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Emergent Behaviour Techniques in Multi-Agent Systems

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Key Aspects of Virtual Organizations

- VE composed of a number of autonomous entities (representing distinct companies, departments, individuals, etc.) each of which has certain problem-solving capabilities and resources available
- These entities co-exist, collaborate, and sometimes compete with one another in a virtual space (representing e.g. a market, a specific research area, etc.)
- Individual entities may advertise their capabilities to their peers, and then enter into different agreements/contracts with the other entities
- Where appropriate, groups of entities may form alliances or coalitions in order to carry out some overall activity cooperatively
- All of the above aspects are highly dynamic: entities may appear and go, capabilities may change over time, and coalitions may be created, improved, reformed or dissolved (coalition life-cycle)

Distributed Artificial Intelligence (DAI)

- DAI studies behavior of sets of autonomous units - called information agents (these are different from software agents known in Software Engineering)
- Fundamental questions:
  - how to decompose the tasks into subtasks
  - how to communicate
  - how to allocate problem-solving resources (knowledge and capabilities) in a coordinated or even cooperative way
- Ideal situation:
  - a multi-agent community organized as a "flat structure" of agents which communicate into peer-to-peer way by message passing
  - no central unit in the community
  - each agent has certain problem-solving capabilities and owns part of the global strategy knowledge (these parts owned by different agents can overlap)

Structure of this Talk

1. Multi-Agent Techniques (state-of-the-art)

2. Emergent Behaviour (incl. examples)

3. Conclusions (applicability of MAS techniques to VEs)

Part 1

Multi-Agent Technology

Main Aspects of Multi-Agent Systems

Communication:

- peer-to-peer versus
- via a central element

Knowledge:

- problem-solving
- social

Rational behavior:

- reactive
- intentional

Communication:

- simple exchange of pieces of information
- negotiations based on well-developed scenarios

Negotiations lead to:

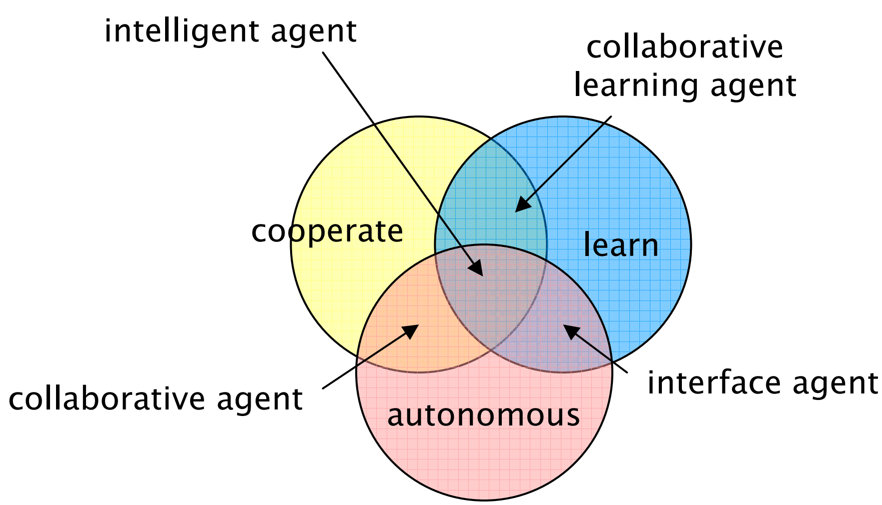
- coordination
- cooperation

Agent Technology for VE

- The agent technology (= result of the Artificial Intelligence research) is a good paradigm supporting - from the technical point of view - the virtual enterprises in manifold ways:
  - good motivation as it provides explanation of many processes in VE
  - helps to understand the role of knowledge and needs in appropriate knowledge organization
  - enables to simulate the VE behavior
  - provides technical infrastructure for automatic or semi-automatic communication and negotiation scenarios

Who/What is an Agent?

- Agent is an encapsulated computational system, that is situated in some environment, and that is capable of flexible, autonomous behaviour in order to meet its design objective.
- An agent is not only an object, process, program, computer, ..
- Agents can be standalone or members of a multi-agent system



Agents – what are they like?

- autonomous - agents are proactive, goal-directed and act on their own performing tasks on your behalf without necessarily requiring user initiation, confirmation, and notification, do not have to be benevolent, have free will, can cheat, can leave/join the community
- reactive - agents are triggered by events and sensitive to real-time domain considerations; able to sense and act
- intentional - ability to maintain agents long term intention, organize its behavior in order to meet targeted goals, agent that uses speech-act-based communication (see ACL), formulates plans in pursuit of its own agenda, and uses reflective reasoning.
- social - agents collaborate together in communities to achieve a shared goals, they are aware one of the other, they perform reasoning about each other. can group into coalitions, teams, they can benefit from this

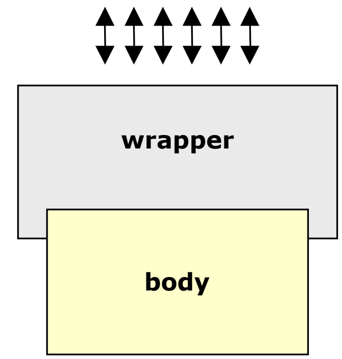
Agents – what are they like?

- adaptive - agents dynamically adapt to and learn about their environment. They are adaptive to uncertainty and change. They can adapt and improve their social role.
- cooperative - agents coordinate and negotiate to achieve common goals. They are self-organizing and can delegate.
- mobile - agents move to where they are needed, possibly following an itinerary
- interactive - agents interoperate with humans, other agents, legacy systems, and information sources
- rational agent – autonomous, at least reactive, based on rules enabling to optimize its profit

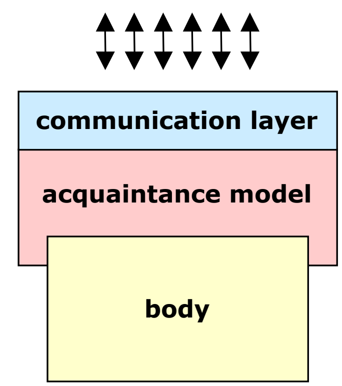
important: the social aspect of the agency, agents social knowledge and social intelligence.

