Deutsches
Forschungszentrum
für Künstliche
Intelligenz GmbH

Research Report
RR-99-04

The Matrix Auction:

A Mechanism for the Market-Based Coordination of Enterprise Networks

Christian Ruß, Gero Vierke

August 1999

Deutsches Forschungszentrum für Künstliche Intelligenz GmbH

Postfach 2080
67608 Kaiserslautern, FRG
Tel: +49 (631) 205-3211
Fax: +49 (631) 205-3210
E-Mail: info@dfki.uni-kl.de

Stuhlsatzenhausweg 3
66123 Saarbrücken, FRG
Tel: +49 (631) 302-5252
Fax: +49 (631) 302-5341
E-Mail: info@dfki.de

WWW: http://www.dfki.de

Deutsches Forschungszentrum für Künstliche Intelligenz
DFKI GmbH
German Research Centre for Artificial Intelligence

Founded in 1988, DFKI today is one of the largest non-profit contract research institutes in the field of innovative software technology based on Artificial Intelligence (AI) methods. DFKI is focusing on the complete cycle of innovation — from world-class basic research and technology development through leading-edge demonstrators and prototypes to product functions and commercialisation.

Based in Kaiserslautern and Saarbrücken, the German Research Centre for Artificial Intelligence ranks among the important "Centres of Excellence" world-wide.

An important element of DFKI's mission is to move innovations as quickly as possible from the lab into the marketplace. Only by maintaining research projects at the forefront of science can DFKI have the strength to meet its technology transfer goals.

DFKI has about 115 full-time employees, including 95 research scientists with advanced degrees. There are also around 120 part-time research assistants.

Revenues for DFKI were about 28 million DM in 1998, half from government contract work and half from commercial clients. The annual increase in contracts from commercial clients was greater than 37% during the last three years.

At DFKI, all work is organised in the form of clearly focused research or development projects with planned deliverables, various milestones, and a duration from several months up to three years.

DFKI benefits from interaction with the faculty of the Universities of Saarbrücken and Kaiserslautern and in turn provides opportunities for research and Ph.D. thesis supervision to students from these universities, which have an outstanding reputation in Computer Science.

The key directors of DFKI are Prof. Wolfgang Wahlster (CEO) and Dr. Walter Olthoff (CFO).

DFKI's six research departments are directed by internationally recognised research scientists:

- Information Management and Document Analysis (Director: Prof. A. Dengel)
- Intelligent Visualisation and Simulation Systems (Director: Prof. H. Hagen)
- Deduction and Multiagent Systems (Director: Prof. J. Siekmann)
- Programming Systems (Director: Prof. G. Smolka)
- Language Technology (Director: Prof. H. Uszkoreit)
- Intelligent User Interfaces (Director: Prof. W. Wahlster)

In this series, DFKI publishes research reports, technical memos, documents (e.g. workshop proceedings), and final project reports. The aim is to make new results, ideas, and software available as quickly as possible.

Prof. Wolfgang Wahlster

Director

The Matrix Auction:
A Mechanism for the Market-Based Coordination of Enterprise Networks

Christian Ruß, Gero Vierke

DFKI-RR-99-04

This work has been supported by SAP RETAIL SOLUTIONS and the Federal Ministry of Education, Science, Research, and Technology.

ISSN 0946-008X

The Matrix Auction:
A Mechanism for the Market-Based Coordination of Enterprise Networks

Christian Ruß, Gero Vierke

German Research Center for Artificial Intelligence (DFKI GmbH)
Stuhlsatzenhausweg 3, D-66123 Saarbrücken
{russ,vierke}@dfki.de

Abstract

We argue that a network of shipping companies, that cooperatively executes transportation tasks, can be viewed as a special instance of a virtual enterprise. We propose the matrix auction as an efficient, incentive compatible allocation mechanism for virtual transportation enterprises. The implementation of the matrix auction in a multi-agent fleet scheduling system is described, and we were able to observe a significant improvement of the task allocation.

1 Introduction

In this paper the problem of efficiently allocating transportation tasks in a network of cooperating shipping companies that are independent and self-interested is adressed from an economic point of view.

