Supply web co-ordination by an agent-based trading network with integrated logistics services

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Abstract

B2B interactions, like electronic negotiations and auctions between suppliers and customers, could be significantly improved by enabling the participants to adapt their bidding strategies to current logistics information (e.g., about transportation condition, cost or dates) while the negotiation goes on. We present an approach of an agent-based information and trading network (ITN) called CASA for dynamic production and sales of timber; the integrated services for logistics and e-commerce are efficiently coordinated by appropriate types of holonic structured intelligent agents of the network. We introduce the agent-based architecture and describe how the agents build their plans and optimize them afterwards. For optimizing their plans, the agents use various market-based negotiation mechanisms, i.e., several auction mechanisms and the simulated trading mechanism described in detail in this article. The effects of the different mechanisms on resulting cost and surplus have been evaluated by various simulation runs in different competitive and co-operative settings. It turned out that the simulated trading mechanism as well as matrix auction mechanisms for two or three items are especially suitable for supply web co-ordination and optimization tasks.

Keywords: Supply web co-ordination; Agent-based trading network; Integrated logistics services

1. Introduction

A supply chain is a chain of possibly autonomous business entities that collectively procure, manufacture and distribute certain products. Since today’s markets are highly dynamic in, e.g., variations of customer demands, current supply chains are forced to respond more accurately, flexibly and quickly to consumer demands than ever before. Additionally, they have to keep the size of the inventory needed to respond to changing customer demands to a minimum. In order to stay competitive, supply chain partner companies are forced to form supply chains on the basis of more flexible and co-operative partnerships. For these reasons, so-called supply webs [11]—i.e., B2B-enabled dynamic networks of supply chain units—will replace today’s static supply chains to an increasing extent.

The partner companies within a supply web announce offers and information about goods and services to each other. They have to quicken their negotiations for reaching deals before, e.g., perish-
able goods deteriorate their quality. The dynamics of the distributed trading and supply processes inherent in supply webs may result in an increase of expenses and delays instead of higher efficiency and flexibility. So new mechanisms have to be instantiated that help to co-ordinate the local activities of the supply web partners.

Hence for handling the interactions between the supply web partner companies efficiently, an largely automated information and trading network is needed that provides the supply web partners with logistics information as well as co-ordination services, e.g., auction mechanisms.

In this article, we present such an information and trading network, called CASA ITN, for the co-ordination of supply webs. It is built-up on holonic agents that are introduced in the next section. CASA offers its users integrated logistics information services helping them reaching efficient deals during e-business negotiation processes.

When such negotiations begin, a buyer within a supply web normally has only a vague idea of the resulting overall costs (including the amount of money to purchase the good plus the transportation and storage cost of the goods in the different locations). Especially when the buyer wants to purchase goods in an auction, it is totally unclear if he will get the desired good from the chosen auction. Using the integrated logistics services of the CASA ITN offers a buyer the possibility to send hypothetical, non-committing requests for transportation and storage to logistics companies. On the basis of the current logistics and cost information received from the logistics companies the buyer is able to produce better cost estimations and to adapt his negotiation and bidding strategies in ongoing negotiation processes. The architecture of the CASA ITN together with its agents and services will be described in detail in Section 2.

Since the buyers’ requests are non-committing, the information systems of the logistics companies in our scenario have to be able to dispatch hypothetical transportation tasks and to produce hypothetical transportation schedules. Hence, they need a modified planning mechanism to answer binding requests as well as hypothetical inquiries. While they build their transportation schedules by using planning agents they might become non-optimal and therefore have to be optimized. We use the simulated trading algorithm as a co-ordination mechanism during the optimization of the schedules which is described in Section 3. This leads to more dependent agent plans, that causes problems during the planning process. Section 4 addresses to these difficulties and describes an approach how to handle these problems.

We have performed several simulation runs and have evaluated the effects of the different CASA co-ordination mechanisms on the performance of supply webs. The simulation results are shown in Section 5 before we provide a short conclusion in Section 6.

