Intelligent Control of Freight Services on the Basis of Autonomous Multi-agent Transport Coordination

Frank Arendt, Oliver Klein and Kai Barwig

Abstract In a highly competitive market, freight forwarders face a fierce pressure to reduce costs by optimizing their dispatch and planning processes. An increasing share of smaller shipments, dynamic markets, traffic problems and a growing variety of special equipment and vehicle types for general cargo render the manual planning of transport logistics a prohibitively complex optimization challenge. The autonomous coordination of transport services and planning processes can help to cope with the dynamics and distributed nature of logistics networks. In this paper, we introduce a multi-agent based approach that enables an autonomous dispatch process in a realistic transport scenario. The presented approach has been used and validated as an appropriate way to solve resource allocation problems when new transport orders can appear at any time. Simulation experiments with real data from the logistics partner STUTE show that the procedure outperforms the previous distributed manual dispatching process significantly in terms of flexibility and speed, leads to a reduction of empty mileage and increases capacity utilisation of trucks. Additionally, the system is designed to serve as a decision-support system (DSS) which provides proposals for allocations of transport orders to trucks to support the decision process of a human dispatch manager.

Keywords Vehicle routing · Multi-agent systems · Decentralised systems · Logistics dynamics

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1 Introduction

Commercial traffic has a significant share of the traffic in the Federal Republic of Germany. Given the limited traffic capacity of the German highway infrastructure and the dynamic growth of commercial freight traffic, a major concern of the Federal Government of Germany is the improvement of commercial freight forwarder dispatch concepts in order to lower the burden on the available infrastructure.

Fulfilling a given amount of orders with fewer kilometres to drive comes along with a competitive advantage: freight forwarders in a highly competitive environment face a fierce pressure to reduce costs by optimizing their dispatch planning processes—a highly complex task predominantly done manually. In recent years this planning process has become increasingly complicated and difficult to optimize due to the mandatory application of the European Community Social Legislation for drivers working hours, which renders the manual dispatch planning a prohibitively complex optimization challenge. For a detailed algorithmic solution including a quantitative analysis, we refer to Meyer et al. (2011). The main reasons for the increased complexity of the planning process are:

- Smaller shipment sizes and an increasing number of shipments
- Quicker market developments implying fast changes
- Increasing traffic problems like congestion harming determinability
- Growing variety of special equipment and vehicle types for general cargo

In this context the objective of the research project AMATRAK has been to reduce traffic and to achieve more efficient vehicle capacity utilization in the procurement and distribution logistics, based on autonomous multi-agent transport coordination. The transfer partner of the project was STUTE Logistics. As a logistics service provider with multiple branches all over Germany, STUTE served as an ideal partner for the practical examination of real world transport logistics processes.

The initial situation is as follows: The logistics service provider maintains a number of offices in Germany and every branch has its own customers and conducts its own dispatch process. The customer and cargo structure is very heterogeneous. Parts of the orders are less than truckload, others are full truckload shipments and the cargo ranges from bulk goods to steel coils to palletized goods. So far there is little coordination between the different branches. The whole system is subject to high dynamics primarily due to the short planning horizon and the current traffic situation.

By means of autonomous control in a cooperative logistics system, which is based on multi-agent technology, a more efficient dispatch process, higher transport efficiency and better vehicle capacity utilization will be enabled by reduction of redundant traffic and improved grouping of small goods in highly complex networks.

In order to handle growing dynamics and complexity of logistics systems one possible strategy is to shift from central planning to a decentralized, autonomous control strategy. Distributed routing concepts, as proposed by Rekersbrink et al. (2009), have proven their potential to solve routing problems. Using *TabuSearch* as a well-established algorithm to solve combinatorial optimization problems, the resulting planning solutions have shown that an autonomous cooperating system with a distributed logistics routing protocol (DLRP) leads to better results with an increasing number of shipments. The planning results changed in favour of DLRP due to the increasing complexity. These findings illustrate that autonomous cooperating systems like multi-agent systems need a certain degree of complexity to show their strengths. The main advantages are primarily evident for dynamic and close to reality scenarios (Rekersbrink et al. 2009).