In the highly competitive haulage business, small and medium sized shipping companies that operate locally are often forced to form temporary inter-regional alliances in order to bundle their resources and to establish competitive prices.

The business process of a transportation task is often split into subtasks: the local pick-up and delivery of the cargo and the transport over the longer distance between the source and destination regions. This split process is often performed by a team of two or three different hauliers that are specialised either on local or long-distance delivery. This regional specialisation, as well as specialisation on certain types of cargo like frozen or dangerous goods, are the core competencies of the hauliers involved.

This constellation matches Arnold's [Arnold et al. 95] definition of a virtual enterprise (VE) as *a temporary cooperation network of legally independent companies which quickly unite and mainly contribute their core competencies in order to exploit a specific market opportunity — i.e., to provide a demanded service or product — on the basis of a common understanding of business. Though the virtual enterprise refuses an institutionalization — it has no central office, no hierarchy and no vertical integration — the autonomous partner companies act to externals as a single corporation.*

Partners in such a virtual transportation enterprise, as well as in any other kind of virtual enterprise, are self-interested, i.e. they rate their own profit higher as the common profit of the group. Hence, a group of agents that try to optimise their own, local utility risks to end up with a suboptimal global solution which might even prevent the coming about of the whole cooperation.

An approach to overcome this dilemma is the usage of *truth revealing* [Ma et al. 88] allocation mechanisms, i.e. mechanism that are designed such that the best strategy for the participants is to reveal their true preferences to the coordinator, i.e. a trusted agent that coordinates the allocation process.

The most common truth revealing mechanism is the *Vickrey auction* [Vickrey 61], which can be used for resource allocation and task assignment. Its pricing rule — called the *Vickrey principle* — determines that the task or item auctioned off is awarded to the bidder who stated the best bid at the price of the second-best bid. This principle enforces that neither bidding higher nor bidding lower then the true valuation or cost is beneficial.

In the resource allocation variant of the Vickrey auction, the bidders submit one sealed bid for a single item which reflects their valuations for the item. The item is granted to the highest bid for the price of the second highest bid. In the task assignment variant, the bidders compete for an order (resp. announced task). They submit one sealed bid for the order which reflects their cost for performing the order. The order is awarded to the lowest bidder and the payment he receives for performing the order equals the second-lowest bid made.

In this paper we investigate the matrix auction, an incentive compatible mechanism for assigning multiple tasks to a group of agents. We implemented and evaluated the matrix auction on the basis of an existing fleet scheduling system. We believe that the matrix-auction is an efficient coordination tool for the management of business processes, and especially of supply chains in virtual enterprises.

In the following sections we explain the allocation mechanism behind the matrix auction, and analyse the complexity of the allocation function. Subsequently, we will shortly describe the — to our knowledge — first real implementation of a matrix auction (see Section 3) and then conclude by sketching some results of empirical evaluations of the performance of the matrix auction in the transportation domain

2 The Matrix Auction

The *matrix auction (MA)* is applicable for the simultaneous assignment of multiple items or tasks to organisational entities. The matrix auction was roughly sketched in [Gomber et al. 96] at first. Unfortunately, this presentation left the reader with some open questions concerning the matrix auction's complexity, implementation, and allocative efficiency. In the following paragraphs, we will answer these questions.

2.1 Truth Revealing Allocation Mechanisms

The *Revelation Principle* [Ma et al. 88] is a fundamental theorem in the economic theory of mechanism design. It states that for any allocation function, that can be implemented in dominant strategies, there exists an equivalent *direct* mechanism that implements that function *truthfully* in dominant strategies. In other words: if there exists a mechanism resp. a multi-player game that a planner can use to realise an allocation function, i.e. to allocate resources to a set of players such that his desired allocation results if the players play their equilibrium strategies, then there does also exist a direct *truth revealing* mechanism where the equilibrium strategy for all players is to reveal their true preferences to the planner by simply sending the planner a message.

For instance, the Vickrey auction is a direct truth revealing mechanism that implements the same allocation function as the English auction.

A mechanism is said to be *incentive compatible* if none of the participants has an incentive to differ from the expected strategy, i.e. if the strategies are in the Nash equilibrium.

