Agent-Based Approaches to Transport Logistics

Paul Davidsson, Lawrence Henesey, Linda Ramstedt, Johanna Törnquist and Fredrik Wernstedt

Department of Systems and Software Engineering, Blekinge Institute of Technology
Soft Center, 372 25 Ronneby, Sweden

Abstract

This paper provides a survey of existing research on agent-based approaches to transportation and traffic management. A framework for describing and assessing this work will be presented and systematically applied. We are mainly adopting a logistical perspective, thus focusing on freight transportation. However, when relevant, work of traffic and transport of people will be considered. A general conclusion from our study is that agent-based approaches seem very suitable for this domain, but that this still needs be verified by more deployed system.

1 Introduction

The research area of agent technology continues to yield techniques, tools, and methods that have been applied or could be applied to the area of traffic and transportation management. The aim of this paper is to present a consistent view of the research efforts made in this area.

We are mainly adopting a logistical perspective, thus focusing on transportation rather than traffic, and on freight rather than people. In particular, we will not survey the extensive work on agent-based modeling of driver and commuter behavior. Also we will not consider approaches to supply-chain management.[1] Traditionally, the term logistics referred mainly to issues regarding physical flows of products on an operational level. Today, the term includes both strategic and tactical issues beside the operational ones and includes the information flow connected to the physical flow.

In the next section, the basic principles of logistics will be defined and the areas where agent technology may be useful will be identified. We then present a framework that will be used to classify and assess the research in the area. This is followed by a systematic survey of the work found in the literature. Finally, we analyze our findings and present some conclusions.

2 Background

In this section we will briefly present the areas of logistics and agent technology.

2.1 Logistics

According to Shapiro (1985) the concept of logistics can be defined by the seven R's: ensuring the availability of the right product, in the right quality, and in the right condition, at the right place, at the right time, for the right customer, at the right cost. Sometimes logistics studies are limited to physical and information flow within an organization (or least to study such flows from the view-point of a particular organization). However, we will here focus on the inter-organizational physical flows, i.e., transport logistics.

There are several components of logistics. The *storage and warehousing* of a product is important when considering the type of operation, the number and size of distribution centers and their location. *Inbound logistics* covers the movement of materials received from suppliers. *Materials management* describes the movement of materials and components within a firm. *Physical distribution* refers to the movement of goods outward from the end of the assembly line customer. The *load planning* and *route schedule* that are decided on have an impact on the logistics system as well as *forecasting* the customer demands in delivering final product. The *information* and *control* of the goods, e.g., by tracking and tracing, is also paramount in the logistics system.

No two organizations are run the same. The logistics systems employed by organizations are designed around the demands of the customer. Customer service is linked to distribution and logistics. Just-In-Time is one popular type of "pull" system, where the focus is on lowering the amount of inventory and increasing quality service. Just-In-Time is basically principled on that all parts of the network are synchronized. The high use of third parties is due to the complex nature in planning and scheduling coupled with intensive communication required to coordinate with other members in the network. Quick response to logistics systems has intensified the use of information technology to assist in integration schemes such as Enterprise Resource Planning and or Enterprise Planning Systems.

2.2 Agent technology

The development of distributed and heterogeneous systems, such as software for automation of, and decision

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[1] These aspects are omitted mainly because of the limited space available in the workshop proceedings.

support for logistics management, poses significant challenges for system developers. *Agent technology* (Weiss, 1999, Wooldridge, 2002) aims to provide new concepts and abstractions to facilitate the design and implementation of systems of this kind.

Software agents may be seen as a natural extension of the concept of software objects. Object-oriented programming added abstraction entities, i.e., objects, that have persistent local states to the structured programming paradigm. Similarly, agent-based programming adds abstraction entities, i.e., agents, that have an independent execution thread and pro-activity to the object-oriented paradigm. Thus, compared to an object, an agent is able to act in a goal-directed fashion (e.g., by interacting with other agents, reading sensors, or sending commands to effectors) rather than only passively react to procedure calls. In addition, an agent typically has also one or more of the following abilities: to communicate with other software agents, to learn from experience and adapt to changes in the environment, to make plans, to reason using, e.g., logic or game theory, to move between different computers, to negotiate with other agents. Also, agents are sometimes programmed, or at least modeled, in terms of "mental states", such as, belief, desires, and intentions. A Multi-Agent System (MAS) is a collection of agents co-operating with each other in order to fulfil common and individual goals (in some environments they may also compete). In a MAS different agents often have different roles and individual goals.