A brief introduction into agent-based systems and their relevance in the field of transport logistics is provided in the next section. After that, we present a solution that has been implemented to enable an autonomous dispatch process in a realistic transport scenario. A discussion of the main simulation results is then followed by the conclusions and, finally, next steps of further research are outlined.

2 Agents and Multi-agent Systems

The term agent is used in a broad context and for a variety of applications. In this paper the term refers to agents as software programs. So far there is no agreement on a single definition of the term (Wooldridge 2009). But most definitions contain similar properties or abilities an agent must have to be considered as an agent. An often cited definition of agents is given by Wooldridge and Jennings (1995). This so called weak notion of agency consists of the properties autonomy, social ability, reactivity and pro-activeness.

There are many more definitions that—depending on the point of view of the researcher—stress different aspects of what an agent should be. Depending on the application for which an agent is used, it should have different properties. This aspect is considered in definitions that distinguish between properties that are essential for an agent and properties that are optional. For a detailed overview of these properties see Lockemann (2006) who based the properties on Wooldridge (2002).

The next step is to examine the interaction of many agents in a multi-agent system (MAS). A MAS consists of several agents that can be heterogeneous and are working on the solution of a specific problem, e.g. on a schedule for machine utilization or the negotiation of a price for a certain service. It is characterized by Jennings et al. (1998) as follows:

- Each agent has incomplete information or capabilities for solving the problem thus each agent has a limited viewpoint
- There is no global system control
- Data is decentralized
- Computation is asynchronous

The need for the agents to be able to communicate arises with these characteristics. There are different forms of communication for agents. Which one is best applicable depends on the environment, the coordination form and the problem that has to be solved. Possible communication forms are blackboard communication (Timm et al. 2006), broadcasting, direct communication and communication via a third party—possibly an agent, labelled as facilitator or yellow pages service (Eymann 2003).

3 Advantages of Multi-agent Applications for Transport Logistics

The contract net protocol (Smith 1980) shows one of the application scenarios of MAS: *resource allocation*. Resource allocation problems illustrate the type of scenarios for which MAS can be used and demonstrate how the use of MAS improves the problem solving process. The use of MAS is best suited for scenarios that include distributed information, problems or resources. Such decentralized scenarios are in addition often dynamic. Using a number of agents to address the different aspects of the problem offers a high degree of flexibility. The ability to use more than one problem solving agent also provides a higher level of security through redundancy or an increase of computational speed. Furthermore MAS typically offer high scalability due to their modular structure (Eymann 2003). The modular structure makes the programming of complex problems easier and changes to the program are simpler to introduce (Dangelmaier et al. 2004).

Centralized systems are often more efficient than MAS because distributed problem solving limits the optimization (Chaib-draa and Müller 2006). But MAS are more flexible and can find solutions for problems that are too complex to be handled by one central instance, especially if the problem itself is distributed. According to Van Dyke Parunak (1999) many industrial problems can be formulated in different ways. If the characteristics of applications are *modular*, *decentralized*, *changeable*, *ill-structured*, and *complex*, an agent-based solution can be more robust and adaptable than one supported by other technologies.

The use of MAS in transport logistics is suitable because it can deal with problems that are non-deterministic and distributed. Most transport logistics applications actually fit the above mentioned characteristics. Nevertheless, a decentralized design is often not chosen by actual projects adopting an agent-based approach (Davidsson et al. 2005). Davidsson et al. provide a survey of existing research on agent-based approaches to transportation and traffic management. As shown in their conclusions, only a few field experiments have been performed and very few deployed systems could be found. A more recent work from Schuldt (2011) describes the implementation of *autonomous control* with multi-agent technology. The proposed system delegates process control to objects like shipping containers in order to cope with dynamics. The actual application of autonomous control is examined by multi-agent based simulation and focuses on the cooperation of logistics entities.

A human dispatcher is not able to consider all possible options for transport schedules because of their high number and frequent changes, especially when some kind of disturbance arises. The planning of transportation routes is a dynamic and complex process which requires a certain level of support and justifies the vital role of information technology in the field of transport. The complexity is determined by a variety of factors and restrictions that have to be considered. First of all there has to be an efficient allocation of goods or transport orders to trucks and allocation of trucks to routes. These allocations are limited by restrictions such as the capacity of the trucks, time windows of the customers, time restrictions of the drivers and special requirements of the cargo. The dynamics are based on factors such as new incoming orders, traffic jams or the breakdown of trucks which require a fast rescheduling of the original plan. Furthermore the planning process is carried out under a latent uncertainty and with incomplete information.

