TEAM FORMATION FOR AGENT COOPERATION IN LOGISTICS
Protocol Design and Complexity Analysis

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Abstract: Supply network management is a challenging task due to the complexity, dynamics, and distribution of logistics processes. Delegating process control to intelligent software agents that represent logistics objects and act on their behalf helps approach these challenges. The resulting problem decomposition reduces the computational complexity. Dynamics can be dealt with locally. An important prerequisite for coordinated process control is that agents can cooperate with each other. Based on requirements from logistics, this paper presents an interaction protocol for team formation. A thorough complexity analysis for the proposed method is conducted because the arising interaction effort is not obvious as it depends on the number of teams formed. Therewith, agent developers can estimate the interaction effort and thus the applicability of the method in advance. Finally, an application of the introduced protocol is outlined.

1 INTRODUCTION

Managing complex supply networks with software systems is a challenging task. In particular, coordinating logistics processes requires dealing with the following challenges:

complexity caused by the high number of logistics objects and their parameters,

dynamics caused, for instance, by transient customer demands and changes in the environment, and

distribution because logistics processes often span over multiple companies and even continents.

These properties prevent the application of centralistic and monolithic software systems. Generating optimal plans centrally consumes a lot of time. Often, the dynamics therefore renders these plans outdated already in the moment their generation is finished. Moreover, the physical distribution prevents relevant information from being available centrally.

Consequently, the paradigm of autonomous control in logistics (Windt and Hülsmann, 2007) delegates decision-making to the participating entities. In contrast to other approaches (Chaib-draa and Müller, 2006), not only companies or departments, but actually individual logistics objects are considered autonomous. For instance, shipping containers are themselves responsible for planning and scheduling their way through the logistics network. The computational complexity is reduced because each entity only considers its own parameters and those of cooperating entities (Schuldt, 2010). This increases reactivity and robustness of process control because exceptions can be dealt with locally. Autonomous logistics can be implemented with intelligent agents being representatives for logistics objects.

An important finding is that individual agents can frequently not satisfy their logistics objectives on their own (Schuldt and Werner, 2007). As a consequence, they must cooperate with other agents. The formal model for cooperation of intelligent agents (Wooldridge and Jennings, 1999) distinguishes four consecutive steps of the cooperative problem-solving process (Figure 1). As a prerequisite, agents must recognise a potential for cooperation because joint action is not reasonable without. Having identified this potential, agents can form a team. Subsequently, they collaboratively elaborate a plan. Finally, the team action step deals with joint execution of this plan.

This paper focuses on the team formation step. There is a demand for a particular interaction protocol for team formation in logistics because interaction schemes are underspecified in the original model for cooperation. This paper has two contributions:

1. Protocol design
2. Complexity analysis

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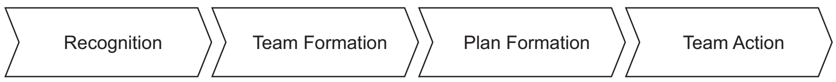

Figure 1: The four steps of the model for cooperation (Wooldridge and Jennings, 1999). As a precondition, agents must recognise a potential for cooperation. Subsequently, agents form both a team and a joint plan before they actually act jointly.

The protocol design is documented in Section 2. Relevant requirements for team formation in autonomous logistics are derived and contrasted to existing approaches. Based on this analysis, an interaction scheme for team formation is introduced. In order to estimate the applicability of the new protocol, the approach is thoroughly analysed with respect to its interaction effort in Sections 3 and 4. Section 5 outlines an application of the introduced protocol.

2 PROTOCOL DESIGN

Team formation is an important prerequisite for cooperation of autonomous logistics entities. Section 2.1 motivates the demand for cooperation by identifying the potential for cooperation. In particular, relevant requirements for team formation mechanisms in autonomous logistics are derived. Section 2.2 contrasts these requirements to existing approaches. Finally, Section 2.3 presents an agent interaction protocol that satisfies the identified requirements.