Architecture of an Agent

- Usualy an agent consists of
  - wrapper and
  - body



- The body will be regarded to have no awarness about the com-munity and the wrapper will be responsible for planning and carrying out social interaction in the broader sence (which is not the case of an ordinary agents)



- The wrapper thus consists of
  - communication layer
  - acquaintance model

What do we want from them?

- we will be commenting the agent's ability to:
  - delegate responsibility,
  - decompose a task into subtask,
  - contract optimal collaborators,
  - form team and coalitions,
  - findout a missing information …
- this usually a task of facilitators and information brokers, mediators, matchmakers or middle agents – these are usually part of the multiagent platform, centralised, bottleneck of the community operation

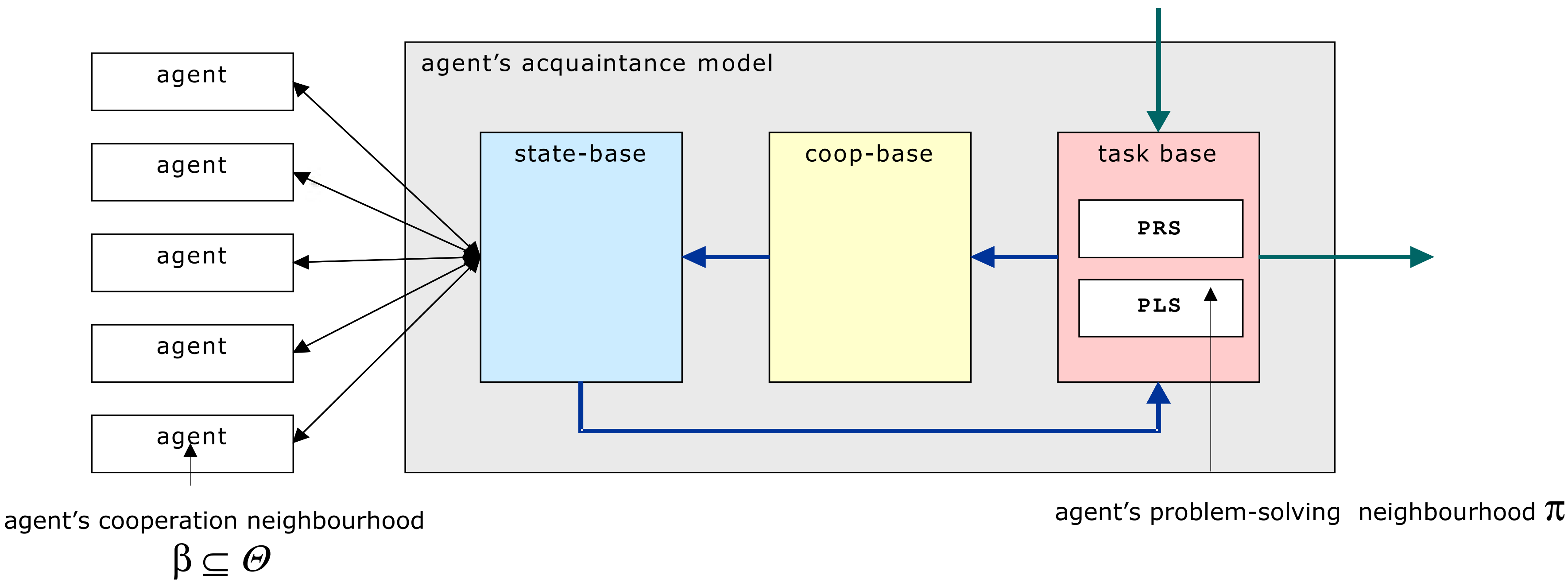
utilisation of acquaintance models will keep the agents independent, (allowing them to make autonomous decision making), the entire community more robust and efficient communication traffic

Concept of Social Knowledge

- agent's knowledge is either:
  - problem solving knowledge – "asocial" type of skill – guide agent's autonomous local decision making processes (aimed e.g. at providing an expertise or search in the agent's database)
  - self knowledge – knowledge about agent's behavior, status and commitments (a special instance of social knowledge – below)
  - social knowledge – knowledge about other agent's behavioral patterns, their capabilities, load, experiences, commitments, but also knowledge and belief

the domain of software integration and agentification – we will be discussing the role of social knowledge when encapsulating an already existing piece of software in multi-agent community

Tri-base Acquaintance Model (3bA)



Knowledge Maintenance

- cooperator-base is semi-permanent
- task-base PRS is permanent and PLS is maintained by replanning
- state-base is maintained either by:
  - periodical revisions – tried out, good for frequent changes and infrequent meta-reasoning
  - subscription based maintenance – suitable in communication intensive applications (an information push)
  - blackboard based maintenance – centralistic approach (fragile)
  - non-cooperative knowledge maintenance – intrusion detection, visualization, etc.

Intentional Agents

- Can deliberate about explicit representation of the environment, its own status, goals, progress of problem solving, they perform symbolic reasoning.

$$\wp(\text{knowledge}) \times \wp(\text{model}) \times \text{percept} \rightarrow \wp(\text{action})$$

- Issue – how to implement this transform function and how to represent the agent's knowledge and the self/environment-models.

Belief-Desire-Intention Model

Framework for reasoning about formal abstract models of mental states

Contains representations (as objects, data structures, or whatever) of:

- beliefs, which constitute its knowledge of the state of its environment (and perhaps also some internal state),
- desires, which determine its motivation - what it is trying to bring about, maintain, find out, etc.,
- intentions, which capture its decisions about how to act in order to fulfil its desires

$$\text{if } \varphi \in \mathrm{L}_{agent} \text{ then } \varphi, (\mathrm{Bel}\ A\ \varphi), (\mathrm{Goal}\ A\ \varphi), (\mathrm{Int}\ A\ \varphi) \in \mathrm{L}_{bdi}$$

$$(\mathrm{Goal}\ A\ (\mathrm{AF}\ \mathit{win\text{-}lottery})) \wedge (\mathrm{Int}\ A\ (\mathrm{EF}\ \mathit{buy\text{-}ticket})) \wedge \neg (\mathrm{Bel}\ A\ (\mathrm{AF}\ \mathit{win\text{-}lottery}))$$

$$(\mathrm{Int}\ A\ \varphi) \Rightarrow (\mathrm{Bel}\ A\ (\mathrm{E}\Diamond\ \varphi))$$