2. CASA agents and services

To follow up the demands for the integration of logistic services in e-business solutions a project, called CASA, was founded by the German Research Centre for Artificial Intelligence (DFKI). The intention of the project CASA (Co-operative Agents and Integrated Services for Logistic and Electronic Trading in Forestry and Agriculture) is to establish mobile integrated services in selected application scenarios within the domains of forestry and agriculture in the local county. Hereby agent-mediated services support the main operative business processes users are performing in each of the following application scenarios: (1) customer-oriented dynamic timber production and (2) trading of timber via different types of auctions.

The paradigm behind the ideas of the CASA project is to establish an information and trading network (ITN) for integrated commerce (i-commerce), which can be seen as an operational extension of traditional e-commerce [15]. The basic ideas of i-commerce are (a) to get customers more involved in the activities related to his orders or tasks to be jointly accomplished by one or multiple contractors, and (b) to get related processes in the considered supply chain more integrated in practice. Information is vague and the correct execution of delegated tasks is uncertain.

The main objective of the CASA project is to offer services, which lead to a better and more effective integration of production, logistics and trading processes. Therefore the CASA project designs, imple-
ments, and evaluates an innovative system for electronic commerce. The system is built to integrate significant future trends and make them usable for users of the information and trading network. These trends are:

- Integrated electronic commerce (i-commerce)—an extension of e-commerce by special information services which could be used during trading processes.
- The use of mobile end devices in e-commerce processes (m-commerce).
- Intelligent software agents.

CASA's Information and Trading Network (ITN) offers its users new integrated services for negotiation, communication and exchange of information; which enable them to work closer together. To improve the accessibility, functions and services of the ITN are usable by a computer connected to the Internet or by mobile end devices like WAP phones. A refinement can be achieved by an integration of logistics services during planning and negotiation phases.

2.1. Holonic agent system of the CASA ITN

The CASA ITN system differentiates between the following participant groups: producers, buyers, retailers, and logistics companies. CASA ITN assigns to each member of these groups an appropriate kind of software agent called holonic agent [3,8,10]. Holonic agents accomplish complex (mostly hierarchically decomposed) tasks and resource allocations in the selected application scenarios. They also coordinate and control the activities and information flows of their subagents. In a holonic multiagent system, autonomous agents can join other agents to form, reconfigure, or leave a holon.

This holonic agent technique lets personal assistants that represent human users act on behalf of their users even if those users are offline. Personal assistants operate like the coordinating heads over a set of other specialized agents designed for enhancing individual negotiation, auction participation, information location, and strategic trading.

In addition to representing users with agents CASA ITN assigns to each corporation a special holonic agent system according to each corporation’s task-oriented classification. These subdivisions treat corporations from the perspective of information management, logistics, and production planning. Information management services provide information either on certain products and related production processes or on current market situations and potential competitors. Logistics services support the coordination of machines for production and transport, human resources, and storage capacities. Finally, production-planning services support short-, middle-, and long-term product planning cycles.

A corporation holon consists of several holonic agents, each of them representing a special department and its corresponding tasks and services. Because CASA ITN can use the roles of buyer, retailer, seller and producer interchangeably, we model all of them with similar holonic agent structures, and we distinguish between buyers that they either have or do not have logistics departments.

The developed agent-based services for a distributed virtual marketplace facilitate different kinds of trading between the participants within CASA ITN. These trading types can include multiple online auctions or sales through fixed or negotiable prices in bilateral negotiations. Each registered user in CASA ITN might, for example, initiate and perform one or multiple auctions of its own goods and products at any time, anywhere.

The aggregate of CASA ITN agents provides several services to its users:

- **Auction mechanisms.** Agents facilitate several auction types, including Dutch, English, Vickrey, and First-Price-Sealed-Bid auctions. At first-price open-cry so-called English auctions bidders win with and have to pay the amount of the highest bid. In descending price open-cry so-called Dutch auctions, the auctioneer sells a single item at the first incoming bid. At a first-price sealed-bid auction each bidder submits one bid in ignorance of all other bids and the highest bidder wins and pays the amount of his bid. Similarly, at second-price sealed-bid so-called Vickrey auctions the winning bidder pays the price of only the second highest bid [16].
- **Integrated services for dynamic pricing.** As a
decision-support service for its users agents can collect information on transportation costs and other constraints to be met.