Parunak (1999) lists the following characteristics for an ideal application of agent technology:

- *Modular*, in the sense that each entity has a well-defined set of state variables that is distinct from those of its environment and that the interface to the environment can be clearly identified.
- *Decentralized*, in the sense that the application can be decomposed into stand-alone software processes capable of performing useful tasks without continuous direction from some other software process.
- *Changeable*, in the sense that the structure of the application may change quickly and frequently.
- *Ill-structured*, in the sense that all information about the application is not available when the system is being designed.
- *Complex*, in the sense that the system exhibits a large number of different behaviours which may interact in sophisticated ways.

As most transport logistics applications actually fit Parunak's characterisation rather well, this would suggest that agent technology indeed is a promising approach for this area. However, it is not suitable for all applications. For instance, in applications that are monolithic, centralized, static, well-structured, and simple, agent technology will probably not provide any added value, only unnecessary complexity.

3. Evaluation framework

For each paper surveyed we describe the problem studied, the approach taken to solve it, and assess the results.

3.1 Problem description

Each problem description includes the following three parts: the domain studied, the mode of transportation, and the time horizon considered.

3.1.1 Domain We have chosen to divide the problem descriptions into three domains *transport*, *traffic* and *terminal*. A transport is an activity where something is moved between point A and B by one or several modes of transport. Problem areas that fall under the category transport are e.g. route planning, fleet management, different sorts of scheduling, i.e., functionalities that takes place to support transportation. Within for example a transport chain where the cargo is be transported by truck, rail, ship and truck again, there are interfaces between the different modes. These interfaces represent nodes for re-loading and are referred to as terminals. Terminals can be any fixed place where the cargo is handled and require access to different kinds of resources. Typical terminal activities are resource allocation and scheduling of cranes, forklifts and parts of a facility.

While transport refer to the movement of cargo from one point to another, traffic refers to the flow of different transports within a network. One train set is thus a transport, or part of a transport, that takes part in the train traffic flow. Hence, a transport can be part of several traffic networks (air, waterborne, road, rail,) and a traffic network constitutes of several transports. Typical traffic activities are traffic flow scheduling such as railway slot allocation, air traffic management, and railway traffic management.

3.1.2 Mode of transportation There are five basic modes of transportation: *road, rail, air, water,* and *pipeline* (Stock and Lambert, 2001). The differences in transport modes is related to the type, bulk, form, speed, service of the raw good or finished product that is being transported. Although the use of pipelines often offers the cheapest method in transporting bulk fluids in long distances, we will in this paper not regard this modality. The water transport via sailing vessels offers one of the most used and less costly means of transporting bulk goods. The use of rail is often associated with bulk items transported less costly than road to far distant markets. The flexibility and often-inevitable use of road for the beginning or final transport mode in a transportation chain makes this the most often used form of transport. Road transport is often associated with faster delivery in short distances and is attractive to Shippers and customers that demand choice and flexibility in scheduling. Finally, air transport mode offers the fastest means of transport and usually the most expensive. This mode is usually reserved for high-valued goods that need to be transported across large distances. The use of air is also considered in short supply times, as in the case of disaster relief.

All freight transport modes can include, for example, fleet management techniques, route and maintenance planning, on-board loading/unloading techniques and on-board computers. In all cases, the emphasis will be on the impact on organizational costs and service levels. Usually in freight logistics the transportation represents the most important single element in logistics costs for most firms (Ballou, 1999, p.135). Transportation is a key decision area within logistics due to on average, a higher percentage of logistics costs are associated with this activity than any other logistics activity (Ballou, 1999, p.185). As indicated above, the selection of which mode of transport is to be used is dependent on several factors, e.g., requirements on speed, handling, costs, distance, flexibility etc.

Intermodal transportation, refers to "movement of goods in one and the same loading unit or vehicle that uses successively several modes of transport without handling of the goods themselves in changing modes" according to the definition of The European Conference of Ministers of Transport. The definition is valid also for personal travelling that includes two or more different modes of transportation.

One of the primary challenges in intermodal transport management is to coordinate several inter-dependent activities within the transport as well as the communication between the multiple actors involved.