2.2 The Matrix Auction Procedure

The agents obtain the information about the outstanding tasks over broadcasting or over a blackboard. Then they calculate their costs for performing these tasks and report them to a trusted coordinator agent who performs the auction. If the set of tasks contains k tasks, the agents are asked to calculate the cost of 2^n-1 potential task combinations.

From the transmitted bids of the agents the auctioneer sets up a matrix the cells of which represent the cost statements of the agents for each combination of tasks. Going out from this he identifies the optimal allocation which causes the minimal cost. For this variation of the *assignment problem* [Ohlsen & Porter 94] he uses an algorithm that takes into account that the maximum of assignments in each row equals one. Beyond this, assigned task combinations must not have any item or task in common, i.e. they must be disjunctive (form a partition of the item set).
After the auctioneer has identified the optimal allocation, he determines the payments the agents receive for the assigned task combinations according to the *Vickrey principle* (see below). Eventually, the auctioneer informs the selected agents about which tasks are assigned to them and which payments they receive for performing them. The bids of the other agents are rejected.

2.3 Settlement of Payments According to the Vickrey Principle

The payment for each assigned task subset equals the second-lowest bid in the matrix column for that task set. This *Vickrey principle* [Vickrey 61] makes the matrix auction *incentive-compatible*, i.e. it assures that the agents reveal their true cost valuations for tasks. This is due to the fact that the bid of an agent — revealing his cost valuation for an item — does determine whether he is selected for performing the task but does not influence the payment he receives for his service. Vickrey points out that his mechanism improves *"...the chances of obtaining or approaching the optimum allocation of resources ..."*.

	Task Combinations						
Agent	{1}	{2}	{3}	{1,2}	{1,3}	{2,3}	{1,2,3}
A	80	60	50	90	110	100	150
B	30	90	20	120	**50**	100	160
C	80	**40**	40	110	80	90	180

Table 1: An example for the settlement of payments in the matrix auction

Table 1 illustrates an example of this mechanism where three different items are allocated to three agents. According to the Vickrey principle agent C gets 60 currency units for performing task 2 and agent B gets 80 currency units as payment for performing the tasks 1 and 3 together.

2.4 Complexity of the Allocation Function

The assignment of tasks or orders according to the matrix auction concept is not a trivial problem. Moreover, at the moment it seems as if there does not exist an efficient algorithm for determining the optimal assignment in larger matrices that are not symmetric.
The problem of matching n individuals to n different slots is known as the *assignment problem* [Olson & Porter 94]. The total number of possible ways of assigning n individuals to n slots or items equals $n \cdot (n-1) \cdot (n-2) \cdot \ldots \cdot 2 \cdot 1 = n!$. As n grows, $n!$ grows very rapidly. Hence, the number of possible assignments grows fast with increasing n. Therefore, the problems in this category can only be handled by efficient algorithms which are guaranteed to obtain a solution within a reasonable amount of time. Integer programs and combinatorical optimisation problems typically belong in this category. For high n these problems become intractable.

The Hungarian method [Kuhn 55, Murty 95] is known to be an efficient method for determining optimal assignments in $n \times n$ matrix auctions. In all applications of the assignment problem, only an integral solution matrix (i.e., a matrix whose cells c_{ij} contain an 1 if bidder i is awarded to item j and 0 if he is not) makes practical sense. However, since in the matrix auction we have to assign k items to n bidders, this method cannot be applied any more.
In the matrix auction, for determining the optimal assignment of a task set consisting of k tasks to n agents, initially, all n bidding agents have to calculate their cost for all the elements (called slots) of the task set's power set. This vectors of cost are sent to the coordinator who has to determine — on the basis of the resulting $n \times (2^k-1)$ cost matrix — the assignment that minimises the sum of the cost of the tasks.
The matrix auction assignment problem can be formalised as follows:

$$A = \begin{cases} \text{minimise} & \sum_{i=1}^{n} \sum_{j=1}^{2^k-1} x_{ij} \cdot co_{ij} \\ \text{subject to} & \sum_{j=1}^{2^k-1} x_{ij} \le 1 \quad \forall i = 1,\dots,n \\ & \sum_{i=1}^{n} x_{ij} \le 1 \quad \forall j = 1,\dots,2^k-1 \\ & x_{ij} \in \{0,1\} \quad \forall i, j \\ & \text{the assigned slots have to be disjunctive and} \\ & \text{to represent a partition of the task set} \end{cases}$$