- **Logistics services.** Agents provide dynamic transportation scheduling and planning. We use an extended version of the Contract Net protocol, which relies on simulated trading to optimize transportation planning and scheduling [1,2].
- **Information management.** Agents gather relevant information on behalf of their users in different trading and production settings.
- **Mobile services.** Agents enable the mobile services that let users access most of the CASA ITN on WAP-enabled mobile devices.

In the CASA ITN system foresters and timber harvesters cooperate with the service—providing agents to satisfy an individual customer’s order and to deliver a certain quantity of timber at a given time. Registered users can set up and participate in multiple timber auctions through WAP-enabled mobile devices. These registered users can also trade grains through auctions or multilateral negotiations with interested parties. In the following we concentrate on the mobile timber sales scenario, which merges the problems of e-commerce, as well as the difficulties in logistics by forming a so-called supply web [11].

### 2.2. The application scenario

The services of the CASA ITN have been built with a special focus on supply-web activities in the forestry domain, in which a lot of dynamic events occur during the production, the negotiation and the transportation process. Regarding these dynamics an adaptive system has to be built to fix the plans of the participants just in time, when a problem occurs.

In this scenario, we concentrate on that point in a supply chain, where the production is finished and the negotiations for the sales begin. The basic component of the ITN is the market place that provides services for direct price negotiation between a seller and a buyer, but also offers services for initiating and performing auctions of various types like English, Dutch, Vickrey and First-Price-Sealed-Bid auctions. These services are built upon autonomous agents in order to enhance the usability and flexibility of the ITN [5]. The main benefits of the agent-based service support are the concurrent execution of delegated tasks like acting in an auction in accordance with the user’s preferences or in finding partners for a given problem. Hereby an agent can undertake the task to find special logistics services, e.g., for a transportation task or a company offering particular machines and know-how to solve a given problem.

The logistics services are especially useful when participating in a fast progressing auction such as the ones the bidder does by himself. In this case he needs assistance to find a forwarding agency that can do the forwarding of bought or sold goods in a certain time span—defined in the auction conditions—at approximately the lowest cost. But these new services need a counterpart in the organization of logistics companies, which allows fast re-planning, dealing with hypothetical requests and flexible resource management.

**Fig. 1** shows the coherence between seller, buyer and (mediated by the market place services) logistics. During a negotiation phase sellers and buyers bargain for the conditions of the contract and its fulfillment. They have to clarify the amount of goods to be transported, when and where to start and end the delivery and the partitioning of the transportation tasks. This information builds the basis for a request to a logistics company, which in turn is then able to compute an answer containing detailed information about the transportation cost, time span and used resources. The planning and scheduling within a logistics company is a very complex task, on which we will concentrate in the following section of this paper.

Hence, the ITN offers all its users the opportunity to invoke such integrated services for decision-support during their participation in one or multiple different auctions. For example, a personal agent may concurrently determine the optimal transportation cost and delivery dates of some auction goods for each individual bid of its user. As a result, the agent may notify its user in real-time if estimated optimal transport costs exceed the allowed limit due to given buying preferences or if some deadlines are at risk to be exceeded.
2.3. The agent society of the CASA ITN

Due to the uncertainties in the execution of an agent’s plan (e.g., traffic, machine failure, etc.) and of the hypothetical requests an agent gets during running auctions, the system has to be flexible in doing fast re-planning and reorganization. We apply a holonic structured multiagent system, as they are well suited for dealing with complex tasks (e.g., planning tasks), that can be divided into a set of subtasks.

The four groups of participants in the ITN (see Fig. 2) will be represented by complex agent structures, which consist of holonic agents: sellers, buyers, logistics and public market places build the elements of the ITN.

Each seller is modeled as a holonic agent, resp., seller holon, consisting of a set of four holonic subagents, i.e., three subagents managing information, logistics and planning tasks and additionally a so-called company agent. This agent covers the internal agent structure of that company and controls the information flow within the holon, as well as to the other ITN participants. But this agent also
represents the company as a whole to the ITN and controls the information flow of all subagents to the other ITN participants. It is the contact for direct negotiations with other supply web companies.