2.1 Motivation and Requirements

As a prerequisite for cooperation among intelligent agents, the model for cooperation demands that a group of agents can jointly achieve a goal (Wooldridge and Jennings, 1999). Reasons for acting collaboratively are twofold. On the one hand, an individual agent may not be capable of achieving its goal in isolation. On the other hand, the agent may have a goal conflict for all of its respective own actions.

In the first case, agents with complementing capabilities should form teams in order to jointly accomplish their task. In autonomous logistics, also the second case occurs quite frequently (Schuldt and Werner, 2007). Think, for instance, of an intelligent package that intends to be transported from a warehouse to a distribution centre. In principle, the package could achieve this objective on its own by negotiating with a truck, also represented by an intelligent agent, that takes over the transport. However, transporting an individual package by truck is frequently not cost-efficient. Instead, it is desirable that multiple packages with the same origin and destination jointly employ a truck in order to prevent a goal conflict regarding their cost-efficiency. Therefore, the important task for autonomous logistics entities is to establish teams based on joint properties such as a common location and destination.

Apart from general interaction design principles (Rosenschein and Zlotkin, 1994; Sandholm, 1999), the requirements for team formation in this area of application are as follows:

1. Unique teams
2. Flexible teams
3. Genericness
4. No prior knowledge
5. Decentralisation
6. Efficiency

The demand for unique teams means that only one team should exist for each instantiation of a team property. In terms of the above example, there should only be one team of packages for each pair of origin and destination. This ensures the highest resource utilisation of the trucks employed. Of course, each team can intentionally employ multiple trucks if necessary. In other words, the requirement for unique teams means that agents group themselves by an equivalence relation with respect to one property. Nevertheless, different properties and thus teams may exist for different purposes, e. g., transport and storage service allocation.

Furthermore, teams should be flexible in the sense that additional members can join after the initial formation. The method should be generic in that it is not restricted to specific descriptors of properties. The team formation mechanism should not make or only make few requirements regarding prior knowledge participants must have about the structure of the multiagent system and other participants. The approach should be decentralised in order to prevent bottlenecks, thereby still being efficient.

2.2 Related Work

Previous work on team formation focused on formalising organisations of agents (Ferber and Gutknecht, 1998; Hannoun et al., 2000; Fischer et al., 2003) as well as the internal states of agents during team formation (Wooldridge and Jennings, 1999; Dignum et al., 2000). Less effort has been spent on agent interaction protocols for team formation. Previous