A further problem for determining the optimal assignment is caused by the constraint that the assigned slots have to be disjunctive and to represent a partition of the task set. This is due to the fact that a task cannot be assigned simultaneously to two distinct agents. The resulting assignment problem is a set covering problem with colouring constraints which is NP-complete. For a detailed description of the matrix auction and several other auction based allocation procedures we refer to [Fischer et al. 98].

3 A Pragmatic Solution Approach in MAS-MARS

What remains to prove is that the proposed — theoretically promising, since incentive-compatible — matrix auction does yield efficient outcomes in practice.
We decided to evaluate the matrix auction mechanism in the field of cooperative transportation scheduling: Several transportation companies form a virtual transportation enterprise, that — disposing of the core competencies of the participating hauliers — is more competitive than each of the single companies.
For this purpose, several types of the matrix auction mechanism differing in the number of simultaneously assigned items, have been implemented and integrated into the MAS-MARS [Fischer et al. 96] multi-agent system for distributed transportation scheduling which has been developed at the German Research Center for Artificial Intelligence.

3.1 Multi-Agent Modelling of the Transportation Domain

Over the past few years, the scheduling of transportation orders has been established as an important field of application for Distributed Artificial Intelligence both from an academic and from a practical perspective [Sandholm 93, Fischer et al. 96, Bürckert et al. 98]. It offers interesting complexity properties, an inherent distribution of knowledge and control, natural possibilities to study coordination and cooperation, and finally, there is a considerable economic interest in obtaining good solutions for these kinds of problems.

We consider a scenario where independent shipping companies form a cooperative network in order to increase their competitiveness. This network of shipping companies can be regarded as a virtual enterprise. In accord with the definition cited in the introduction [Arnold et al. 95] this network unites the core competencies of the involved hauliers to model the business processes of executing transportation tasks.