4 Amatrak Mas

To support the dispatch manager, a MAS system will be introduced. With the support of the AMATRAK MAS an overall more efficient dispatch and transport process will be enabled.

The present manual planning process is limited in terms of information that can be evaluated during the available time until a dispatcher must come to a decision. Even if electronic information systems are used, timely access to all necessary and useful information during a particular decision process is hardly achievable, especially when each dispatch manager is responsible for a dedicated set of trucks and transport orders are managed at different branches. The AMATRAK MAS should therefore provide an efficient information flow between human dispatchers and software agents acting on behalf of logistics objects like trucks and other organizational units like branch offices. The advantage of the AMATRAK MAS compared to the present dispatch process arises from its ability to take into account all trucks with their current workload, even if they are controlled by another dispatch manager or at another branch office (see Fig. 1).

The system is designed to serve as both a decision-support system (DSS) and a fully automated system. As a DSS it provides proposals for allocations of transport orders to trucks to support the decision process of the dispatch manager. However, the dispatch manager can also enable a fully automated allocation for any selected transport order.

4.1 System Integration

To ensure that the implementation of the MAS can be conducted without major technical difficulties, the existing IT infrastructure of the logistics service provider

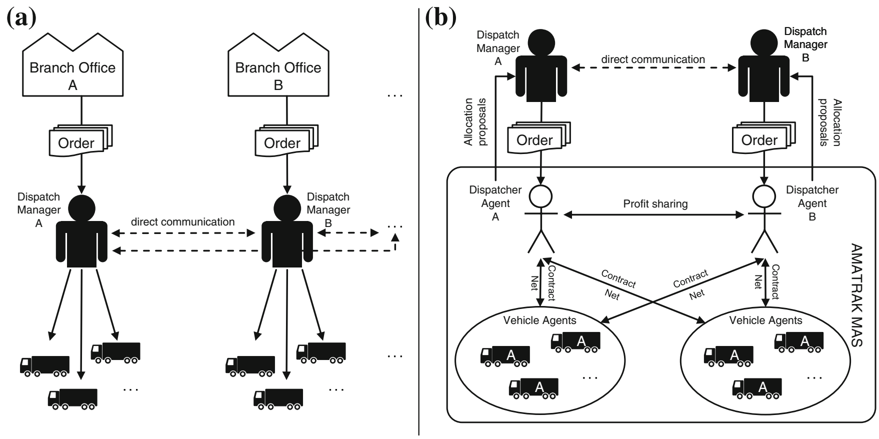


Fig. 1 **a** Present versus **b** MAS-based dispatch process control

has to be considered. The following systems are used by STUTE: active-m-ware: a software that supports the dispatch process; PSV3: a communication system integrated in a PDA (Personal Digital Assistant) that is used for the communication of data between driver and dispatch manager (via active-m-ware); FleetBoard: a system that traces the trucks, controls the driving time and the utilization of the truck. The interaction of the different systems including the MAS is depicted in Fig. 2.

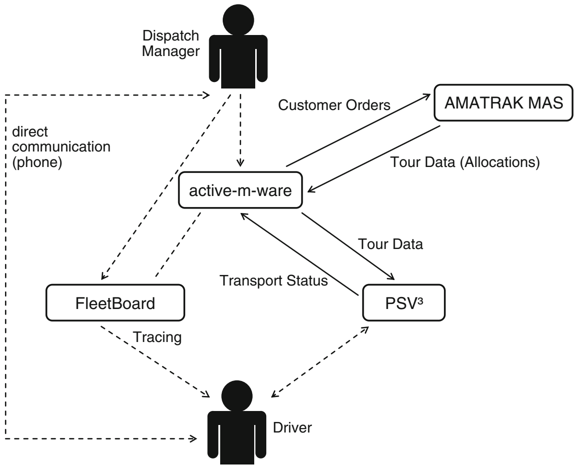
The customer orders being filed in active-m-ware are handed over to the MAS where the orders are processed and the computed tours are reported back to active-m-ware. If the dispatch manager accepts the proposed tours the information is sent to the PSV3 PDA of the driver. Changes on the status of the shipment are reported back by the driver the same way. If problems like a breakdown of a truck occur, the information is handed to the MAS and an alternative schedule will be generated. Besides that, the FleetBoard system monitors the truck. The dispatch manager has a complete and nearly real time overview of the shipments and is still in control of the whole process.