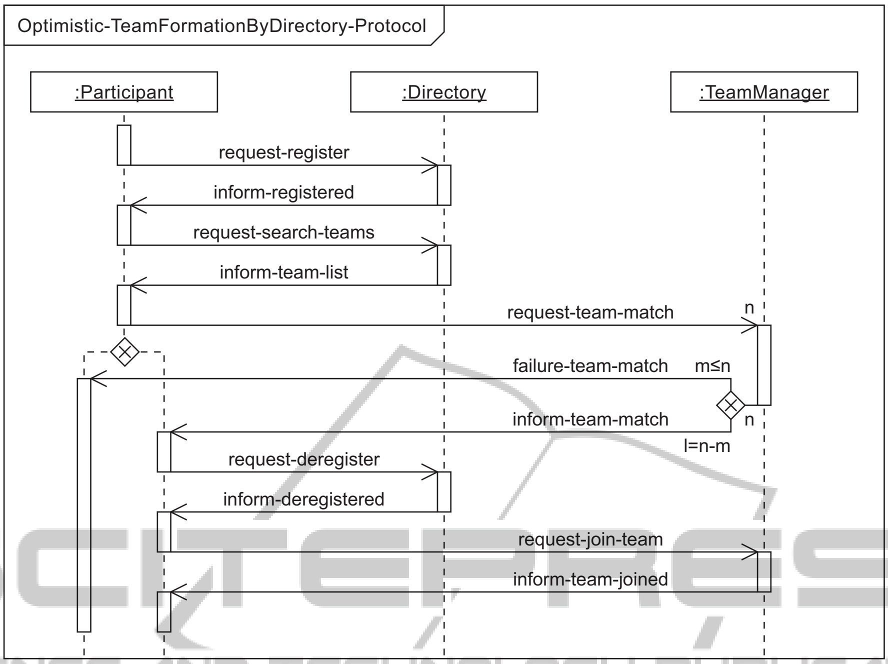

Figure 2: Agent interaction protocol for team formation based on a directory service. Participating agents are optimistic in that they initially assume that they can form a new team before possibly joining an existing one.

clustering algorithms such as k-means (MacQueen, 1967) take a centralised perspective on the data to be clustered. This perspective, however, is usually not available in the distributed setting of multiagent systems in general and autonomous logistics in particular. Hence, they cannot be applied.

Distributed clustering is, for instance, applied in wireless sensor networks (Akyildiz et al., 2002). However, these approaches are not applicable because they focus on spatial data and thus make implicit assumptions on the environment (Heinzelman et al., 2000) that do usually not hold in autonomous logistics. In particular, this contradicts the requirement for generic descriptors.

Peer-to-peer approaches (Ogston and Vassiliadis, 2001) provide each agent with an arbitrarily chosen set of other agents it is initially connected with. Agents inform their peers about each other so that they can exchange their direct partners by others that are more similar. Unfortunately, this setting is purely artificial for autonomous logistics because autonomous logistics entities do not have any prior knowledge about other agents in the systems. Consequently, there is no natural choice for initial peers.

Often, the contract net (Smith, 1977) interaction protocol is applied to implement team formation. However, it only fits the case (Section 2.1) that an agent aims at finding others that supplement its own capabilities. In particular, the requirements for unique and flexible teams are not met. It cannot be prevented that teams with similar properties are established. This is particularly because members cannot join after a team has been established. This would require that team managers continuously advertise their team to potential new members. The question, however, remains open what might be an appropriate frequency for such announcements.

2.3 Team Formation Protocol

To summarise the discussion in Sections 2.1 and 2.2, there is a demand for a new method for team formation. Figure 2 depicts an agent interaction protocol that reflects the identified requirements. The protocol is based on a previous one (Schuldt and Werner, 2007). A comparison follows below.

The involved agent roles comprise the initiating participant, the existing team managers, as well as a directory service that administers the list of current team managers. When an agent decides to participate in the team formation process, it initially registers itself as a new team manager with the directory. This behaviour is optimistic in that the participant assumes that there is currently no team manager matching its respective properties for team formation. In order to check whether this assumption is actually true, it requests the list of all current team managers from the directory. Afterwards, it provides all team managers with its own properties so that the managers can determine whether their properties are matching. This communication is done in parallel to be time-efficient.

The check conducted by the team managers has three possible outcomes. Firstly, the match process may fail for all team managers, i. e., no team matches the properties of the new participant. In that case, the initial assumption was right and the new participant actually becomes a new team manager. Secondly, one team manager may determine a match. In that case, the optimistic assumption turns out to be wrong. Hence, the new participant deregisters from the directory and joins the matching team instead. Finally, it might also occur that multiple team managers determine a match. This is the case whenever multiple agents have concurrently registered with the directory with same properties. To resolve this problem of redundant teams, each team manager is assigned an individual timestamp when registering with the directory. Based on this timestamp, all agents including the superfluous team managers can join the initial team.

As an alternative to the optimistic behaviour, it would also be possible to act conservatively as it is done in the ancestor of the protocol (Schuldt and Werner, 2007). In the conservative case, new participants would first contact all existing team managers before registering themselves with the directory service. Due to concurrency, however, still multiple agents with same properties might register as team managers. After the registration process, it would therefore be necessary to contact the existing team managers again in order to resolve redundancy. The advantage of the optimistic procedure is thus that team managers only have to be contacted once.