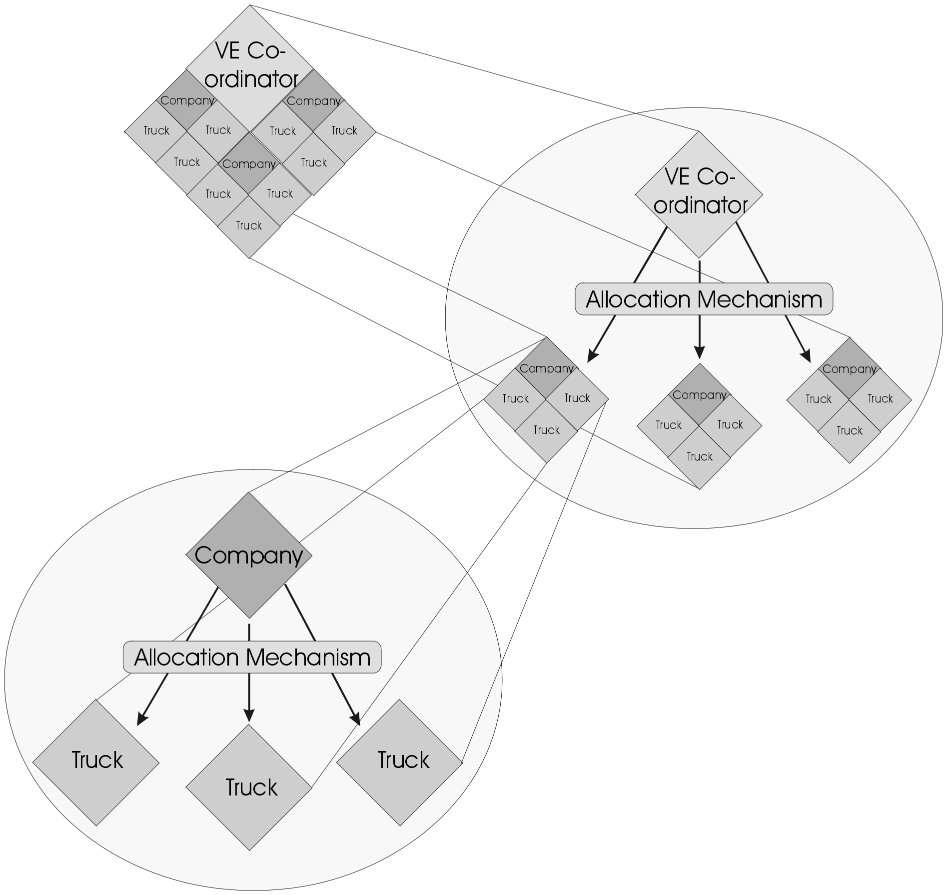

Figure 1: The holonic structures of the transportation domain.

Figure 1 illustrates an approach to map the structures of such a virtual transportation enterprise to a multi-agent society: The participating companies that form the VE are modelled by agents that represent the company's vehicles and by a company agent that coordinates the vehicles and represents the company to the rest of the agent society. The VE coordinator represents the VE to the user and manages the interaction between the participating companies. The use of *holonic agents,* i.e. agents that are composed of sub-agents and that act as if they were a single agent, allows to model the relevant structures of the domain in a natural way: the trucks, the companies, and the virtual enterprise are modelled as autonomous agents. Realistic tour planning may even enforce further decomposition of the vehicles into physical components like driver, truck, and trailer. However, this is not in the scope of this paper. For a detailed overview on holonic fleet management we refer to [Bürckert et al. 98].

3.2 The MAS-MARS System

The MAS-MARS multi-agent system simulates a scenario of cooperating transportation companies. The companies have to carry out transportation orders which arrive asynchronously and dynamically. The purpose of the MAS-MARS system is the planning and scheduling of these transportation orders which is usually done by the human dispatchers of the companies. Many of the problems which must be solved in this area, such as the Travelling Salesman and related scheduling problems, are known to be NP-hard. Moreover, not only since *just-in-time* production has come up, planning must be performed under a high degree of uncertainty and incompleteness, and it is highly dynamic. In reality, these problems are far from being solved.

Corresponding to the physical entities in the domain, there are two basic types of agents in MAS-MARS: *transportation companies* and *trucks*. Each truck agent is associated with a particular shipping company from which it receives orders. Company agents can communicate with their truck agents and among each other. Furthermore, a *coordinator* agent announces transportation orders to the shipping company agents. The coordinator agent acts internally as a broker but represents the virtual transportation enterprise to the outside. The shipping company agents compete with each other for getting awarded the orders.

Looking upon trucks as agents allows us to delegate problem-solving skills to them (such as route-planning and local plan optimisation). The company agents themselves do not have facilities for planning orders. Only the truck agents maintain local plans. The actual solution to the global order scheduling problem emerges from the local decision-making of the truck agents. The company agent has to allocate orders to its trucks, while trying to satisfy the constraints provided by the user as well as local optimality criteria (costs). A company may also decide to cooperate with another instead of having an order executed by its own trucks.

In the MAS-MARS system, the orders are allocated to the companies by the broker, and to the trucks by their companies. One can choose among several allocation procedures. The announcement and awarding of orders can be performed by the contract net protocol [Smith 80, Sandholm 93], the Vickrey auction, or the matrix auction.

3.3 The Implemented Solution Approach

In spite of the problem complexity of the matrix auction allocation function characterised in Section 2.4, it is not sufficient to find an approximating heuristic solution. If there is some probability that the optimal solution will not be found, truth-telling might no longer be the dominant strategy in the matrix auction.

In the MAS-MARS system we solve the allocation problem for task or order sets of small size by

1. calculating all possible partitions *p* of the task set,
2. determining an optimal assignment for each of the *p* possible partitions of the task set instead of determining an optimal assignment for the huge cost matrix of the original problem formulation in Section 2.4,
3. selecting the one that causes the minimum cost.