Active-m-ware has a central position in this process. It is the interface for the dispatch manager, responsible for the communication between MAS and PSV3 and in addition it is connected to the database that holds the master data, for example of the customers.

4.2 Multi-agent-Based Design

The MAS is built using the agent framework Jade, a Java based and FIPA (Foundation for Intelligent Physical Agents) compatible platform (Bellifemine et al.

Fig. 2 Interaction of systems



2007). The central communication protocol used by the MAS is based on the contract net protocol which is slightly adapted in order to allow for the direct influence of the dispatch manager. The most important agents of the MAS are the dispatcher agents and the vehicle agents.

4.2.1 Contract Net Based Vehicle Allocation Process

The dispatcher agent is the direct representative of the dispatch manager inside the MAS. Through the dispatcher agent the manager selects the orders to be processed next. Negotiations between the vehicle agents and the dispatcher agent are started by the dispatcher agent. A dispatcher agent can choose the best proposals from vehicle agents and present them to the manager who decides which one will be taken. The manager might agree with the best offer the agent has chosen, but he still may overrule this decision. An autonomous dispatcher agent usually selects the best proposal (Fig. 3).

A vehicle agent will always reply to a call for proposals request (CFP) of a dispatcher agent. This includes the information on whether the agent is able to take the offered order and an individual bid for the order. In addition, vehicle agents also trigger information functions, for example to inform other agents if the tour schedule is changed.

The negotiation process starts with the dispatch manager offering the transport order to all truck agents. The truck agents check if they meet the requirements to fulfil the order. Requirements are typically constraints which are modelled as basic rules e.g. to check if the trailer is suitable for the transportation of the specific cargo, the capacity is sufficient, the truck is allowed to serve the customer, the driver has necessary permissions to handle specific load types, etc. However, some constraints, like preset time windows for pickup and delivery, driving time and working

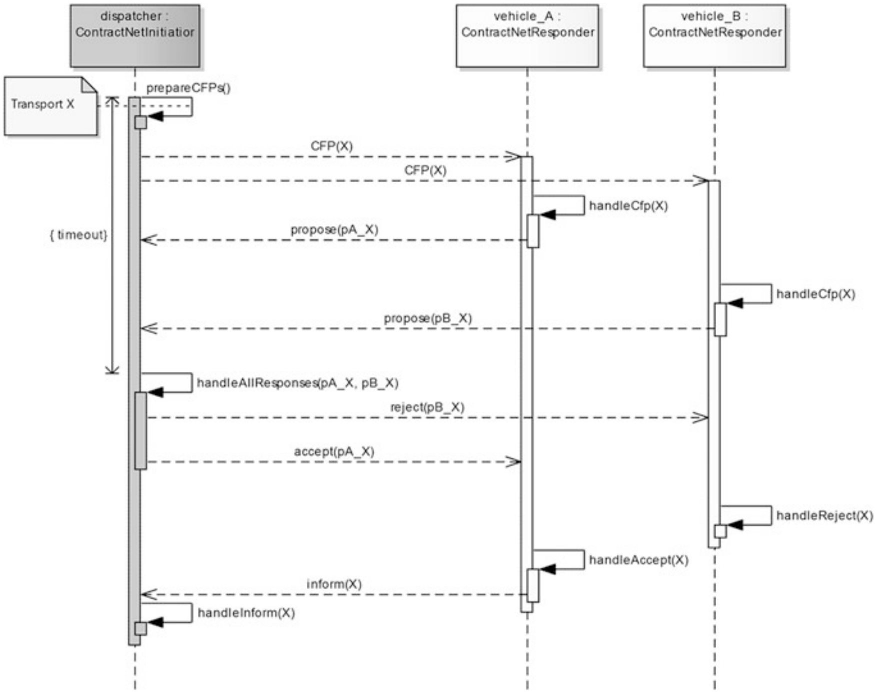


Fig. 3 Contract net interaction between a single dispatcher agent (initiator) and two vehicle agents (responder)

