of agent *i* on individual *j* that is the ratio of agent *i*'s positive trust upon individual *j* to the *i*'s average positive trust on all individuals, and the ratio of negative trust resp. The calculation of these values at time point *t* is defined below, here *n* is the number of individuals,

$$\tau_{ij}^{+}(t) = \frac{T_{ij}^{+}(t)}{\sum_{m=1}^{n} T_{im}^{+}(t) / n} \quad \text{and} \quad \tau_{ij}^{-}(t) = \frac{T_{ij}^{-}(t)}{\sum_{m=1}^{n} T_{im}^{-}(t) / n}$$

The change in the agent's total trust can be calculated as the difference of change in positive and negative trust of the agent as follows:

$$\frac{dT_{ij}(t)}{dt} = \frac{dT_{ij}^{+}(t)}{dt} - \frac{dT_{ij}^{-}(t)}{dt}$$

In the multi-agent system change in every agent's trust is modeled as described in the above equations. The trust is updated on every time step based on the feedback communicated by the other agents. The *reputation* $r_j(t)$ of individual *j* at time point *t* in the community of *m* agents is defined as the average trust of the community members on that individual:

$$r_j(t) = \sum_{i=1}^{m} T_{ij}(t) / m$$

3. Communication of Trust

In the model presented in Section 2 the agent's trust on an individual depends on the agent's initial trust and the trust feedback of other agents about the individuals. In the interaction among agents, it is assumed that all agents are centrally synchronized and at each time step one agent will receive feedback about the trust values of individuals from another agent in a predefined agent interaction protocol.

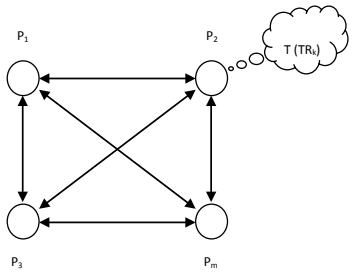

Figure 1. *m* agents communicating reputation of *k* individuals

The agent interaction protocol follows the right shift circular row major order of ardency matrix (see Table 1; numbers in the cells represent the order in which the feedback is sent) of the completely connected graph of agents (see Figure 1). This guarantees that every agent will send its feedback to other agents in the same pattern at an average of the time steps equal to the total number of agents present in the community. This gives a fair chance to every agent to give its opinion. On every received feedback from other agent in the group, the receiver's trust level is updated accordingly. Note, this update of the trust is based on the feedback sent by the other agents, and agent's the personality characteristics.

Table 1: Interaction protocol for four agents

Agents	A1	A2	A3	A4
A1	X	1	2	3
A2	6	X	4	5
A3	8	9	X	7
A4	10	11	12	X

4. Dynamics of Trust and Reputation in Different Aagent Communities

Using the model expressed in Section 2 and 3, this section studies the patterns of trust and reputation that occur in different agent communities. Agent communities are designed based on the personality attributes of agents present in the community. For experimental purposes these attributes are divided into two levels namely low and high (see Table 2). Low and high values of the attributes are selected in such a way that their change should be visible in different cases and should not superimpose the other attributes.

Table 2: Parameters used in model (*note that the parameter setting is the inverse of the actual meaning, high means a low parameter setting, and low a high parameter setting)

Parameter	Name	Low	High
Gama*	awareness of history	0.25	0.05
Beta	openness to other's opinions	0.25	0.75
Eta*	dependency between individuals	1.00	0.50

Using the values described in Table 2, four different personalities of the agents are classified in Table 3.

Table 3: Agent personalities with low and high values of the parameters

Agent Personality	Awareness of History	Openness to others Opinion
$\mathbf{P_1}$	High	Low
$\mathbf{P_2}$	High	High
$\mathbf{P_3}$	Low	Low
$\mathbf{P_4}$	Low	High

It should be noted that for experimental purposes and to maintain effectiveness of the presentation of results, the agent's personality attribute named dependency between individuals is not taken into account in the personalities described in Table 3. Rather the effect of this personality attributes (η) is studied in separate experiments. All experiments have been performed on a desktop computer with an Intel® Core™ 2 Duo 3GHz processor with 2 GB of RAM.