The other subagents characterize the further departments of the company involved in the trading process. There is a planning holon for representing the planning department of a company. An information holon has to cope with the information needed for the offering. It administers not only the information for the current offer, but it also has the information about the own production, storage capacities and if available, the information about the market situation. This information builds the basis for the plan generation, the internal pricing and the choice of selling strategy.

The last holon, called personal assistant holon, represents the user in the agent network. It behaves as it is described before to support the user during his work and interaction with the system.

The holonic agent structure of a buyer, resp. buyer holon, within the ITN is of a similar design as the one of a seller. We distinguish between buyers with logistics departments and such without. If logistics is not included, the company holon has to find partner forwarding companies, when there is a transportation task and therefore it can use the logistics services of the market place. If the company has a logistics department but not enough resources left to fulfill a logistic task, the logistics department, modeled as a logistics holon, is responsible to find other forwarding companies that can do the job.

The logistics company has to co-ordinate, control and schedule the resources and is not involved in any trading process. These companies provide special services, which can be accessed by the other groups of the ITN. Such companies are also represented by a holonic multiagent-system, which is more complex than those of the others. In the logistics part of the system each entity of the real world has its pendant in the multiagent system. This is necessary because of the huge amount of constraints of each entity that have to be taken into account during the planning and scheduling process. Especially in logistics, there exists a large variety of machine-types—concerning the tractors’ power and the purposes of the semitrailers—and groups of persons, which has to be represented. Hence, each of the physical components of a logistics company and each employer is represented by an agent that administers the resources of the component or person. These agents have their own plans, desires, constraints and goals, so that they are able to act autonomously during the planning and scheduling process of its own company.

For the distribution of tasks to this agent society the contract net protocol, a popular DAI allocation mechanism, can be applied, because the agents of a company behave co-operatively. In its original version [12] the protocol consists of a manager, who announces a task to a set of contractors (see Fig. 3). Based on their local cost estimations, these contractors compute bids, which are sent to the manager. The manager selects the best bid, rejects the others and grants the task to the best bidder. This contractor is committed to report the success or failure of the execution to the manager.

The manager of the protocol is in our scenario the logistics holon agent, which encapsulates the internal agent structure to the outer world. The manager agent is therefore the coordinator of the other agents, representing the real world’s entities. In the protocol these agents appear as bidders applying for the announced tasks. In such a co-operative setting, the contract net protocol is a simple method to find an allocation of a set of tasks to an agent society. But as the agents act independently during their decision process, the plans only become locally optimized. To achieve approximate global optimization of the initial plans, we intend the contract net protocol by incorporating simulated trading.

Fig. 3. The contract net protocol.
3. Simulated trading as a co-ordination mechanism

However, the use of the (extended) contract net protocol [14] has the drawback, that the results are dependent on the insertion order of the task into the algorithm. By changing the order of the incoming tasks, the plans of the agents could be totally different and so the result of the overall solution. To avoid this trap and to handle the huge complexity of optimizing dependent plans in a supply web, an optimization procedure is needed to improve the result after a first valid solution is found, for example be the use of the contract net protocol.

3.1. The basic idea

The basic idea of this algorithm is to exchange abstract items among a number of agents. Trading is done in several rounds, each of which consists of a number of decision cycles. In each cycle, the participants submit one offer to sell or buy a task. At the end of each round a central manager agent, the central coordinating instance, tries to match the sell and buy offers of the contractors in a way that the cost of the global solution decreases.

Looking at these two approaches, it seems to be a good choice to combine them in a new protocol, where the agents do not lose too much of the autonomy, and a centralised entity for an efficient matchmaking also exists. During the optimisation the agents act autonomously and communicate with the others using a blackboard. The agents write the offers on the blackboard and read from the blackboard what items and tasks are available. After a certain time a supervisor puts an end to the communication and, having a look at the blackboard, it generates a match between buy and sale bids, so that the overall situation increases. This approach has the advantage that the agents are only minimally dominated by another manager agent. The agents are free to decide what they want to do, but in the end they are only restricted by the amount of actions, which are allowed by the manager. However, the manager has the advantage of having a more global view; so that it is able to detect interdependencies a single agent will not be able to see.