The requirements derived in Section 2.1 are reflected as follows. The proposed interaction protocol ensures that the resulting teams are unique. If teams with identical properties are established, e. g., due to concurrency, this can be resolved by the protocol. Team formation is flexible because the participants and not the team managers initiate team formation, i. e., participants can join teams after initial establishment. The protocol is generic because it does not restrict the possible descriptors for team properties. Furthermore, only few prior knowledge about the system is required because participants can retrieve the list of existing team managers from the directory. The approach is decentralised in that all decisions are made autonomously by the participants and team managers. The only central entity and thus a potential bottleneck is the directory. But the directory service is not necessarily provided by only one agent. Instead, it can be offered by multiple agents which coordinate with each other internally (Bellifemine et al., 2007). Regarding efficiency, the asymptotic interaction complexity for team formation is $O(mn) = O(n^2)$ from a coarse perspective. However, the number m of team managers is usually only a small fraction of all n participants, i. e., $m \ll n$. A more detailed analysis follows in the subsequent Sections 3 and 4.

3 INTERACTION COMPLEXITY

The analysis of the interaction effort for the proposed team formation protocol is approached in two steps. Section 3.1 examines the possible range of team configurations for given sets of agents. Based on this foundation, Section 3.2 presents the analytical examination of the team formation interaction effort.

3.1 Possible Team Configurations

As elaborated in Section 2.1, all agents in one team are characterised by similar properties. Although these properties may change over time, each agent has specific properties at the time it initiates team formation. The task is thus to find the other agents with the same properties. There exist numerous combinations how intelligent agents can be partitioned into similar properties and accordingly teams. The distribution of agents to teams can be regarded as integer partitions (Zoghbi and Stojmenovic, 1998). As an example, the possible integer partitions of four are:

$$4 = 3+1 = 2+2 = 2+1+1 = 1+1+1+1 \quad (1)$$

Thinking of four agents, they could all pertain to the same team. Another possibility is that there is one team of three agents and one singleton team and so on. The possible partitions can be written as a set of multisets:

$$\{\{(4,1)\},\{(3,1),(1,1)\},\{(2,2)\},\\ \{(2,1),(1,2)\},\{(1,4)\}\} \quad (2)$$

More generally, the integer partitions for arbitrary natural numbers can be defined as follows:

Definition 1 (Integer Partitions)**.** *Let* $\mathrm{N} \subset \mathbb{N}$ *be a set of natural numbers, let* $\mathrm{M} = (\mathrm{N}, \mathrm{m})$ *be a multiset over* N *with* $\mathrm{m} : \mathrm{N} \to \mathbb{N}^+$ *defining the multiplicity of the elements of* N. $\mathrm{M} = (\mathrm{N}, \mathrm{m})$ *is a partition of* $\mathrm{s} \in \mathbb{N}$ *if* $\sum_{\mathrm{n} \in \mathrm{N}} n \cdot m(n) = s$. *The set of all partitions of* s *into* p *summands is*

$$partitions(s,p) := \left\{ (N,m) \;\middle|\; \sum_{n \in N} m(n) = p \wedge \sum_{n \in N} n \cdot m(n) = s \right\}$$

The total set of all partitions of i *is*

$$partitions(s) := \bigcup_{p=1}^{s} partitions(s,p)$$

Definition 1 is the foundation for examining the possible partitions of integers into parts (van Lint and Wilson, 1992) and agents into teams, respectively. Fast algorithms exist that compute all possible integer partitions (Zoghbi and Stojmenovic, 1998).