3.3.1 Calculating the Number of Possible Partitions of a Set

For doing this calculation, we have to use some close relatives of the binomial coefficients, the Stirling numbers [Stirling 30], named after James Stirling (1692-1770). Analogous to the binomial coefficients in Pascal's triangle, they also form patterns of coefficients. Stirling's triangle for subsets can be found in [Graham et al. 89].

The Stirling symbol stands for the number of ways to partition a set of *n* elements into *k* nonempty subsets. Therefore, for partitioning a set of 5 elements we have 52 possibilities:

possibilities. For a task set consisting of *n* elements, the number of possible partitions grows more than exponentially as shown in Table 2.

N	Number of possible partitions	Mightiness of the power set
9	21147	511
8	4140	255
7	877	127
6	203	63
5	52	31
4	15	15
3	5	7
2	2	3
1	1	1

Table 2: Number of possible partitions and mightiness of the power set of a set of n elements.

4 Evaluation

The MAS-MARS system offers outstanding opportunities for testing the efficiency of auction-based coordination mechanisms. For our evaluation, we used the test data that [Solomon 87] generated for the Vehicle Routing Problem with Time Windows. In this setting, a certain amount of goods has to be transported from a central depot to a number of customers, surrounding the depot. For each customer there are time constraints specified that restrict the delivery time of the cargo. Solomon's Benchmarks are available in the MAS-MARS system. They have different characteristics concerning geometry (whether the destinations are distributed in clusters or not), number of clients per tour, and more or less restrictive time constraints. For each order set, there are between 8 and 12 single problems that differ only by the time windows. The geographical position and the quantity of the cargo remain the same.

In our evaluations, we focussed on the following points:

- We compared the quality of the solutions produced by the contract net, the Vickrey auction, and different types of the matrix auction. The quality can be measured in terms of distance, execution time, or number of vehicles used.
- We analysed the changes in the qualities of the global solution that are implied by strategic bidding behaviour of agents, i.e. agents that do not reveal their true preferences but try to maximise their profit by overbidding.
- Additionally, we examined the scalability of the matrix auction for large order sets and high numbers of trucks.

The detailed results of the evaluations are documented in [Ruß 97] and [Gerber et al. 98]; below we summarise the results.

Performance Comparison

The matrix auction is an efficient allocation mechanism, that significantly outperforms single-item allocation procedures like the contract net or the Vickrey auction, even if only a MA-3 or MA-4 auction is carried through (see Table 3). This is due to the fact that the matrix auction mechanism assigns several tasks simultaneously. Thus, in contrast to traditional sequential auction mechanisms it can take into account cost-lowering interdependencies between single transportation tasks while allocating them.

Procedure	Solution Costs	Improvement
Contract Net	205.494	0%
MA3	185.451	9.7%
MA4	175.105	14.78%
MA5	176.138	14.28%

Table 3: Synopsis of the test results

Table 3 gives an overall overview of our test results that. It is based on test runs with clustered, semi-clustered, and non-clustered order sets. It starts with the initial CNP solution as a basis for comparing the efficiency of the different allocation procedures. Then, the overall solution cost of the matrix auction procedures as well as the improvements they have yielded compared with the CNP solution are listed. The matrix auction has been implemented with the option to choose among four task cluster sizes. That is, we are free to auction three (MA-3), four (MA-4) or five (MA-5) orders simultaneously.
Though the MA-5 auction was supposed to yield the best outcome among the matrix auctions, it is slightly outperformed by the MA-4 auction on the average. This could be due to the fact that the 5-clustering unluckily separates coherent orders in the partition of the order set so that they are assigned to two different trucks even though the orders could be cost-efficiently performed by one truck agent.

Analysis of Strategic Bidding Behaviour

The matrix auction mechanism is theoretically incentive compatible. Due to the Vickrey principle no single bidder has an incentive to submit bids that exceed his true costs, because the price he is paid depends solely on the bids of the others. This situation changes when either strategic coalitions are formed or a significantly high number of bidders does differ from the equilibrium strategy.
It is not possible for a coalition to get round an auction based on the Vickrey principle as long as there is one interested bidder who submits realistic bids. Such a coalition has to include all bidders and there is a high motivation for the participants to leave it. Hence, it is difficult to form a coalition and it is even harder to maintain it.
Nevertheless, in a setting where the bidders' preferences for tasks are highly dependent on the actual situation as in the tour scheduling context, the equilibrium strategy may not remain optimal if a significant number of bidders submit bids exceeding their costs.