4.1 Experimental Configurations

This section describes the configuration for experiments that have been presented in the following sections (see Table 4). Here the number of agents, individuals, and the initial trust of the agents on the individuals are kept constant while the agents A_1. A_3, and A_2, A_4 are given the same initial trust values so that the effect of different personality attributes for the same initial trust values can be studied. Also, the initial trust of the agents on the individuals is set in such a way that the reputation of the individuals differs, so that dependencies between individuals can be analyzed. Hence, S_1, S_2, and S_3 have high, medium and low initial reputation in the system resp. Finally, the time step taken is 0.1, which is used to perform the calculation of the difference equations as presented in Section 2.

Table 4: Parameters used in model

Attribute	Value
Number of individuals	3
Number of Agents	4
Initial Trust of Agents A_1, A_2, A_3 and A_4 on individuals (S_1, S_2, S_3)	A_1={0.25, 0.25, 0.00}, A_2={0.00, -0.25, -0.25}, A_3={0.25, 0.25, 0.00}, A_4={0.00, -0.25, -0.25}
Initial Reputation of individuals (S_1, S_2, S_3)	0.125, 0.00, -0.125
Time Step	0.1

In the following sections the influence of the agents personality upon the dynamics of trust of the agents on the individuals are studied in communities where all agents have the same personality attributes (homogenous communities, Section 4.2 and 4.3) and also where agents having different personality attributes (heterogeneous communities, Section 4.4 and 4.5). Furthermore, the reputation of the individuals for the various settings is discussed in Section 4.6.

4.2 Dynamics of Trust in Homogeneous Agent Communities with Low Dependency

In this section, the trust dynamics are studied in communities whereby the personalities of the agents are homogeneous. In the simulations, the value of the agent's personality attribute trust dependency between individuals is kept low, which means that the calculation of trust on an individual, the agent will not consider the trust it has on other individuals. The experimental configurations are taken from Table 3 and 4.

The simulation results are shown in Figure 2, where the time and trust level are shown on the x and y axis

resp. Hereby, each graph represents a community with agents having personalities from Table 3 (i.e. Figure 2a represents an agent community of personality P_1, etc.). In all graphs, A_iS_j stands for agent A_i trust on individual S_j. As in this experiment agents A_1, A_3 and A_2, A_4 have the same initial trust values and personalities, only the trust levels of A_1 and A_2 are shown the graphs (which are identical to A_3 and A_4 resp.).

It can be seen that the communities of agents with high history awareness (Figure 2a and 2b) show a slower convergence of the trust value compared to the equivalent cases with low history awareness (Figure 2c and 2d). The figures also show that communities with high openness to others opinion (2b) end up in an equilibrium faster than the low openness personalities (2a). In Figure 2c the community of agents with low history awareness and low openness cannot retain their trust value for a substantial period, and drop their trust on individuals immediately showing equilibrium at zero trust value (neutral trust). In Figure 2d however, the community with high openness besides having low history awareness can attain a trust equilibrium without stabilizing at a trust value of zero. The thick lines in Figure 2d demonstrate the fluctuations in the trust values of agents due to the low history awareness in combination with the high openness, resulting in communication of other agents having a severe effect on the trust level. Here it should also be noted that the individual with an initial high reputation (S_1) also attains a stable reputation earlier than others.

4.3 Dynamics of Trust in Homogeneous Agent Communities with High Dependency

As there might be a dependency between the individuals (e.g. substitutable information sources). In the following section, the behavior of the model is analyzed with a setting of high dependency between individuals. This means that calculating trust on one individual, agent will give significant weightage to the trust on other (competitive) individuals as well. Here the increase in trust on one individual will affect others competitively. The values of the personality attributes and experimental configurations are taken from Table 3 and 4 respectively. The results of the simulations are represented in Figure 2e, 2f, 2g, and 2h.

In Figure 2e and 2f the communities of agents with high history awareness again can retain their trust value much longer. Here, the community with high openness (2f) attains higher values of the trust than the low openness (2e). In Figure 2g a community of agents with low history awareness and low openness again cannot retain their trust value for a longer period, and drop their trust on all individuals immediately showing an equilibrium at a trust value of zero. In Figure 2h the community with low history awareness and high openness can attain a slightly higher trust in the beginning compared to case (2c) without trust dependency, but the trust soon stabilizes at a trust value of zero as well. When looking at the competitive aspect that has been introduced through the parameters, the