Inter-Agent Communication

- Specific communication languages (Agent Communication Languages ACLs) are used
- Interoperability depends on standards: JINI, KQML, FIPA
- FIPA (Foundation for Intelligent Physical Agents) standards concern:
  - message structure
  - knowledge ontologies (helping to understand the message semantics)
  - negotiation scenarios

The FIPA Abstract Architecture contains agent system specifications in the form of both the descriptive and the formal models. It covers three important areas, namely

- Agent Communication
- Agent Management
- Agent Message Transport

FIPA Specifications

FIPA specifications:

- normative (ACL, SL, AMS)
- informative: (Approved: personal travel assisstant, audio-visual entertinment, network management,…. , under development: AgentCities, Holonic Control Devices)

- All the specifications are neutral abstractions (machine and language independent)

- Neither normative nor informative specifications for VE are available or under development

FIPA-oriented Platforms

Fully FIPA-compliant platforms:

- April Agent Platform (Fujitsu Labs of America),
- FIPA-OS (Emorphia),
- Grasshopper (IKV++),
- JADE (CSELT - Telecom Italia Labs),
- Zeus (British Telecom).
- LEAP (Lightweight Extensible Agent Platform) allows FIPA-compliant agents to run on PDAs and cell phones (backdrop of JADE).

Negotiations

- Advertise & subscribe
- Auctions
- Contract-net-protocol

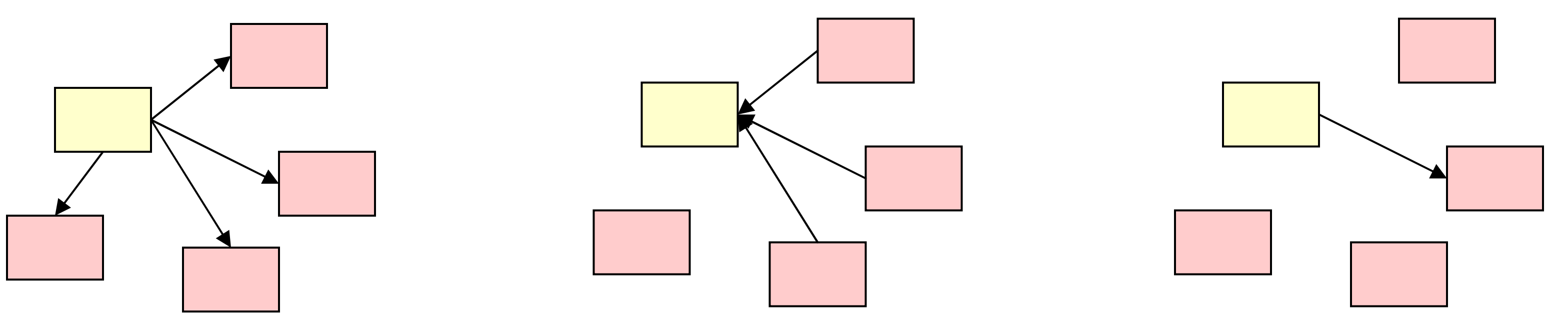
Auctions

- While in voting the outcome is binding for all parties in auctions it is an agreement between the buyer and the auctioneer
- The voting strategies assumed to establish a social good while auctions maximize the auctioneer's profit
- private value, common value, correlated value auctions
- Auction Protocols:
  - English (first-price open-cry) – sometimes an open-exit
  - Sealed-bid first-price
  - Dutch auction
  - Vickery (sealed-bid second-price)
  - All-pay auctions (computer science)

Contract Net Protocol (CNP)

- Task allocation negotiation:
  - via mediator/broker/facilitator/middle agent, or
  - autonomously via CNP
  - by means of acquaintance models

- contractee sends contractors a call for cooperation
- contractors provide contractee with bids
- contractee contracts the best contractor



Coalition Formation Problem

- A coalition is a set of agents who agreed to fulfill a single, well-specified goal. Coalition members commit themselves to collaboration with respect to the in-coalition-shared goal. An agent may participate in multiple coalitions.
- As a coalition formation/planning we understand the process of finding a coalition of agents who may participate in achieving respective goal.
- Coalition planning may be:
  - central or collaborative
  - hierarchical or autonomous

Autonomous Coalition Formation

- there is no supervisory actor that initiates and runs coalition formation process
- each agent can equally form a coalition – peer-to-peer negotiation
- agents do not provide their private information to a central unit
- high amount of computational redundancy and communication traffic overload
- agents have to maintain computational models of their social awareness
- clustering agents into alliances – we distinguish between:
  - public information and
  - private information
  - alliance-accessible (semi-private) information

Who is a Meta-agent?

- central agent acts as a communication/ collaboration center and may directly control the actions and knowledge: facilitators, brokers, matchmakers, mediators, or middle agents.
- meta-agent is a loosely coupled (either active or passive) agent:
  - active meta-agent directly affects some or all of the agents within the community. By directly delivered messages, the meta-agent may revise the acquaintance models of the agents.
  - passive meta-agent does not influence the community lifecycle. It just simply observes and provides the user with suitable information about how the community is evolving over time. It is up to the user to perform such a change as a feedback.

meta-agents provide the community with meta-level knowledge about the community while it will keep the agents autonomous

Role of Meta-Agents

- To observe and evaluate the communication traffic ➔ change of the community structure, of rules and their parameters ➔ change the global emergent behavior from the long-term perspective
- To serve as an external interface to the multi-agent system (simulation of the third party interference)
- To enable self-reflection in the system as a whole

Part 2

Emergent behavior

Emergent organizations and behaviour

Emergent:

- Unpredictable resulting structure or behaviour which appeared as consequence of local application of global rules in a complex environment
- The paradigm of emergent behaviour:
  - comparatively stable solution is achieved
  - the system is very flexible to changes in the environment
  - supported by evolution
- MAS - a good technology for modelling of emergent systems
- Agents X Objects:
  - Agents have their own internal state (incl. intentions, beliefs, emotions)
  - Agents are programmed for local activities (which might cause global emergent behaviour)