The feasibility of doing so is provided by the simulated trading algorithm, which has been developed by [1]. This optimisation algorithm is not so restricted that the agents totally loose their autonomy, they are still able to act in some parts of the algorithm independently and in consolidation phases an advisory agent directs them. The simulated trading algorithm is based on a market-based parallel improvement. It is a randomised mechanism, where the agents optimise the overall solution by iterative selling and buying of tasks. Hereby selling is an abstraction of getting rid of an agent’s task and buying is a pseudonym for demanding a new task.

In the following we describe in brief how the algorithm works and how it can be used in other domains except the transportation domain, for which it was developed. But we also discuss a scenario, where this approach is not applicable as it is in the transportation domain.

3.2. The procedure

The simulated trading procedure assumes a stable cooperative environment and an initial solution, which has to be optimized. Before this optimization algorithm can be used, an initial solution by the use of the contract net protocol has to be found first. In a cooperative setting, the contract net protocol is a simple method to find an allocation of a set of tasks to an agent society. But as the agents act independently during their decision process, the plans only become locally optimized. To improve the overall solution the simulated trading algorithm can be applied on the basis of the initial plans. But when during the optimization process occur changes in the set of tasks or some agents have problems during the execution of tasks that cannot be handled locally, the optimization process then has to be interrupted. Methods for building an initial solution have to be applied again to fix the problems. When the environment is stable again, the optimization process can be restarted.

In order to deal with impassability, the optimization mechanism has to be an anytime algorithm. Such algorithms have to be interruptible at any point in time and give back a correct solution. The simulated trading is also an anytime algorithm, which is based on two nested loops (see Fig. 4). Initially, the current plans of the agents are saved.
optimization process never decreases. Sometimes it is the same, when an improvement cannot be found.

Each trading round is then sub-divided into several decision levels (which is usually \( \equiv 10 \)) and for each one, the agents generate a bid to sell or buy a task. Some constraints apply, e.g., an item can only be bought on a certain level if there has been an offer to sell this item on a previous level. Then the sell and the buy offers are matched in order to increase the quality of the solution. In early rounds of the trading process, a deterioration of the solution is allowed in order to leave local maxima in the solution space. When the current plan at the end of a trading round is better than the saved plan, the saved plan is replaced by the current plan. When the algorithm is terminated or interrupted, it returns the saved plan which is the best plan ever considered. Hence, the anytime property of monotonically growing quality of the solution is guaranteed.

### 3.3. The simulated trading protocol

In order to distribute this protocol to an agent society, the simulated trading algorithm has to be adjusted. Each agent gets a precise function in the protocol workflow. Fig. 5 shows a chronological flow of the single steps of the simulated trading protocol. There is a manager, who is able to coordinate the protocol and to find matches in the end of the trading round. The other agents have to choose in each decision level among three operations: (a) sell,
(b) buy and (c) no operation (noop). When the protocol starts, the manager initiates it by generating a selling list, which is empty at the beginning. All the other agents are then informed, how to access this list. In each decision level the bidder agents, which want to optimize their plans, have to choose exactly one of those trading operators. The bidders compute bids, where they choose randomly a task from their plan to sell, an item from the selling list that can be incorporated into their plans to buy, or still do nothing by choosing the noop-operator. After a trading operator is chosen, the bidder agent reports to the manager the type of the trading operator (buy, sell, or noop) and the cost value of the execution of the operator.

If the agent wants to buy a task, the cost value represents the costs for the insertion of the task into its plan. When selling a task the cost value is equal to the savings for the removal from the plan.

The modifications of the plans are not stable until the manager has confirmed the offers at the end of a trading round. So the agents have to execute their operations on hypothetical plans to determine the trading operator’s cost value.