Order Set	Total Cost	Total Profit	Strategy / Profit			
			1.0	1.1	1.2	1.3
R101	23.311	16.442	5.106	**6.256**	3.628	1.452
RC201	15.688	14.086	2.589	**8.348**	2.527	622
C101	10.068	13.385	1.773	2.085	**5.931**	3.596
C201	8.931	18.023	4.438	5.881	**6.736**	968

Table 4: Division of total surplus among strategic bidding groups of truck agents

We have partitioned the agents society in four strategic bidder sets of equal size.
Table 4 illustrates that it pays off to follow no extreme bidding strategy if the strategies are approximately equally distributed among the agent society. Though the subset of the truck agents that bid their truthful valuations (bidding factor 1.0) gets the most tasks awarded, it realises a smaller payoff than the 10 % or 20 % overbidding agent groups. The highest surplus for each order set is emphasised in bold print (see Table 4). We conjecture that this is due to the fact that in the beginning of the matrix auction the truthful agents mutually force down their payments. Because all start at the same location, initially they make almost equal bids for outstanding orders (as long as they stay close together). That means, that the second-lowest price they receive as payment can be assumed to only slightly exceed their cost. Hence, in the early stages of the allocation only the truthful truck agents are awarded orders. In the later stages, when several orders are allocated and the valuations of the trucks vary significantly, the lying agents often do not have to compete with truthful agents and, therefore, are able to realise high profits.

Scalability of the Matrix Auction

The major constraining factor for the matrix auction procedure is the computational complexity of the allocation function, which is exponential in the number of bidders and the number of possible partitions of the task set. Because of this, MA-4 and MA-5 cannot be scaled up to large sets of orders resp. bidders. Table 5 lists the average CPU time a 233 MHz Pentium II PC needed for allocating 120 tasks to 18 trucks on the average.

Mechanism	Vickrey	MA-2	MA-3	MA-4	MA-5
Run Time	3.4s	9.0s	42.0s	338.8s	8691.4s

Table 5: Run Time Results

Since the MA-3 auction is eligible for improving the contract net solution significantly (see Table 3) while possessing only a moderate complexity, even in complex transportation domains it can be used to realise cost-efficient task allocations in real-time.

5 Conclusion and Outlook

In this paper we discussed the matrix auction as an efficient allocation mechanism in the transportation domain. In comparison with the contract net allocation procedure, the matrix auction improved the task allocation significantly.
To make use of the general principle underlying the matrix auction, the Vickrey pricing principle, some requirements have to be fulfilled. A minimal number of bidders are needed to prevent the formation of coalitions. Since the auctioneer receives the true valuations of the bidders, he must be reliable, i.e. he must be neutral.
The outcome of this paper is that the matrix auction is well suited for task allocation within a virtual transportation enterprise.
The matrix auction procedure is generally suitable for improving allocation processes in all e-commerce scenarios in which a parallel or simultaneous matchmaking is needed or at least reasonable. Besides other applications, it can be used to implement market-based e-commerce systems that are open, i.e. built-up by a dynamically changing group of heterogeneous and anonymous business entities or agents. In such systems, the matrix auction mechanism has to be extended by an authentification mechanism for the participants (e.g. a certificate like X.509).

Our future work will focus on applying the matrix auction procedure for the planning and scheduling of interorganisational business processes within the more general domain of virtual enterprises. Additionally, we will investigate if the performance of mediator information systems can be improved by using the matrix auction for matching information queries with resource agents that gather the desired informations by accessing heterogeneous databases on the Internet .

Acknowledgements

The authors thank Klaus Fischer who laid the foundation for this work by designing and — together with Darius Schier and others — implementing the MAS-MARS multi-agent system. This work has been supported by SAP RETAIL SOLUTIONS and the Federal Ministry of Education, Science, Research, and Technology.