Emergent organizations and behaviour

Two steps

- emergent process of the development of the multi-agent community structure
- emergent behaviour of already well-formed (well-structured) alliances/coalitions

Examples of Emergent MAS

2 different examples:

Life/NetLife simulation systems:

internal structure of the multi-agent systems evolves in an emergent style

(no social knowledge, no negotiations among the agents)

CPlant system for coalition formation:

internal structures of alliances and coalitions are developed as well as the action plans, separation of private/semiprivate/public knowledge

(rich social models, several methods of negotiations, meta-agents to add flexibility and emergency to the behaviour)

Emergent MAS Structure Development

- A simple example: System LIFE (Conway, 1970) simulating dynamic societies of living organisms
- Two-dimensional grid of cells, each cell has 8 neighbours, initial configuration given (some cells are empty, some are occupied)
- Conway's rules:
  - *Survivals* - every organism with two or three neighbours (occupied cells) survives to the next generation
  - *Deaths* - each organism with four or more neighbours (overpopulation) or with one neighbour (isolation) dies
  - *Births* - each empty cell adjacent exactly to three neighbours is a birth cell (it is occupied in the next step)
- As a result, three behaviours may appear after many iterative steps:
  - stable structure with no changes
  - all configurations fade away (grid remains empty)
  - periodic or oscillating populations

Emergent structures - NetLife

- NetLIFE (Goldman, Rosenschein, 2002):
  - Modified and enhanced LIFE
  - Simulates evolution of an organization of experts
- Each agent “owns” certain pieces of knowledge (documents), each document is represented by a cell
- The neighbouring cells represent the nearest documents with respect to their contents (a new, specific “distance”)
- The population density PopDen= (number of agents assigned to the documents which are neighbours of the documents owned by the agent A) / (number of documents which are neighbours of the documents owned by A)
- Four rules:

  If PopDen>HighDen & Doc(A)<Min ==> Dies

  If PopDen<LowDen & Doc(A)>Max ==> Spawning a new agent

  If PopDen<HighDen & Doc(A)<Max ==> Take another document

  Else ==> Do nothing
- Results: Stable, Fading, Oscillating, Ever-Growing Patterns

CPlanT – Coalition Formation System

- Domain: Operations Other Than War (OOTW): Humanitarian Relief Operations, Peace-keeping Missions, Non-combat Operations
- Each entity (governmental institutions, troops, humanitarian bodies, NGOs, charitative organisations) represented by an agent
- Domain specifics (simplified):
  - equality – anyone can initiate forming a coalition – no hierarchy
  - reluctance to share vital planning information
  - agents inaccessibility – poor communication links, …
  - collaborative/self interested – different cultural backgrounds

Goals & Key Ideas

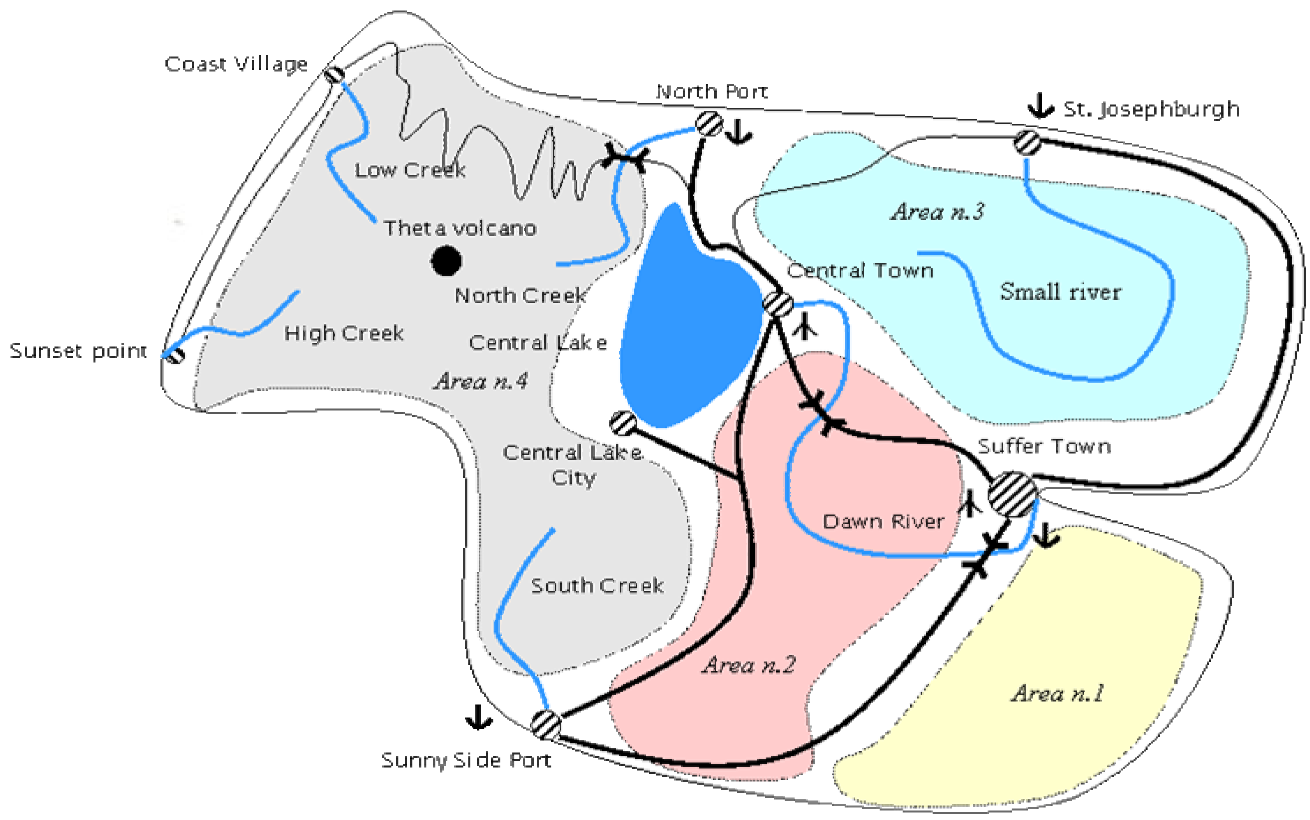
GOALS:

- minimize required communication traffic and problem solving efficiency
- keep the quality of the coalition 'reasonably good'
- minimize the loss of agents' private knowledge
- minimize the amount of shared information
- allow to reason about inaccessible agents

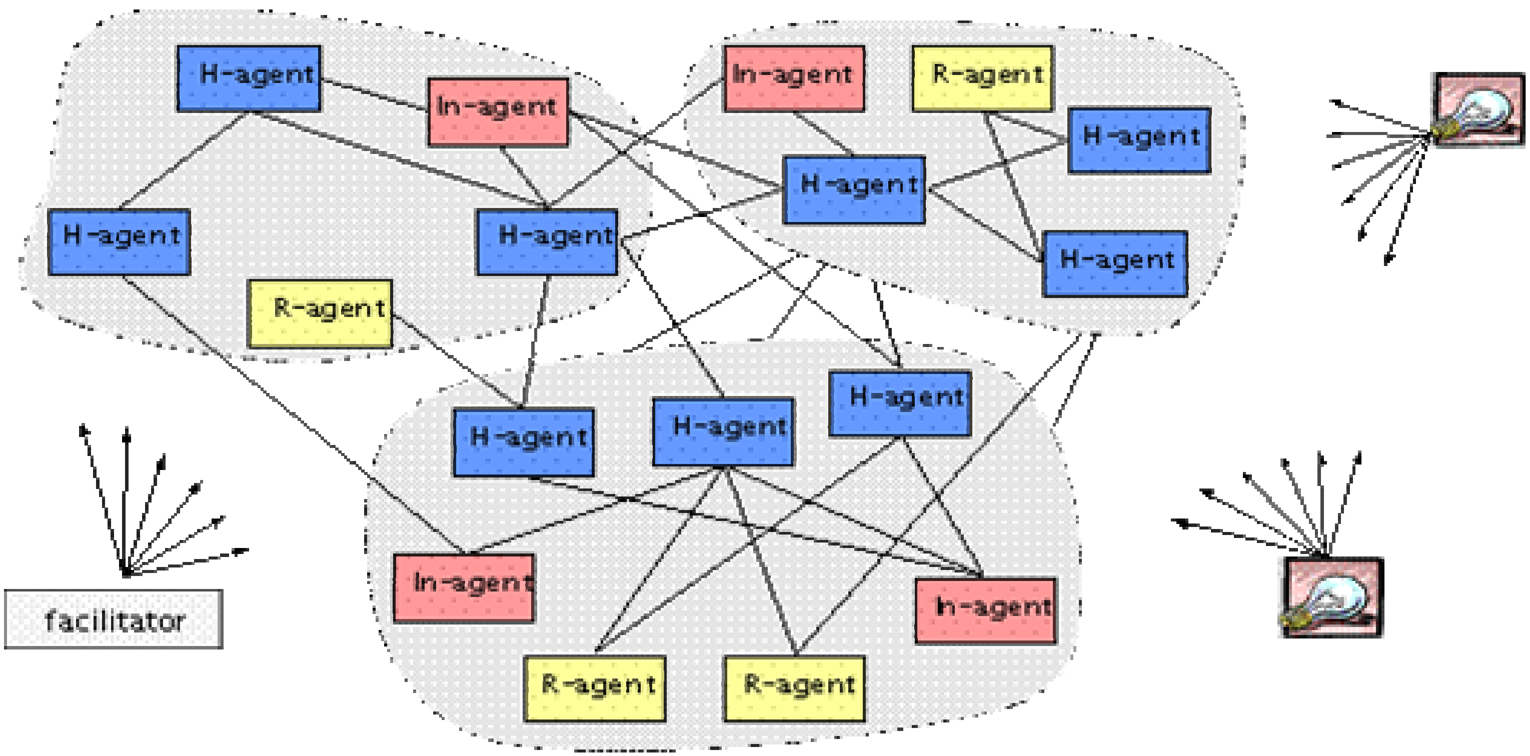
KEY IDEAS:

- organizing the agents into alliances (structural decomposition)
- a particular task (a mission) accomplished by a coalition (preferably created as a subset of an alliance)
- structuring the agents private, semi-private, public knowledge
- using the concept of the tri-base acquaintance model and social intelligence

Sufferterra Humanitarian Scenario



CPlanT Architecture



Agent’s Interaction Neighbourhoods

- agents’ neighborhood:
  - $\alpha(A_0)$ – agent's total neighbourhood
  - $\mu(A_0)$ – agent’s social neighbourhood – an alliance
  - $\varepsilon(A_0)$ – agent’s cooperation neighbourhood

$\varepsilon(A_0) \subseteq \mu(A_0) \subseteq \alpha(A_0) \subseteq \Theta$ and $\forall A \in \Theta : \mu^{-}(A) = \mu^{+}(A) = \mu(A)$

Agent's Knowledge Architecture

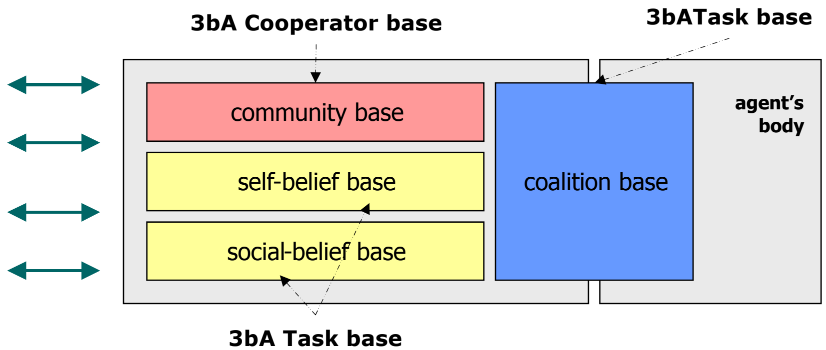
- shared knowledge $\mathrm{K}(A_0)$ within agents $\delta(A_0) \subseteq \Theta$, where $\Theta = \{A_0, .., A_n\}$

$$\mathrm{K}(A_0) = \{\varphi\} : \forall\varphi \in \mathrm{K}(A_0) : \forall A_i \in \delta(A_0) :$$
$$(\mathbf{Bel}\ A_i\ \varphi) \wedge \forall B_i \notin \{\delta(A_0) \cup \{A_0\}\} : (\mathbf{Bel}\ A_0\ \neg(\mathbf{Bel}\ B_i\ \varphi)).$$