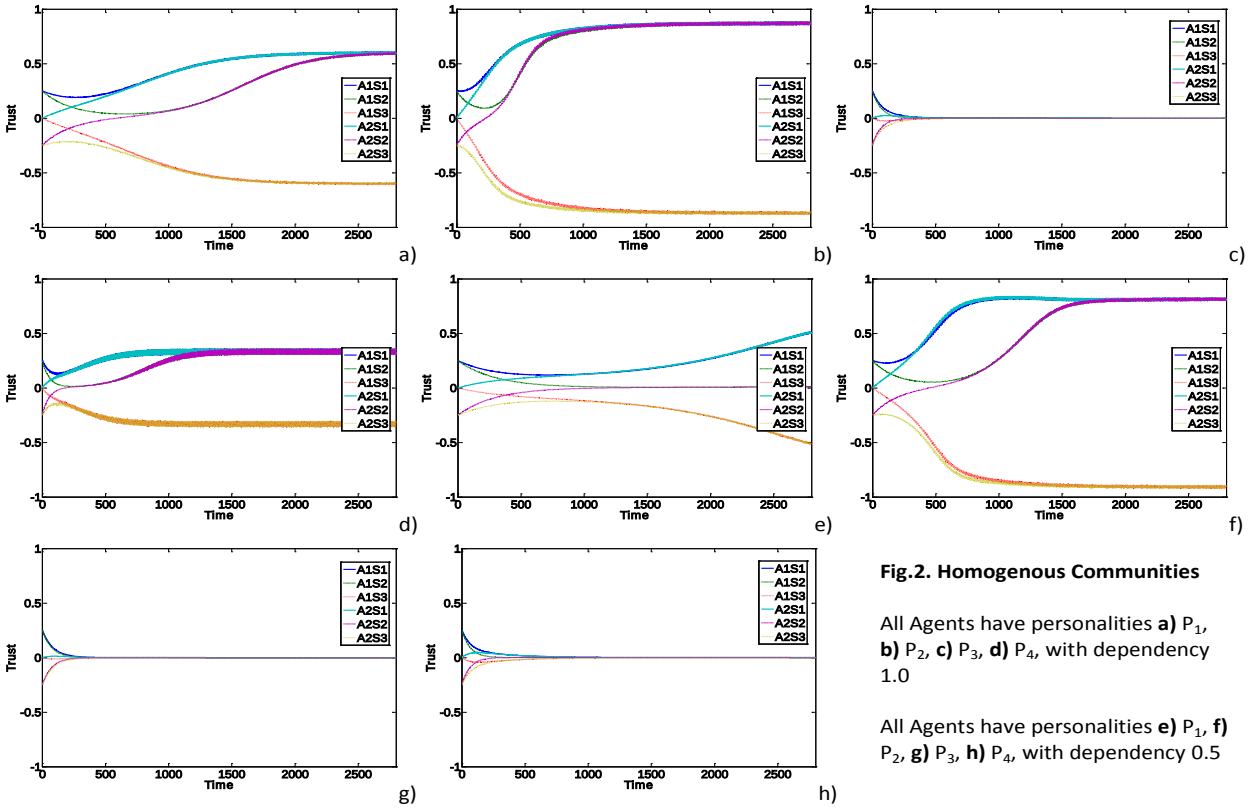

Fig.2. Homogenous Communities

All Agents have personalities **a)** P_1, **b)** P_2, **c)** P_3, **d)** P_4, with dependency 1.0

All Agents have personalities **e)** P_1, **f)** P_2, **g)** P_3, **h)** P_4, with dependency 0.5

community with low openness (2e, 2g) shows this competitiveness quite clearly through keeping the individual with an initial neutral reputation (S_2) low in curves compared to the individual with an initially high reputation (S_1) in the community.

4.4 Dynamics of Trust in Heterogeneous Agent Communities with Low Dependency

In this section, the behavior of the model is analyzed in communities where agents have heterogeneous personalities. For the following simulations the value of agent's personality indicating the dependency between trust levels of individuals is set to low. The results of the simulation for these communities are shown in Figure 3. In Figure 3, for the sake of presentational clarity of the results, two graphs are shown per setting, whereby each graph shows the trust levels of two agents.