3.2 Interaction Effort Analysis

As elaborated in Section 2.3, the asymptotic interaction complexity of the team formation protocol is $O(mn) = O(n^2)$ from a coarse perspective. The actual interaction effort depends on two factors:

1. The total number of team managers
2. The times at which additional participants become team managers

Every agent that joins the multiagent system contacts all existing team managers to find a matching team. To determine the interaction effort for a particular agent, one must thus find out how many team managers exist at its creation time. The question how many agents in the multiagent system are team managers at a certain point in time can be reformulated. It is equivalent to the question to how many teams the agents in the multiagent system pertain. The questions are interchangeable because the first agent of each team is the responsible team manager.

The question of the number of teams can be approached in two steps. Firstly, one must determine the probability that an agent of a particular team has already been created. Secondly, the resulting probability must be accumulated for all teams to get the total number of different teams existing. A foundation for this investigation is the hypergeometric distribution (Bronshtein et al., 2004). It is defined as follows:

Definition 2 (Hypergeometric Distribution)**.** *Let* $\mathrm{A} \in \mathbb{N}$ *be the size of the population, let* $\mathrm{T} \leq \mathrm{A} \in \mathbb{N}$ *be the number of successes in the population, let* $\mathrm{a} \leq \mathrm{A} \in \mathbb{N}$ *be the number of draws, and let* $\mathrm{t} \leq \mathrm{A} \in \mathbb{N}$ *be the number of successful draws. The probability for* t *given* a, T, *and* A *is*

$$P(X=t) := h(t\,|\,a,T,A) = \frac{\binom{T}{t}\binom{A-T}{a-t}}{\binom{A}{a}}$$

Let A denote the total number of agents. All agents are numbered by a in the order of their creation. That is, $a-1$ agents have been created before agent a with $1 \leq a \leq A$. Let T denote the number of agents pertaining to a particular team. Based on Definition 2, the probability that at least one member of the team is in the total number of agents examined so far can be derived as follows:

$$P(X>0) := \sum_{t=1}^{T} h(t\,|\,a,T,A) = 1 - h(0\,|\,a,T,A) \quad (3)$$

Therewith, the question of the probability that at least one agent of a team has already been created is answered. The extension to all teams follows.

The respective partitioning of agents to teams, or to properties to be more precise, can be considered an integer partition (Definition 1). The respective partitioning of all agents A is represented by the multiset

$$M = (N,m) \in partitions(A) \quad (4)$$

Summing up the probabilities for the existence of individual teams (Equation 3) for all teams (Equation 4) in the multiagent system reveals the number of already existing teams at the creation time of agent a:

$$f(a,(N,m),A) := \sum_{n \in N} m(n) \cdot \big(1 - h(0\,|\,a,n,A)\big) \quad (5)$$

To recapitulate, the number of teams corresponds to the number of team managers agent a has to interact with, i. e., it specifies the expected interaction effort of agent a. The total interaction effort of the whole system until the creation of agent a can be derived from Equation 5 as follows:

$$\begin{aligned} F(a,(N,m),A) &:= \sum_{i=1}^{a} f(i,(N,m),A) \quad (6) \\ &= \sum_{i=1}^{a} \sum_{n \in N} m(n) \cdot \big(1 - h(0\,|\,i,n,A)\big) \end{aligned}$$

4 CASE STUDY

A considerably high number of possible agent partitions into teams exists. Hence, following the general analysis of the interaction effort for team formation, this section investigates a particular configuration in more detail. Out of the variety of possible partitions, the case in which all teams have approximately the same size is examined. This means that those partitions $M = (N,m) \in partitions(s)$ with the following numbers of s agents into p teams are considered:

$$N = \left\{ \left\lfloor \frac{s}{p} \right\rfloor, \left\lceil \frac{s}{p} \right\rceil \right\} \quad (7)$$

The multiplicity m of the numbers of agents in M is:

$$m = \left\{ \left(\left\lfloor \frac{s}{p} \right\rfloor, p - (s \bmod p) \right), \left(\left\lceil \frac{s}{p} \right\rceil, s \bmod p \right) \right\} \quad (8)$$