During a trading round the manager adds the sell offers to the selling list and sends the updated list to the bidders. This process is iterated until the last decision level of the trading round is reached. If the last decision level has been finished, the manager computes the best match of sell, buy and noop operations and informs the bidder agents about the acceptance or rejection of their bids. Hence in one trading round the bidders generate several hypothetical plans that depend on the acceptance of their sell and buy offers.

As the agents act during a trading round, the agents behave autonomously in the choice of the next trading operator and in the way of choosing an item from the selling. This is because the selling is only filled and if an agent buys an item from the selling list, the item will not be removed. When an item is in the selling list, it stays there until the end of a trading round. This behavior is based on the fact that each decision level produces a next step in the action sequence of an agent, where all the following choices are dependent on the choices done before and on the selling operation of all the other agents. Hence the actions of the agents are independent in the buy operator, because this operator does not make any change in the list. But the actions are dependent in the sell operator, because another agent can then buy the offered item.

Because the agents observe only the selling list, the manager has to solve the inter-dependencies between the sell and buy offers in a way that it finds a match, were:

(a) the overall solution is the best match of all sell, buy and noop operations and therefore increases the benefit of the whole agent society (that is involved in the optimization process),

(b) no item is left in the selling list. The algorithm has to take care of the fact that all the tasks of the initial solution are distributed to the agents after the optimization ends.

This is a very important assumption, because when the society as a whole accepts a task, it is like a contract that cannot be broken without a renegotiation. As a consequence during the matching process the manager has to decide how many actions of an agent’s action sequence it will allow. As an outcome of the algorithm, the manager tells each agent how many actions of its action sequence (beginning with the first entry of the action sequence) are allowed to be accomplished in real. For example, some agents are able to realize their overall hypothetical plans and others might not be allowed to do anything. The order in the action sequence is also very important. So the confirmation from the manager includes instructions, where the sequences are only shortened, but not divided into pieces.

3.4. Matching the trading graph

After the bidding phase, there are for \( i \) decision levels and \( n \) agents \( i \times n \) sell, buy and noop offers available. The sell and buy offers are to be matched to each other by the manager at the end of a trading round. In order to represent the search problem of finding the optimal match (based on user alleged parameters like costs, efficiency, etc.) for these offers the trading graph, a data structure to represent the dependencies of the sell and buy offers, is generated (see Fig. 6). We build this graph by using a binary representation for the acceptance of an agent’s
action. The number of an item of the action sequence is equal to the depth of the search tree, e.g., if the matching algorithm reaches the third level of its search tree, it decides if the third actions in the action sequences will be allowed or not. So each node contains a binary number of length \( i \) and the value of each bit represents, whether the action of agent \( i \) is allowed \((=1)\) or not \((=0)\). To shorten the search space, we can use the constraints of the algorithm, that an action sequence only can be shortened but not divided into pieces. This means if in the search tree the bit of an agent is turned to zero, it will never be turned to one.

In addition to the binary data in each node, we also need to store the costs of the action and the actual selling list, based on the allowed actions in the past of the checked search path. A solution is found at a node, when the selling list is empty. This might not only be at the end of a search path, so while making a depth first search, many solutions can be found, while a single path is checked.

When a solution is found, the costs of this solution have to be compared to the costs of the saved solution, which used to be best before. If the new solution is better, it is saved as the best and if not, it is discarded.

4. Planning with dependencies

The extended version of the contract net protocol applied to the transportation domain [2] also turns out not to be suitable for the case where the environment gets more complex in a way that the actions of the agents are not independent from each other any more. This is the case, when machines and workers are represented separately and the elements of the combination (machine–worker) changes over time. Hereby the change in the plan of a worker might influence the plan of another worker, who uses the same machine at a different time.

In our setting we have to face this problem and therefore have developed an efficient representation of the plan steps to include the interdependencies in the plan. In this way there is no need to consult all the members of the convex hull over the dependencies beginning with the plan of that agent, which has to make a change. Normally the agent has to compute a new plan for each request. However, often these requests are only of hypothetical nature and after the answer of the agent is known, the effect of the request has to be discarded. This is often done during the execution of the contract net protocol, when the manager sends his announcement to all sub-agents and after the answers are analyzed, only one agent gets a grant and the others have to discard their modifications.