6 References

[Arnold et al. 95] O. **Arnold**, W. **Faisst**, M. **Härtling**, and P. **Sieber**. *Virtuelle Unternehmen als Unternehmenstyp der Zukunft?* In: Handbuch der modernen Datenverarbeitung - Theorie und Praxis der Wirtschaftsinformatik, Volume 185, Heidelberg: Hüthig-Verlag, 1995.

[Bürckert et al. 98] H.-J. **Bürckert**, K. **Fischer,** and G. **Vierke**. *Transportation Scheduling with Holonic MAS — The TeleTruck Approach*. In: Proceedings of the Third International Conference on Practical Applications of Intelligent Agents and Multiagents (PAAM´98), 1998.

[Fischer & Kuhn 93] Klaus **Fischer** and Norbert **Kuhn**. *A DAI Approach to Modeling the Transportation Domain*. DFKI: Research Report RR-93-25, 1993.

[Fischer et al. 96] K. **Fischer**, J.P. **Müller**, and M. **Pischel**. *Cooperative Transportation scheduling: an application domain for DAI*. In: Journal of Applied Artificial Intelligence. Special issue on Intelligent Agents, 10(1), 1996.

[Fischer et al. 98] K. **Fischer**, C. **Ruß**, and G. **Vierke**. *Decision Theory and Coordination in Multiagent Systems*. Research Report RR-98-2, DFKI, 1998.

[Gerber et al. 98] C. **Gerber**, C. **Ruß**, and G. **Vierke**. *An Empirical Evaluation on the Suitability of Market-Based Mechanisms for Telematics Applications*. Technical Memo TM-98-02, DFKI, 1998.

[Gomber et al. 97] Peter **Gomber**, Claudia **Schmidt** and Christof **Weinhardt**. *Efficiency and Incentives in MAS-Coordination*. In: Proceedings of the 5th European Conference on Information Systems (ECIS´97), Volume II: 1040-1051, 1997.

[Graham et al. 89] Ronald L. **Graham**, Donald E. **Knuth**, and Oren **Patashnik**. *Concrete Mathematics: A Foundation for Computer Science*. : Addison-Wesley, 1989.

[Kuhn 55] H. W. **Kuhn**. *The Hungarian Method for the Assignment Problem*. In: Naval Research Logistics Q. 2, no. 1: 83-97, 1955.

[Ma et al. 88] C. **Ma**, J. **Moore**, and S. **Turnbull**. *Stopping agents from "cheating"*. In: Journal of Economic Theory 46: pp. 355-372, 1988.

[Murty 95] Katta G. **Murty**. *Operations Research: Deterministic Optimization Models*. New Jersey: Prentice-Hall, 1995.

[Olson & Porter 94] Mark **Olson** and David **Porter**. *An experimental examination into the design of decentralized methods to solve the assignment problem with and without money*. In: Economic Theory 4, 1994.

[Ruß 97] Christian **Ruß**. *Economic Mechanism Design for the Auction-Based Coordination of Self-Interested Agents*. Diplomarbeit, Universität des Saarlandes, 1997.

[Sandholm 93] Tuomas **Sandholm**. *An Implementation of the Contract Net Protocol Based on Marginal Cost Calculations*. In: Proceedings of the Eleventh National Conference on AI (AAAI-93), Volume I, 1993.

[Smith 80] Reid G. **Smith**. *The Contract Net Protocol: High-Level Communication and Control in a Distributed Problem Solver*. In: IEEE Transactions on Systems, Man, and Cybernetics 11(1):61-70, 1980.

[Stirling 30] James **Stirling**. *Methodus Differentialis, (English translation, The Differential Method, 1749)*. London: , 1730.

[Solomon 87] M. **Solomon**. *Algorithms for the Vehicle Routing and Scheduling Problems with Time Window Constraints*. Operations Research, 1(35):254-265, 1987.

[Vickrey 61] W. **Vickrey**. *Counterspeculation, Auctions, and Competitive Sealed Tenders*. In: Journal of Finance 16: 8-37, 1961.

The Matrix Auction:
A Mechanism for the Market-Based Coordination of Enterprise Networks

Christian Ruß, Gero Vierke

RR-99-04
Research Report