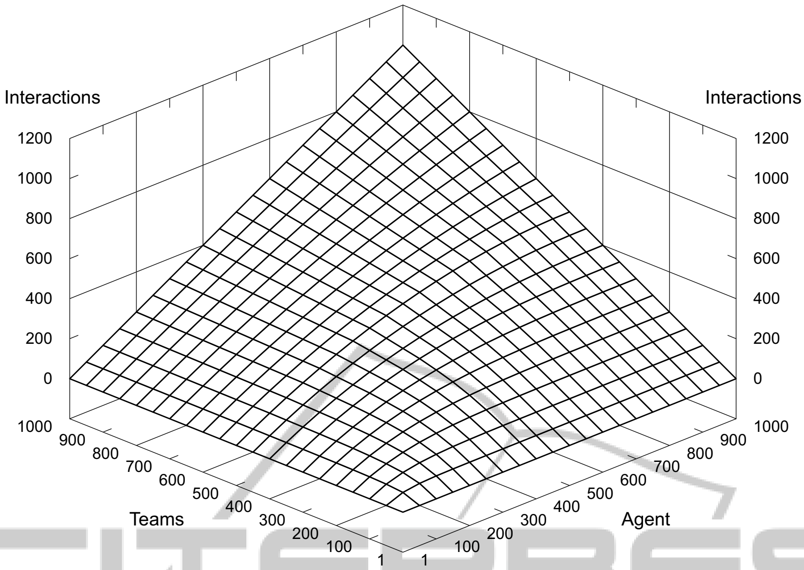

Figure 3: The number of interaction partners for participants in the team formation interaction protocol. The number of interactions depends on the number of predecessors in the team formation process.

For the sake of understandability, the partition can also be written as a sum. It corresponds to the following equation:

$$s = \left\lfloor \frac{s}{p} \right\rfloor \cdot (p - (s \bmod p)) + \left\lceil \frac{s}{p} \right\rceil \cdot (s \bmod p) \qquad (9)$$

Note that the remainder $s \bmod p$ may be zero. Then, the right element in the sets of Equations 7 and 8 is omitted. This is in accordance with Definition 1 which demands multiplicities to be positive. In this case, all teams have the same number of agent members. Otherwise, it holds that all teams have approximately the same number of agents, i. e., the difference of the number of agents does not exceed one:

$$\forall_{n_1,n_2 \in N} \; |n_1 - n_2| \leq 1 \qquad (10)$$

Figure 3 depicts Equation 5 for such average teams for all $1 \leq a \leq A$ when varying the number of teams $1 \leq T \leq A$ for a total of $A = 1,000$ agents. Figure 4 shows the overall interaction effort for the same team partitions investigated in Figure 3. Figures 3 and 4 have a different scale. The maximum interaction effort is $1,000$ for an individual agent and about half a million for the whole system of $1,000$ agents.

5 PROTOCOL APPLICATION

The team formation interaction protocol is currently applied in autonomous logistics applications, such as autonomous onward carriage (Schuldt, 2010). In onward carriage, containers arriving from overseas at container terminals have to be transported to appropriate warehouses. In autonomous onward carriage, intelligent shipping containers are expected to solve this task on their own. To this end, they have to choose the warehouse based on their properties. For instance, containers with valuable goods should choose a secured warehouse. After having chosen a warehouse, the containers must organise their transport by choosing a means of transport out of truck, train, and barge.

The autonomous logistics approach has been implemented with JADE (Bellifemine et al., 2007) and validated with PlaSMA (Schuldt et al., 2008). For evaluation purposes, real-world container data has been provided by a major European retailer of consumer products. Multiagent-based simulations with over 11,500 shipping containers show that process control can actually be delegated to autonomous logistics entities. In particular, it can be shown that cooperation is advantageous in autonomous logistics (Schuldt, 2010). Both choosing storage and transport resources requires cooperation. Regarding storage, containers with similar cargo should be received in the same warehouse. This helps aggregating similar goods for subsequent distribution processes. Team formation for this purpose requires establishing teams based on descriptors for the articles loaded. Utilising means of mass transport requires cooperation by shipping containers with same origin and destination. Hence, spatial criteria have to be considered for this purpose. This means that teams for allocating storage and transport resources differ in this application (Schuldt, 2010).