The community in Figure 3a1 and 3a2 has four agents A_1, A_2, A_3 and A_4 with personalities P_1, P_1, P_4 and P_4 resp. Here A_1 and A_2 have high history awareness and low openness and A_3 and A_4 have low history awareness and high openness. It can be seen that agents A_1 and A_2 retain their previous trust value, and gain highest trust on the individual with an initially high reputation (S_1), and the individual with an initially neutral reputation (S_2). Hereby, S_1 gets this high trust level a substantial period before S_2. Furthermore, agents A_1 and A_2 have the lowest trust level on the individual with an initially negative reputation (S_3). A_3 and A_4 with low history awareness and high openness maintain equilibria which are less extreme (i.e. closer to neutral) than agent A_1 and A_2. The community in Figure 3b1 and 3b2 has four agents, whereby agent A_1 and A_2 have high history awareness and high openness and A_3 and A_4 with low history awareness and low openness. Here, A_1, A_2, A_3 and A_4 have almost the same pattern of trust for S_1, S_2 and S_3 as in Figure 3a. The only difference is that A_1 and A_2 in Figure 3a1 have low openness and in Figure 3b1 have high openness. This makes their trust values higher in Figure 3b1 than in Figure 3a1 and similarly lower in 3b2 than 3a2. The community in Figure 3c1 and 3c2 has four agents: A_1 has high history awareness and low openness, A_2 has high history awareness and high openness, A_3 and A_4 have low history awareness and low openness. Here, A_2 attains the highest trust values compared to other agents due to high history awareness and high openness. Agent A_1 (with high history awareness and low openness) attains the second highest values. Also, A_3 and A_4 have the lowest trust values due to low history awareness and low openness. Three equilibria can be distinguished on each side of the x-axis due to three different personalities of the agents present in the community. The community in Figure 3d1 and 3d2 has four agents: A_1 with high history awareness and low openness, A_2 with high history awareness and high openness, A_3 and A_4 with low history awareness and high openness. The pattern of the graphs is almost the same as in Figure 3c. The only difference is that the agents A_3 and A_4 of Figure 4d are much more open to the opinion of others than the personalities of agents A_3