- public knowledge – $\mathrm{K_P}(A_0) = \mathrm{K}(A_0)$ where $\delta(A_0) = \alpha(A_0)$
- semi-private knowledge – $\mathrm{K_S}(A_0) = \mathrm{K}(A_0)$ where $\delta(A_0) = \mu(A_0)$
- private knowledge – $\mathrm{K_{pr}}(A_0) = \mathrm{K}(A_0)$ where $\delta(A_0) = \{\}$

Acquaintance Model

- acquaintance model is a computational model of agents' mutual awareness, it stores and maintains agents' social knowledge, based on the 3bA model (used in production planning):



reduces the communication traffic and thus the problem's complexity, while it requires substantial communication for the acquaintance model maintenance

Private Knowledge Disclosure

- **Indirect** information disclosure: If an agent looses some type of private (or semi-private) knowledge in the strong sense, it does so as a side effect of some proactive step (such as sending a request)
  - disclosure of an intent
  - disclosure of service availability

- **Direct** information disclosure: If an agent looses the private knowledge in the weak sense, it deliberately discloses some piece of its knowledge to other agents being asked for this specific piece (e.g. when sending an inform-type message)
  - when forming an alliance

Alliance

- Provided $\forall A \in \Theta: A \in \mu(A)$, an alliance is a set of agents κ, so that

$$\forall A \in \Theta : \exists \kappa : A \in \kappa \wedge \forall A_i \in \kappa : \kappa = \mu(A_i)$$

  - The semiprivate knowledge is shared reciprocally within the alliance

$$\forall A \in \kappa : \kappa = \mu(A)$$

  - An alliance cannot overlap with another alliances

$$\forall \kappa_1, \kappa_2 \subseteq \Theta: (\exists A: A \in \kappa_1 \wedge A \in \kappa_2) \Rightarrow \kappa_1 \equiv \kappa_2$$

Coalition

- Provided $\forall A \in \Theta\colon A \in \varepsilon(A)$, a coalition is a set of agents χ, so that

$$\forall\chi(\tau) \subseteq \Theta\colon \forall\, A \in \chi(\tau) : \chi(\tau) \subseteq \varepsilon(A)$$

  - If $\varepsilon(A) = \bigcup_{\tau} \varepsilon(A,\tau)$, for each task τ

$$\forall\chi(\tau) \subseteq \Theta\colon \forall\, A \in \chi(\tau) : \chi(\tau) = \varepsilon(A,\tau).$$

Team Action Plan

- A team action plan $\pi(\tau)$ is as a set $\pi(\tau) = \{\langle\tau_i, A_j, \text{start}(\tau_i), \text{due}(\tau_i), \text{price}(\tau_i)\rangle\}$.
  - $\pi(\tau)$ is correct if all the collaborators A_j are able to implement the task τ_j in the given time and for the given price.
  - $\pi(\tau)$ is accepted if all agents A_j get committed to implementing the task τ_j in the given time and for the given price.
  - τ is achievable, if there exists such $\pi(\tau)$ that is correct.
  - τ is planned, if there exists $\pi(\tau)$ that is accepted
- We say that a coalition $\chi(\tau)$ achieves a goal τ by implementing a team action plan $\pi(\tau)$ if and only if $\chi(\tau)= \{A_j\}$ and $\pi(\tau)$ is correct.

Communication Mechanisms

- In the life-cycle of a coalition, the following communication mechanisms can be used:
  - communication via a central component
  - contract net protocol (multi-stage)
  - acquaintance-model-based contracting

Communication Mechanisms

- communication via a central component
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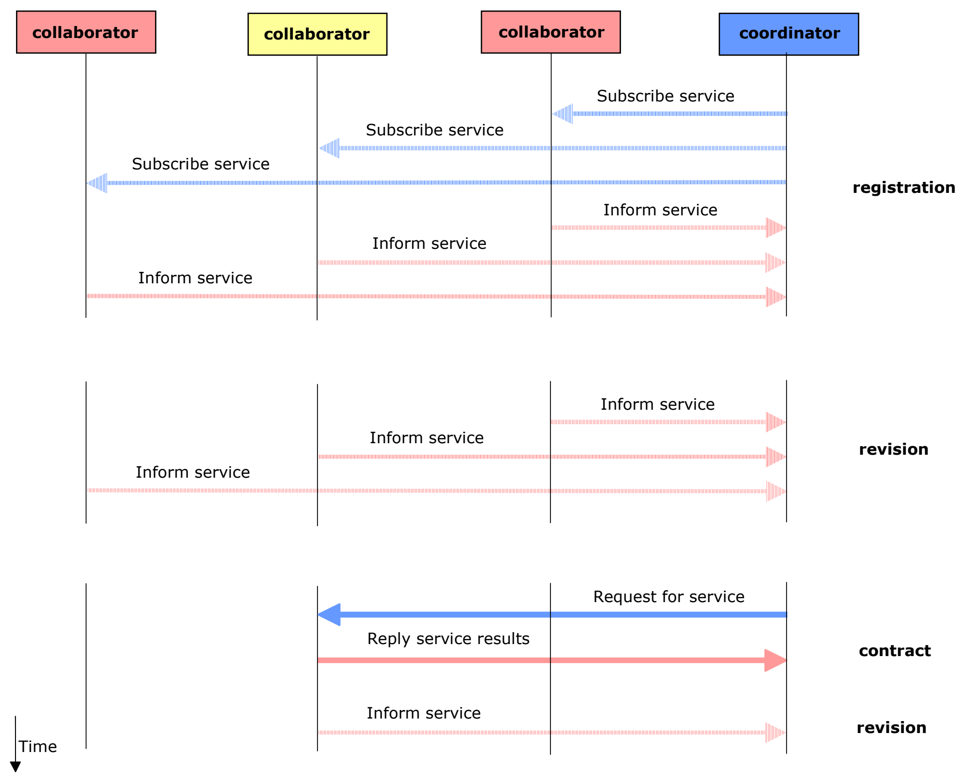
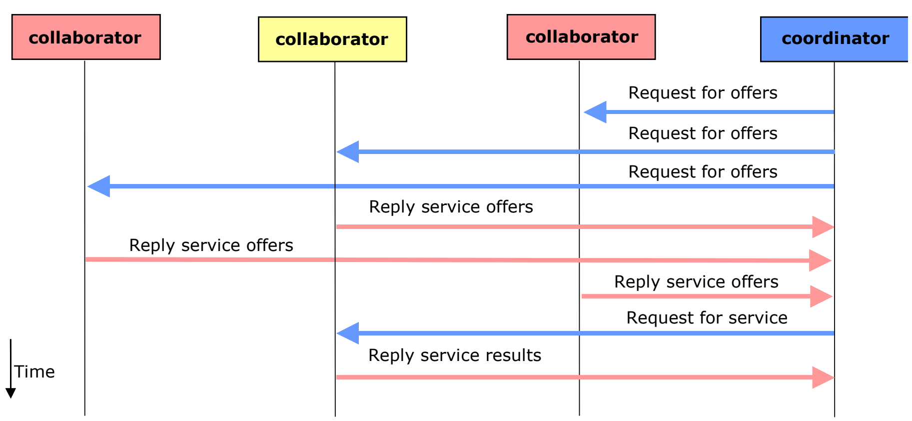