hour limitations of the driver, can only be validated after a concrete potential route is calculated. If the truck is able to fulfil the request, an algorithm is run which determines the "price" of the truck's bid. The result of the algorithm is not a monetary value but an abstract unit that could be regarded as costs. In order to find the best matching route, a cost function to find the optimal route is applied by each truck. This cost function takes into account the actual total distance as well as empty mileage of the route since the trucks are usually not directly located at the pickup location of the transport order. However, in case of additional load alongside the current route, if a trailer is not yet fully loaded, the extra distance can affect the costs of the existing load. In order to get comparable bids from all participating vehicle agents, the cost function calculates the difference of the costs before and after the allocation takes effect, hence the increase of total costs will be minimized while new orders can be allocated incrementally at any time.

For the fully automated allocation method the dispatcher agent chooses the lowest bid to ensure an economical order allocation to the trucks. Alternatively, the system can present the bids as proposals to the user (decision support mode) so that the dispatch manager keeps full control over the actual allocation. The algorithm is designed in such a way that a cost-effective solution for all order allocations is achieved with the decision for the lowest bid, which, additionally, can be calculated within very short time.

However, it has to be considered that all dispatch managers now in general have access to all trucks, or, from the agents' perspective, all vehicle agents potentially take part in negotiations started by any dispatcher agent. This leads to problems if several of these interactions take place concurrently, since transport allocations to the same truck mutually influence each other. In order to cope with concurrent access issues and to enable a robust multi-agent coordination, vehicle agents implement an optimistic *first-come, first-served* approach in their contract net behaviour (Fig. 4). In any case, proposals are submitted independently on the basis of the current route of the truck when the agents receive the CFP message. If the vehicle agent receives the first positive response on one of its proposals, it finally confirms the allocation with an *inform* message as usual. All other acceptances of pending proposals will be answered with a *failure* message so the responsible dispatcher agent can either restart a new CFP for the transport order or select an alternative responder.

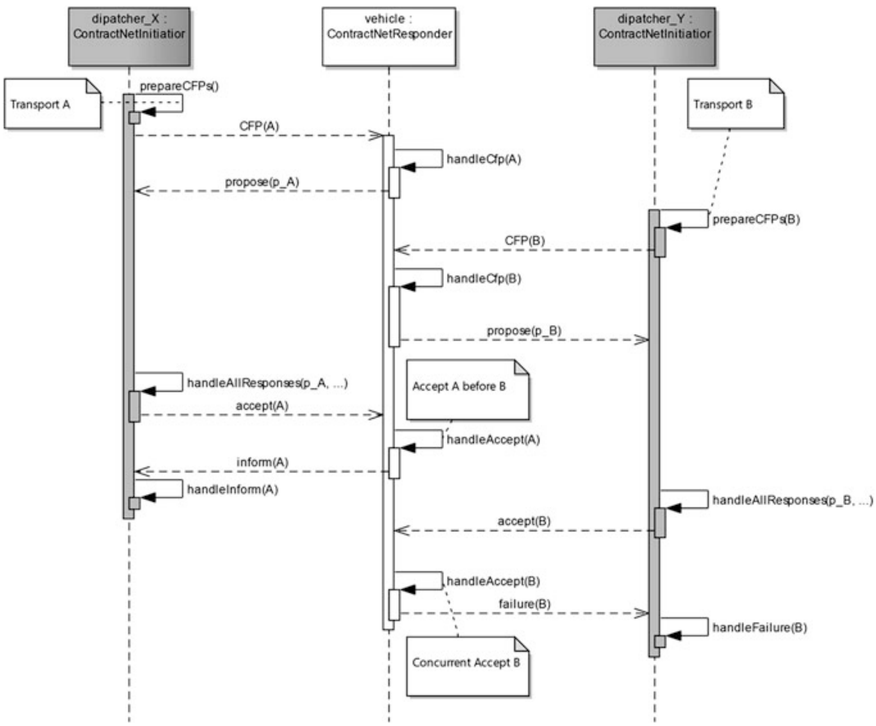


Fig. 4 Concurrent contract net interaction between two dispatcher agents and a single vehicle agent

5 Simulation

To evaluate the MAS, the system has been tested with real data from the transfer partner STUTE. The tests are based on past customer orders. For the simulation two types of test runs are generated, one is a rebuild of the orders in the way the dispatchers allocated them to the trucks, so actual performance figures can be generated. In the other test runs the orders are allocated by the MAS so that a comparison of the different runs can be used as an indicator for the MAS' performance.