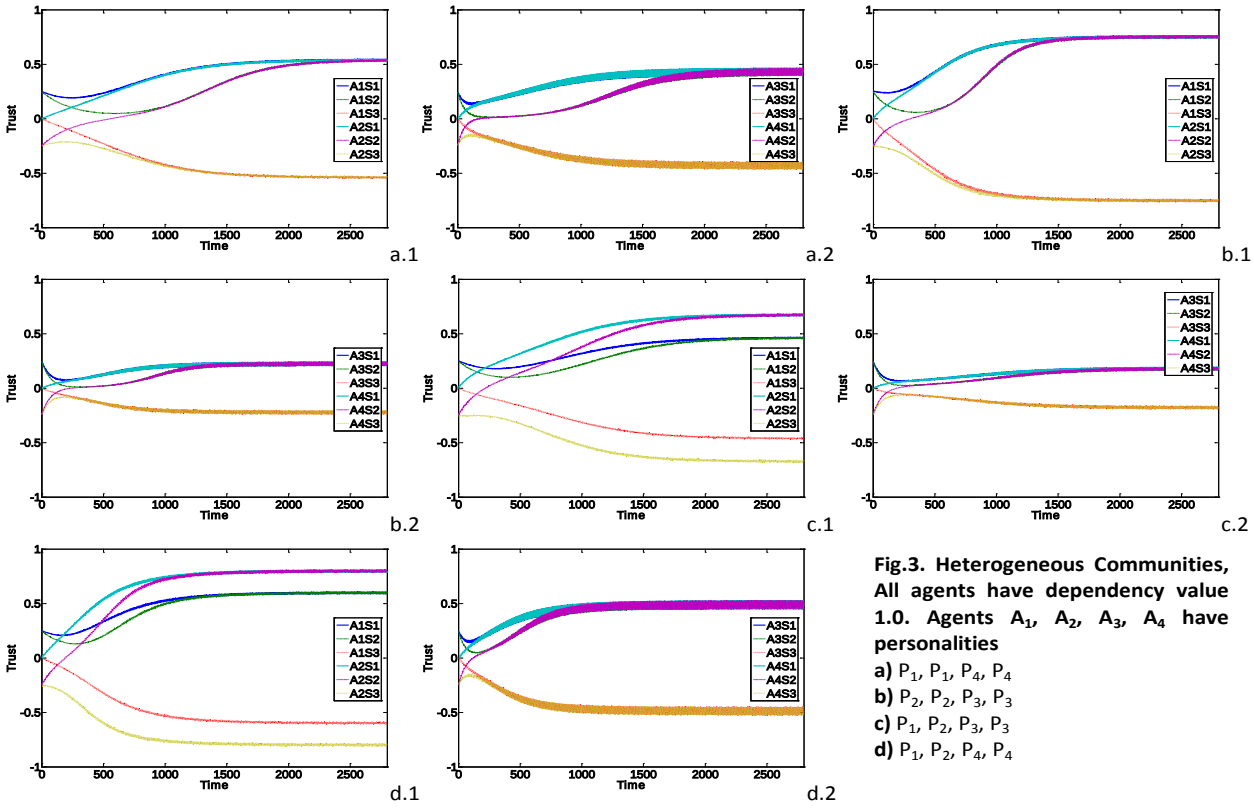

Fig.3. Heterogeneous Communities, All agents have dependency value 1.0. Agents A_1, A_2, A_3, A_4 have personalities

a) P_1, P_1, P_4, P_4

b) P_2, P_2, P_3, P_3

c) P_1, P_2, P_3, P_3

d) P_1, P_2, P_4, P_4

and A_4 in Figure 3c. This makes the trust values of the agents in Figure 3d more extreme compared to the values in Figure 3c. This shows that the attributes of the agents have a significant effect on the community.

4.5 Dynamics of Trust in Heterogeneous Agent Communities with High Dependency

The behavior of the model is studied in communities having heterogeneous personalities with high dependencies between the trust levels of the individuals. The experimental results are shown in Figure 4. Here it could be noted that due to the high dependency between individuals the trust values of the agents on individuals are lower in Figure 4 than Figure 3. Furthermore in Figure 4 several different equilibria can be distinguished among the trust values of the agents. This is already observed in Figure 2 as in the communities with a high dependency among individuals, the individuals with an initially low reputation obtain a lower trust value than individuals with an initially high reputation thereby producing different trust equilibriums.

4.6 Dynamics of Reputation of Individuals in different Agent Communities

Finally, in this section the dynamics of the reputation of individuals in different communities are described. It is observed that the individual with initially negative reputation (S_3) in the system can at most obtain a neutral reputation (zero). This only holds in communities where there is low history awareness and low openness to others opinion (see e.g. Figure 2c, 2g and 2h). Otherwise, the negativity of the reputation of the individual increases over time and stabilize afterwards. The dynamics of the reputation of individuals with an initially high reputation (S_1) in the community is approximately the same, but in the opposite direction. Hereby, only in the communities where there is low history awareness and low openness to others opinion (see Figure 2c, 2g and 2h) the reputation decreases and stabilizes at a neutral reputation level. Otherwise, the positivity of reputation of the individual increases over time and stabilizes afterwards. An individual with a neutral reputation (S_2) in the community always ends up with a lower reputation in the community than the individual with an initially high reputation, however this difference becomes smaller over time. In the case of a community where the agents have high history awareness, low openness, and a high dependency between trust levels of individuals, the reputation of an individual with an initially neutral reputation becomes stable at a relatively low point compared to the individuals with an initially high reputation (see Figure 2e, 4a, and 4c). In Figure 4b and 4d where agents have high openness this also appears to occur, but this is due to the length of the simulation. The simulations have however also been conducted for a longer period of time, the results of which show that this phenomena eventually does not occur.