Communication Mechanisms

- communication via a central component
- contract net protocol (multi-stage)
- acquaintance-model-based contracting



Coalition Operation Lifecycle

- Registration:
  - registering public knowledge within agents' total neighbourhood (via DF)
- Alliance Formation:
  - formed in order to share semi-private knowledge in agents' social neighbourhood – communicated via selective single-stage CNP
- Coalition Formation:
  - forming agent's cooperation neighbourhood wrt. a task τ – communicated via acquaintance models
- Team Action Planning:
  - collective planning of a team action – combination of CNP and AM

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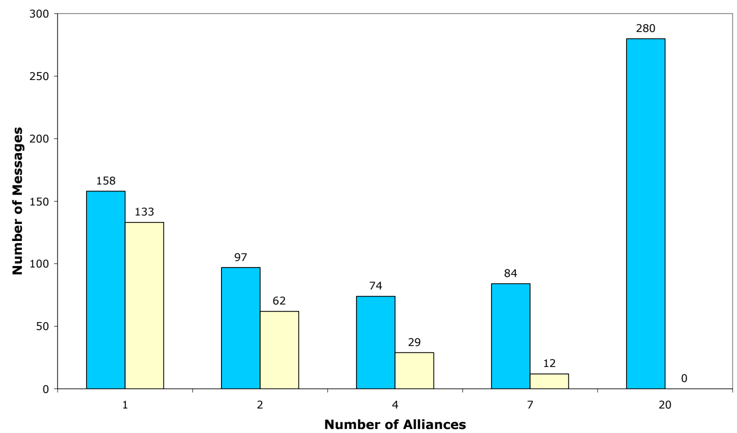
Experiments

- communication and computation requirements,
- quality of the solution provided,
- disclosure of private and semiprivate knowledge, and
- initialisation phase of the community.

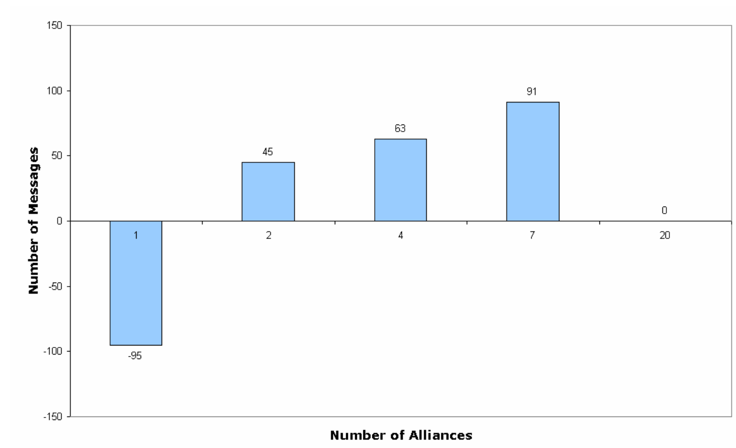
- 2, 4, 7 and 20 alliances
- 19 measurements for each community arrangement

Experiments cont'