The results for one example day with 70 trucks and 160 orders are shown in Table 1.

The total distance travelled by the trucks can be reduced by about 10 %, though the freight mileage remains nearly at the same level. The decrease in the overall mileage comes mainly from the reduction of empty mileage. This reduction is not only important for the logistics service provider that is not paid for these tours but also on a social-ecological level because the empty mileage doesn't produce any value but is a burden for the infrastructure and emission limits. A slight increase in vehicle utilization can also be recognized. The improvements can be generated because the system is able to dispatch all trucks for the whole company and achieve synergies that are lost when the different branches each conduct their own dispatch process. This example shows that the MAS is able to process real data and achieve efficient results. Test runs with data from other days lead to similar performances. A considerable influence on the results comes from the order structure and sequence in which the orders are dispatched. The geographical distribution of the pick-up and delivery locations, the share of less-than-truckloads and full truckloads and the way the tours are dispatched in (the rebuilt) reality have an impact on the level of mileage reduction that can be achieved. Although the simulation is based on real orders, there is a small degree of fuzziness in the results shown in Table 1 due to the fact that some aspects could not be quantified and modelled such as the personal knowledge and experience of the dispatchers. In contrast to a computer system a human being is always able to deal with irregular or special orders.

The sequence in which the orders are processed by the MAS also has an influence on the quality of the results. During the evaluation experiments best results were achieved when full truckload and long distance orders were put first. Nevertheless, the results achieved by the MAS show, that it is an applicable and useful tool for dispatchers. Future work will focus on different strategies to arrange the orders before they are processed by the MAS.

Table 1 Simulation results

	Rebuild	AMATRAK
Total mileage	35.637	31.798
Freight mileage	27.558	27.052
Empty mileage	8.079	4.746

6 Conclusions and Outlook

In this paper an agent based approach to enable the intelligent allocation and control of freight transport services has been presented. Software agents and multi-agent systems have been introduced as an appropriate means to cope with resource allocation problems that involve distributed information and process control in a dynamic environment. These potentials have been aligned with real-world requirements and approved by the logistics service provider STUTE. The AMATRAK research project facilitates this transfer into a practical application. The simulation results of the AMATRAK MAS with its distributed problem solving approach shows that the procedure outperforms the previous distributed manual dispatching approach significantly in terms of flexibility and speed, and results in a severe reduction of empty mileage and a slight increase of capacity utilisation. The MAS is able to deal with a number of dynamic influences due to its good scalability, modular structure and distributed problem solving capability. The case study shows that the AMATRAK MAS is able to process real data and achieve efficient and effective results. Due to the increased visibility enabling a global planning perspective, benefits are particularly demonstrated in a distributed setting with multiple branch offices.

There are still questions and possible adjustments to the proposed approach open for future research. The possibility to arrange orders for their later sequential negotiation has been mentioned briefly but a comprehensive evaluation of possible strategies is a pending task. Another well perceived aspect is the possibility to incorporate real-time data from trucks in order to adjust route schedules and to automatically react on deviations from the current routing plan. Additionally, a future extension of the agent model could also take an inverted allocation control mechanism into account, such that vehicle agents can actively call for additional load if a waste of spare capacity is imminent. The capabilities of this mechanism have been investigated generally with respect to the possible integration of web-based freight exchange services.

A market research carried out by STUTE shows a lack of mature applications with comparable features, particularly with regard to supporting dynamics and concurrent interaction between multiple autonomous branch offices. Currently the project partners ISL and STUTE are developing AMATRAK MAS into iTL|dispo, a new system based on the MAS approach as described above. Mid of 2015, the first module will be released and put into service by STUTE.

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