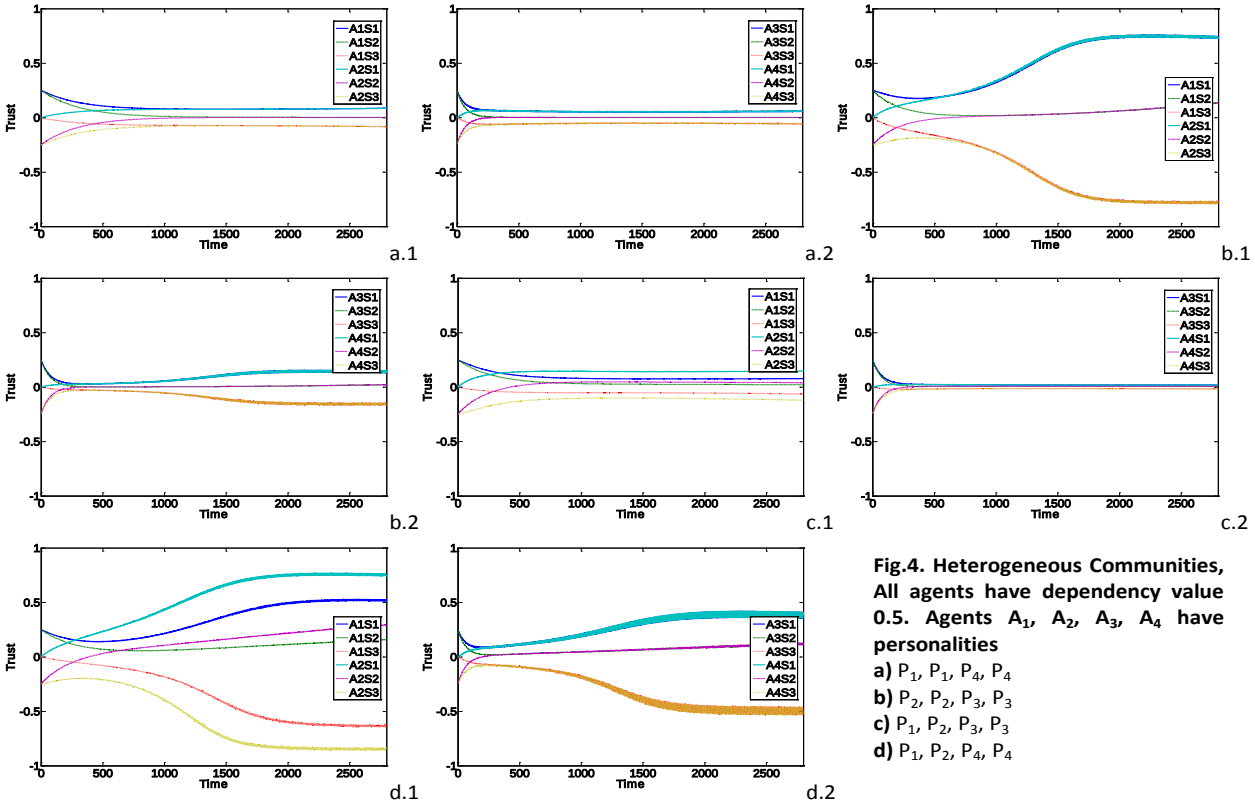

Fig.4. Heterogeneous Communities, All agents have dependency value 0.5. Agents A_1, A_2, A_3, A_4 have personalities

a) P_1, P_1, P_4, P_4
b) P_2, P_2, P_3, P_3
c) P_1, P_2, P_3, P_3
d) P_1, P_2, P_4, P_4

5. Formal Verification

Besides merely presenting the graphs of the simulations, also properties have been specified which express certain expected patterns of the trust and reputation over time. These properties are based upon observations as they are seen in the real world. This way, it can be shown that the presented approach indeed is able to generate realistic patterns. These properties are specified in a logical format, enabling an automated verification. First, the logical language and tools used are explained. Thereafter, the properties and the result of the verification are shown.

5.1 Temporal Trace Language (TTL)

The verification of properties has been performed using a language called TTL (for Temporal Trace Language) [6] that features a dedicated editor and an automated checker. This predicate logical temporal language supports formal specification and analysis of dynamic properties, covering both qualitative and quantitative aspects. TTL is built on atoms referring to *states* of the world, *time points* and *traces*, i.e. trajectories of states over time. In addition, *dynamic properties* are temporal statements that can be formulated with respect to traces based on the state ontology Ont in the following manner. Given a trace γ over state ontology Ont, the state in γ at time point t is denoted by state(γ, t). These states can be related to state properties via the infix predicate |=, where state(γ, t) |= p denotes that state property p holds in trace γ at time t. Based on these statements, dynamic properties can be formulated in a sorted first-order predicate logic, using quantifiers over time and traces and the usual first-order logical connectives such as $\neg$, $\wedge$, $\vee$, $\Rightarrow$, $\forall$, $\exists$, see [6].

5.2 Properties

Below, the properties that have been verified are shown. First, the ontology used in these properties is expressed in Table 5.

Table 5. Ontology used in properties

Predicate	Explanation
highest_trust_level: AGENT x INDIVIDUAL	The agent has the highest trust value on the specified individual of all agents.
lowest_trust_level: AGENT x INDIVIDUAL	The agent has the lowest trust value on the specified individual of all agents.
has_trust_level_on: AGENT x INDIVIDUAL x REAL	The agent has the specified trust level on the individual.
has_reputation_level: INDIVIDUAL x REAL	The individual has a particular overall reputation.
stable_trust_level: AGENT x INDIVIDUAL x REAL x REAL	The specified agent has a stable value on the individual which is centered around the real value specified, and has a deviation of the specified value.
stable_reputation_level : INDIVIDUAL x REAL x REAL	The reputation of the individual has a stable value which is centered around the real value specified, and has a deviation of the specified value.