By now, when a modification becomes a real and stable, we have to find all the agents that are affected by the change of the plan. This has to be done after the modification is become stable, so that afterwards the agents are able again to give answers to such requests.

When a new plan step has to be incorporated into
an existing plan of an agent there will be no problem as long as each agent is solely responsible for its plan. Hence, no other agent is affected by the changes to already existing plan steps. But if any dependency exists between the plans (‘connected plan steps’) of two or more agents, we have to be aware of the consistency among their plans. Consistency can be retained by the following two steps:

- Plan steps have to remain consistent among the society from the beginning (i.e., the empty plan) on. In detail, whenever a plan step requires the action of more than one agents then this plan step has exactly the same parameters (start time, duration, end time) in each of the related agents’ plan. Hereby the setting of the correct parameters is done by a central coordinating agent during the matching phase within a contract net protocol. Thus whenever a request for an insertion is issued the agent can decide on his own if it is possible to grant this request. This prevents that an agent $A_1$ grants the request because it could adjust its plan steps in a way that an insertion is possible, while these changes make it impossible for another agent $A_2$ to fulfill its plan because it cannot change its plan step parameters accordingly, for instance because of other already inserted plan steps which are not shared with agent $A_1$.

- Any changes of plan steps have to be propagated to the other agents of the society. This prevents connected plan steps from becoming inconsistent within the different plans of related agents. In detail the following describes, what has to be done whenever a new plan step is inserted or deleted in an agent’s plan:

  Each agent, which makes changes on its plan, re-computes it independently from the others even if they have some relations to this agent. Then all changed steps are collected, sorted according to the related agents and sent to each of them in a single message. Thus the update process is independent from the number of changed plan steps and so it only depends on the number of agents in the society (quadratic runtime).

  When an agent receives such an update message it checks its own plan if the received changes narrow the time slot of an existing plan step; if so, it adopts the new times. Otherwise it does nothing.

  After all messages have been sent and been processed, the plans of all agents are consistent again (remember that only narrowing time slots were allowed in the update process). These techniques build the basis for the following optimization algorithm, which is needed because the contract net protocol only produces a sub-optimal plan dependent on the incoming order sequence.

5. Evaluation of market-based supply web co-ordination mechanisms

Several market-based allocation mechanisms are suitable for the co-ordination of supply web activities, e.g., the allocation of a set of tasks to a set of supply chain agents. Such mechanisms are the simulated trading algorithm [1], the Vickrey auction [13], and the matrix auction for multiple heterogeneous items [7]. We compared their suitability, using the allocation of transportation tasks to a set of truck agents within the multiagent scheduling system MASMARS [4] in a co-operative and a competitive setting.

5.1. Market-based co-ordination mechanisms

Simulated trading (ST) [1] is a randomized algorithm that realizes a market mechanism where the participating contractors optimize a task allocation by successively selling and buying tasks. Trading is done in several rounds, each of which consists of a number of decision cycles. In each cycle, the participants submit one offer to sell or buy a task. At the end of each round the stock manager, the central coordinating instance, tries to match the sell and buy offers of the contractors such that the costs of the global solution decrease.

In the sealed-bid second-price or Vickrey auction (VA) [13] each bidder submits a sealed bid for the item to be auctioned off to the auctioneer. The bidder who submitted the best bid receives the item for the second highest bid made. In contrast to traditional auctions like the English and Dutch auctions, this
procedure is truth revealing, i.e., it forces the bidders to submit bids that equal their true valuations for the items.

Matrix auctions (MA) [9] are—in contrast to ST and VA—applicable for the simultaneous assignment of multiple items or tasks to bidders. The auctioneer announces in a matrix-k-auction (MA-k) the k offered items to the bidders who, in turn, calculate their valuations for each potential combination of items and report them to the auctioneer. From the transmitted bids or reported valuations of the bidders the auctioneer identifies the optimal allocation of all k items. The price for each assigned subset of items equals the second-highest bid in the matrix column for that set of items. Like the Vickrey auction, the matrix auctions are truth-revealing.