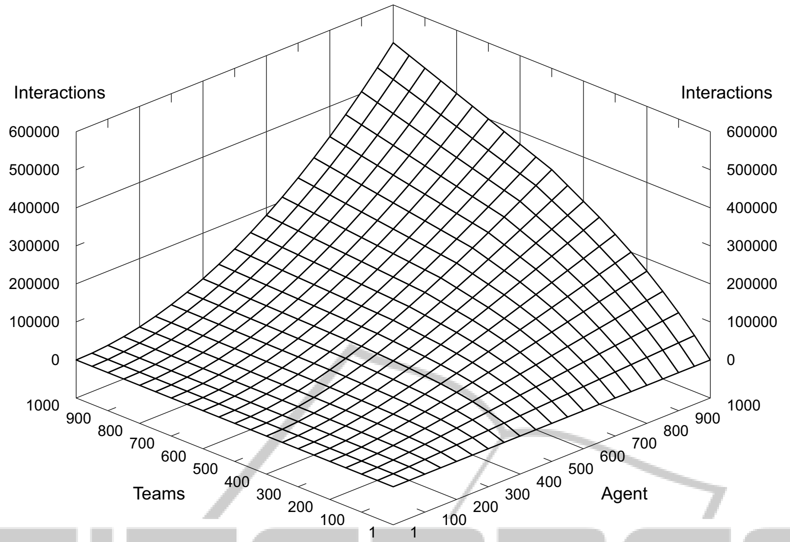

Figure 4: The total number of interactions for team formation. Depending on the number of teams, the interaction effort ranges between linear and quadratic.

The simulation shows that the multiagent system outperforms the previous approach in which humans dispatch containers manually with support by information systems. In particular, more relevant parameters can be considered, thereby increasing resource utilisation efficiency for standard cases. Moreover, being relieved from handling standard cases, human dispatchers can solve exceptional cases which are not covered by the multiagent systems more efficiently.

The thorough investigation of the interaction complexity helped estimate the interaction effort even before deploying agents to an actual application. In particular, the interaction effort was estimated based on previous container data. Therewith, it was possible to decide that the exchanged messages can actually be handled by the multiagent system and, thus, that autonomous control is actually possible in this process.

6 CONCLUSIONS AND OUTLOOK

This paper presents an interaction protocol for team formation of autonomous logistics entities. The protocol satisfies the domain-specific requirements for unique and flexible teams, as well as genericness of team descriptors. Furthermore, it demands only minimal prior knowledge about the system and is highly decentralised. Therewith, it lays important foundations for cooperation of autonomous logistics entities which in turn increase the reactivity and robustness of logistics process control.

The motivation for the new protocol as well as its current application are in the field of logistics. However, it is not restricted to logistics and can be applied also in other areas with similar requirements. In terms of the model for cooperation of intelligent agents, it is particularly applicable whenever agents with similar properties want to cooperate.

The interaction effort of the new protocol has been derived analytically. This is an important prerequisite for estimating the effort and limitations for autonomous control already before the actual deployment. A thorough analysis as provided in this paper is necessary whenever the interaction effort is not obvious, e. g., if the number of participants changes over time. Limitations of the protocol are reached whenever the interaction effort exceeds the capability of the individual agents or the whole system. A solution for such a case is to employ an interaction protocol with a lower degree of decentralisation (Schuldt, 2010). An alternative might be to restrict the number of participants, for instance, based on spatial regions of relevance (Gehrke, 2009).

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