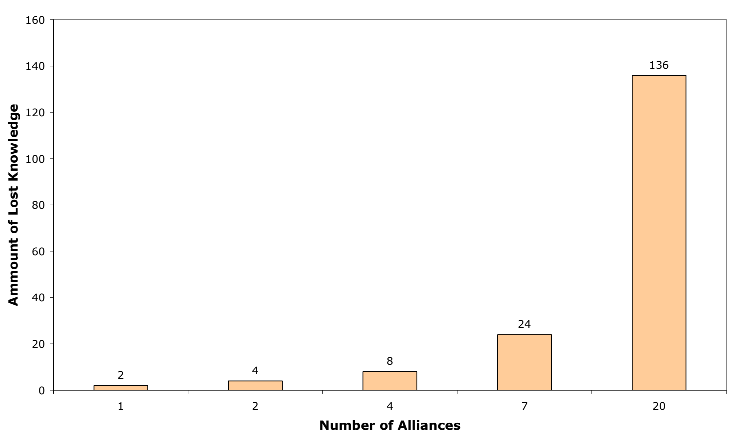
Communication Traffic



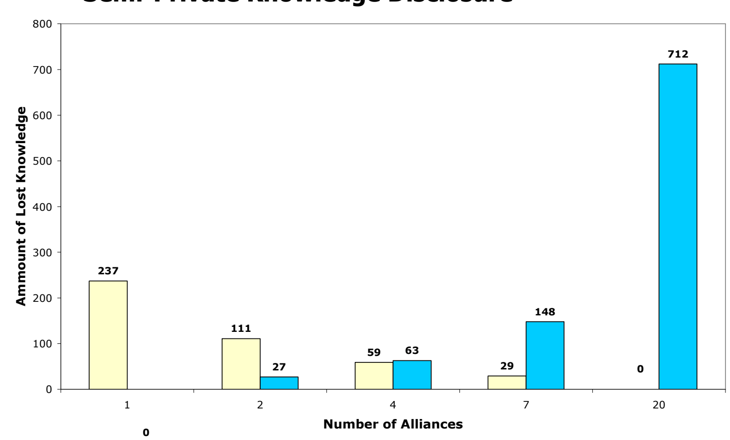
Communication Savings



Private Knowledge Disclosure

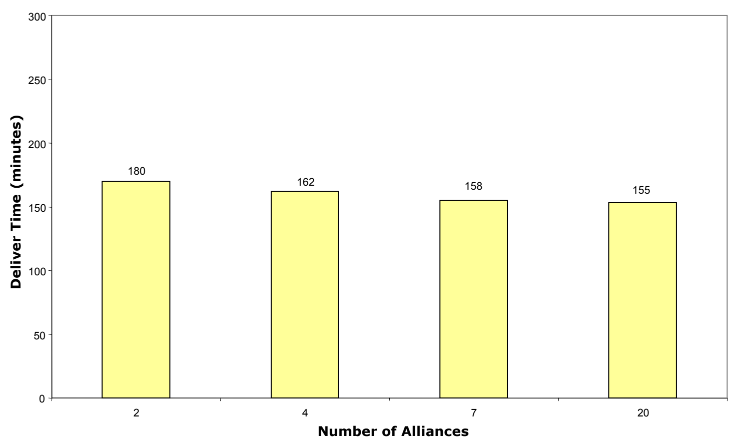


Semi-Private Knowledge Disclosure

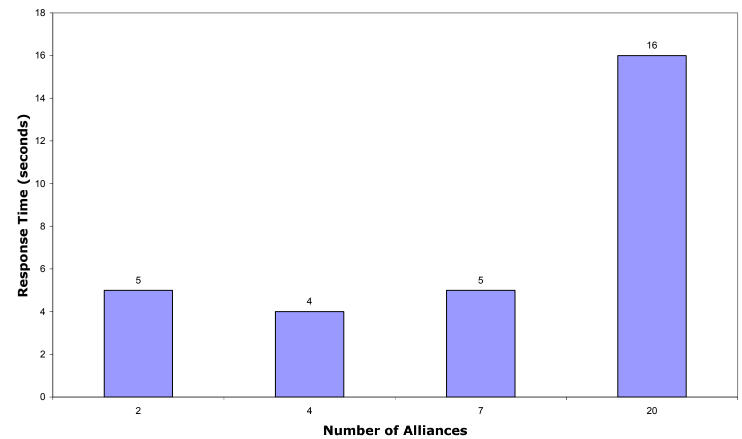


Experiments cont'

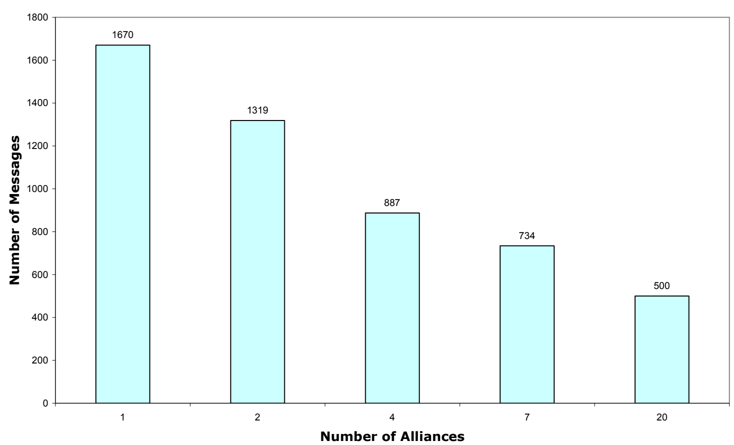
Quality of the Solution



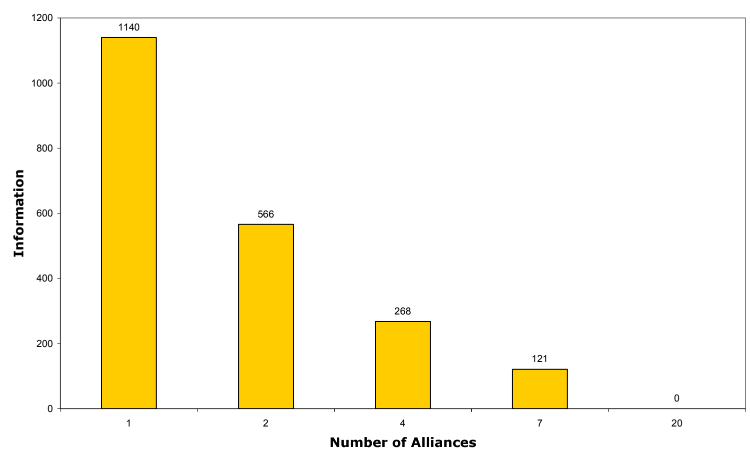
Response Time



Initial Communication Traffic



Initial Semi-Private Knowledge Disclosure



Part 3

Conclusions

Applications of Agent-based Systems

- **Typical tasks**
  - real-time control (holonic systems)
  - reconfiguration of manufacturing and diagnostic modular systems
  - planning and scheduling
  - system integration
  - coalition formation (e.g. for humanitarian operations)
  - simulation of parts of virtual enterprises

Agent Technology for VE

- The agent technology (= result of Artificial Intelligence research) is a good paradigm supporting - from the technical point of view - the virtual enterprises in manifold ways:
  - good motivation as it provides explanation of many processes in VE
  - helps to understand the role of knowledge and needs in appropriate knowledge organization
  - private versus public knowledge – important issue
  - enables to simulate the VE behavior: because of the emergent, unpredictable behavior – simulation seems to be extremely important

Agent Technology for VE

- provides technical infrastructure for automatic or semi-automatic communication and negotiation scenarios
- meta-agent technology can simulate activities of third parties, can help to achieve optimal contracting from the long-term point of view
- a specific, dedicated to VE platform not available yet