5.2. Suitability of the mechanisms for supply web co-ordination tasks

5.2.1. The co-operative setting

In the co-operative setting, the truck agents belong to one company and have no interest in optimizing their individual profits. The auctioneer agent represents the company and tries to minimize the overall cost per order (see Fig. 7). An analogous setting in the supply web domain would be the intra-organizational optimization of the supply flow by a retail company.

5.2.2. The competitive setting

In the competitive setting the truck agents represent independent self-interested forwarders. They compete on an open electronic market—by sending bids in the FIPA ACL message format—for the assignment of transportation tasks in order to optimize their route plans and in this way their surplus per order. The auctioneer agent does not represent a forwarding company but acts as an independent broker. You can think of an analogous setting in the supply web domain where some independent companies form a short-term supply path, a virtual company or co-operate with other companies within the framework of a strategic alliance.

In Ref. [7], we empirically examined the scalability and tractability of the market-based co-ordination mechanisms mentioned above by comparing their processing time and allocative efficiency for order sets of different size. Thereby, the allocative efficiency of the mechanisms is measured in terms of cost, and surplus.

5.2.3. Simulation results

In the cooperative setting—where cost per order is the crucial issue—the simulated trading procedure

![Cost](image)

Fig. 7. Overall cost per order in the co-operative setting.
produces generally the best results with tractable effort. The simulated trading procedure is proved to be most efficient for large order sets where much optimization can be done. MA-3 and MA-4 perform slightly better than the remaining protocols. Hence, ST would be the protocol of choice for the auctioneer. Nevertheless, MA-3 achieves acceptable results as well.

In the competitive setting—where individual agents try to optimise their benefit—the individual surplus of the agents taking part in the co-ordination process has to be compared (Fig. 8). In this setting ST is not applicable. Here, the MA-2 procedure ensures a maximal payoff for the self-interested agents and outperforms dominantly all other mechanisms, followed by the Vickrey auction.

In summary, especially ST, MA-2, and MA-3 are very suitable for supply web co-ordination tasks and therefore are integrated into our supply web co-ordination architecture.

With respect to the tractability of the mechanisms, the evaluation showed that ST, VA, MA-2, and MA-3 can be rated as scalable, while MA-5 and, for large order sets, MA-4 do not provide better results, but loose tractability, indicating that matrix auctions where six or even more items are traded in parallel are not expected to be particularly efficient.

Due to the space restriction we could not present all results; more results of the evaluation can be found in Ref. [6].

6. Conclusion

In this article, we dealt with some issues of agent-based supply web co-ordination. We introduced parts of an agent-based information and trading network (ITN), called CASA, enabling supply web entities to optimize their interaction strategies. The openness, scalability and negotiation abilities of a holonic multi-agent system build the basis for its realization.

CASA offers its users a set of co-ordination mechanisms, as, e.g., auctions, for reaching efficient deals during electronic negotiations. Additionally, CASA optimizes the information flow between the network, resp. supply web partners, by providing agent-based information services. Transportation requests from a seller or buyer are directly forwarded to logistics companies participating in the ITN during auction run-time. The CASA logistics services allow their users to check on the availability, conditions and cost of requested transportation orders. Later on, the users have also access to current

![Fig. 8. Overall surplus per order in the competitive setting.](image-url)
order and delivery information anywhere and at any
time by their company agents.

The described integrated services of CASA enable
their users to integrate current information about the
availability and costs of logistics services into their
decision processes during the run-time of auctions
and thus to adapt their bidding strategies such that
lower cost or higher surplus can be reached.

One interesting mechanism for co-ordinating the
optimisation of a supply web is the simulated trading
algorithm which we have described in detail in this
article. We have performed several simulation runs in
competitive and co-operative settings and have
evaluated the effects of the different mechanisms on
resulting cost and surplus within supply webs. In
summary, especially the Simulated Trading mecha
nism as well as matrix auction mechanisms for two
or three items are suitable for supply web co-ordina
tion tasks.

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