The first property which has been specified concerns the occurrence of a stable trust point within the traces.

RTP1(P): Stable point trust

For all agents and individuals there exists a time point such that after that a stable trust point occurs which does not fluctuate more than P.

$\forall\gamma$:TRACE, A:AGENT, I:INDIVIDUAL
[$\exists$t:TIME [$\forall$t2:TIME > t, r:REAL, p2:REAL
  [state(γ, t2) |= stable_trust_level (A, I, r, p2) $\Rightarrow$ p2 < P]]]

This property is satisfied for all traces with a setting of P=0.04. Besides the stable trust point, also the influence of other group members is an interesting element in this setting. Hereby, first a property is specified about group members that decrease the trust level of the agent which currently has the highest trust level. Thereafter, a property expresses the opposite.

RTP2(D): Negative influence of group

if an agent has the highest trust level t for an individual i in the group, then within D time this trust level will go down.

$\forall\gamma$:TRACE, A:AGENT, I:INDIVIDUAL, r:REAL, t:TIME
[[state(γ, t) |= highest_trust_level(A, I) &
  state(γ, t) |= has_trust_level_on(A, I, r)]
 $\Rightarrow$ $\exists$t2:TIME > t & t2 < t + D, r2:REAL
  [state(γ, t2) |= has_trust_level_on(A, I, r2) & r2 < r]]

This property is satisfied for all traces with a setting of D = 20 time steps.

RTP3(D): Positive influence of group

If an agent has the lowest trust level t for an individual i in the group, then within D time this trust level will go up.

$\forall\gamma$:TRACE, A:AGENT, I:INDIVIDUAL, t:TIME
[[state(γ, t) |= lowest_trust_level(A, I) &
  state(γ, t) |= has_trust_level_on(A, I, r)]
 $\Rightarrow$ $\exists$t2:TIME > t & t2 < t + d, r2:REAL
  [state(γ, t2) |= has_trust_level_on(A, I, r2) & r2 > r]]

This property is again satisfied for all traces for D = 20. Besides the patterns on the individual trust level, properties have also been expressed on the combination of trust levels of all agents about an individual, the reputation. The first property addresses the occurrence of a stable reputation point.

RRP1(P): Stable point reputation

For all individuals there exists a time point such that after this a stable reputation point occurs which does not fluctuate more than P.

$\forall\gamma$:TRACE, I:INDIVIDUAL
[$\exists$t:TIME [$\forall$t2:TIME > t, R:REAL, P2:REAL
  [state(γ, t2) |= stable_reputation_level (I, r, P2) $\Rightarrow$ P2 < P]]]

This property is satisfied for the setting P=0.02. Finally, the last property expresses that once an individual has the highest reputation, the individual will remain the highest.

RRP2: High reputations remain

If an individual i initially has the highest reputation, then this reputation will never become lower than the reputation of other individuals.

$\forall\gamma$:TRACE, I:INDIVIDUAL
[highest_reputation(γ, I, 1) $\Rightarrow$ $\forall$t:TIME [highest_reputation(γ, I, t)]]

Where

highest_reputation(γ:TRACE, I:INDIVIDUAL, t:TIME) ≡
∀r:REAL
[state(γ, t) |= reputation(I, r) ⇒ ∀I2:INDIVIDUAL, R2:REAL
[[state(γ, t) |= has_reputation_level(I2, r2) & r2 ≥ r] ⇒ T2 = T]]

This property is also satisfied for all traces.

6. Discussion

In this paper, an existing computational trust model [5] has been taken as a basis, and has been modified to apply the model in a social context. Hereby, the setting included a group of agents that exchange their trust level about certain individuals, and update their trust value based upon these communications. The agents are not influenced by actual experiences with individuals to avoid the distortion of the group process, and the resulting trust level. This study is applicable particularly when the individual resides outside the community, and the direct interaction with the individual lacks (e.g. historical figures) or is not frequent. The personalities of the agents in the group have been varied by changing parameter settings in the computational model. The parameters include the awareness of history, the openness to others opinion, and the dependency between agent's trust level of different individuals. Simulation runs have been performed, showing interesting patterns in communities. Hereby, communities consisting of homogeneous and heterogeneous agents have been investigated, showing quite diverse results. As expected, individuals with high awareness of history, and low openness tend to stick to their initial opinion longer, whereas individuals that are more open to others, or have a lower awareness of history, tend to move towards newer trust values faster. Furthermore, in case trust levels of individuals are dependent upon each other, the trust levels tend to diverge more, which is in accordance with the results shown in [5]. Finally, the results have been formally analyzed, thereby showing that stable trust levels eventually occur, and showing how the most positive agents are negatively influenced by the group, and vice versa. Moreover, the persistence of high reputation was also shown to hold.

In the research of trust and reputation in agent communities (see [7]-[12]) personality attributes of the agents involved have not been investigated in depth. In [11] the notion of a personalized rating is used to calculate the trust and reputation in an agents community, which is based on an agent bias towards the context rather than the agent's personality attributes. In [12] a model is proposed which includes the influence of social structure on trust and reputation. The work by Sabater and Sierra [13] is closely related to the work presented in this paper, as they develop a system structure called **Regret** in which they model the reputation of agents. One of the ways to form such a reputation is by using the social dimension, not via actual interaction with the agents. Hereby, one option included in the system is to retrieve the reputation via witnesses that did have direct interaction with the agent. General personality attributes of agents, i.e. awareness of history, dependencies of trust levels, and openness are however not considered in such depth as in this paper.

For future work, larger communities will be investigated, and also the trust level of the agents upon each other will be investigated (one might trust the opinion of an agent more than another). Finally, instead of the current sequential communication, parallel communication will be investigated as well thereby allowing the mathematical model to be analyzed, and hence, define equilibria up front.

7. References

[1] F. Fukuyama, Trust: the social virtues and the creation of prosperity, Free Press, 1996.

[2] T.D. Huynh, N.R. Jennings, and N.R. Shadbolt, An integrated trust and reputation model for open multi-agent systems, Autonomous Agents and Multi-Agent Systems, vol. 13(2), 2006, pp. 119-154.

[3] S.D. Ramchurn, , D. Huynh, and N.R. Jennings, Trust in multi-agent systems, Knowledge Engineering. Review, vol. 19(1), 2004, pp. 1-25.

[4] A. Jøsang, R. Ismail, and C. Boyd, A survey of trust and reputation systems for online service provision, Decision Support Systems, vol. 43(2), 2007, pp. 618-644.

[5] M. Hoogendoorn, S.W. Jaffry, and J. Treur, Modeling Dynamics of Relative Trust of Competitive Information Agents, Proceedings of the 12th international workshop on Cooperative Information Agents XII, Springer-Verlag: Prague, Czech Republic, 2008, pp. 55-70.

[6] T. Bosse, C.M. Jonker, L. van der Meij, A. Sharpanskykh, and J. Treur, Specification and Verification of Dynamics in Agent Models, International Journal of Cooperative Information Systems, vol. 18, 2009, pp. 167-193.

[7] L. Mui, M. Mohtashemi, A. Halberstadt, A Computational Model of Trust and Reputation for E-businesses, Proceedings of the 35th Annual Hawaii International Conference on System Sciences, 2002, pp. 188.

[8] Y. Wang, J. Vassileva, Trust and Reputation Model in Peer-to-Peer Networks, Proceedings of The Third IEEE International Conference on Peer-to-Peer Computing, 2003.

[9] S. Zhang, D. Lu, Y. Yang: A Fuzzy Set Based Trust and Reputation Model in P2P Networks, IDEAL 2004, pp. 211-217.

[10] R. Aringhieri and D. Bonomi. A Simulation Model for Trust and Reputation System Evaluation in a P2P Network. In Computational Intelligence, Theory and Application, Proceedings of International Conference 9th Fuzzy Days, 2006, pp, 169-180.

[11] L. Mui, Computational Models of Trust and Reputation: Agents, Evolutionary Games, and Social Networks, Ph.D. Dissertation, Massachusetts Institute of Technology, 2003.

12] J. Patel, A Trust and Reputation Model for Agent-Based Virtual Organisations. PhD thesis, University of Southampton, 2006.

[13] J. Sabater and C. Sierra, Reputation and social network analysis in multi-agent systems, Proceedings of the First international Joint Conference on Autonomous Agents and Multiagent Systems, 2002, pp. 475-482.