3.1.3 Time horizon Historically, the term logistics referred mainly to issues regarding issues in technical and physical flows of products on an *operational* level. Today, the term includes both strategic and tactical issues beside the operational ones and includes the information flow connected to the physical flow. Therefore, the applications and concepts studied and presented are divided into levels of time perspective; *strategic*, *tactical* and *operational* level of decision-making. This is an established classification that is widely used. It can also be seen as a hierarchy in decision time (Schneeweiss, 1999). We will here by *time horizon* refer to at what stage in the decision-making process the application is used, or is intended to be used. There are two dimensions often distinguished, the level of decision-making and its time frame:

Level	**Time frame**	**Purpose**
Strategic	Long term (typically years)	Decide what to do.
Tactical	Medium term (months - weeks)	Decide how to carry it out.
Operational	Short term / Real time (days - hours)	Performing (confirm and adjust, execute, monitor and control).

There is no definite line of separation, but strategic decision-making typically involves determining what to do while tactical deals with issues of setting up an action-list and operational how to conduct the work set out in more specific terms (Paulsson et al., 2000, Schneeweiss, 1999, Lumsden, 1995). The time horizon for these levels is highly domain dependent.

In this paper we also include the execution of tasks and real-time controlling functionalities within the operational decision-making. For a transport operator, as an example, a strategic issue to address would be where to locate distributions centres, while a tactical issue would be to tailor the vehicle fleet to satisfy the customer demands, and the operational level would involve scheduling of each and every transport and the controlling function with monitoring and ad-hoc planning if necessary.

As can be seen there is no established definition on time frame or content in the different planning hierarchy, and it is highly dependent on what type of business that is addressed.

3.2 Approach

Each approach is described by the following three parts: the intended usage of the system, the type of agents used, and the type of coordination used.

3.2.1 Usage The applications studied can be classified, according to this paper, as either to serve as an automation system, or a decision-support system. An *automation* system can be defined as "having a self-acting mechanism that performs a required act at a predetermined time or in response to certain conditions" (McGraw-Hill Encyclopedia of Science & Technology). In this context it refers to a system's ability to act upon its decisions, i.e. it has a direct influence on the controlled environment and there is no human involved.

On the contrary, a *decision-support system*, DSS, has only at most an indirect impact on the decision-making. A DSS is a system that provides output of some specified type to support the decision process for the user. The user, i.e. the decision-maker, takes the suggested decision(s) into consideration, and then acts. Thus, the final decision is made by a person, not the software system.

3.2.2 Agent architecture Depending on their tasks, the complexity of the agents varies. Purely *reactive* agents only perform a simple mapping from sensor data to effector signals. (Sensing and effecting should here be given a very general interpretation, including receiving and sending messages.) In the most basic case, the behavior of a reactive agent can be specified by a collection of independent situation-action rules. A slightly more sophisticated approach is the *subsumption* architecture (Brooks, 1991) which consists of a hierarchy of behaviors where each behavior is a simple rule-like structure that "competes" with others to exercise control over the agent. Reactive agents have been proved to be good at doing a limited number of simple tasks in real-world domains. However, besides of not being particular versatile, they have problems to handle tasks that require knowledge about the world that must be obtained by reasoning or from memory. Moreover, each behavior must be separately encoded in the agent, which may lead to complexity problems both at both design and execution time.

In contrast to reactive agents, *deliberative* agent architectures have modularized their cognitive abilities (perception, world modeling, planning etc.). In this way it is possible to begin with the design of the overall architecture of the agent and then develop the different components separately. Purely deliberative agents contain an explicitly represented model of the world that is used for decision making. The working of a deliberative agent can be described as a sense-model-deliberate-act cycle. The sensors sense the environment and receive messages, which are used to update the world model. The world model is used by the deliberation module to decide which actions to take, which serve as input to the effectors that carry out the actions. Many deliberative agents use the world model to make a plan of how to accomplish their goals. They do this by searching through the space of possible action sequences until one is found that will transform the current state into the goal state. Although purely deliberative agents may be suitable for more complex tasks, they have problems with "simpler" tasks such as routine reaction that require fast action but no extensive deliberation since planning is very time-consuming, requiring exponential search through potentially enormous problem spaces. Consequently, deliberative agents tend not to work well in highly dynamical environments that require fast reaction.

Hybrid agent architectures try to integrate the reaction ability of reactive agents necessary for routine tasks with the power of deliberation necessary for more advanced or long term tasks. Two categories of hybrid agents can be distinguished. *Uniform* agent architectures, such as the Procedural Reasoning System (Ingrand et al., 1992), employ a single representation and control scheme for both reaction and deliberation, whereas *layered* agent architectures, such as InteRRaP (Müller, 1997), use different representations and algorithms (implemented in separate layers) to perform these functions.

3.2.3 Coordination (control, structure and attitude) Researchers in many fields including computer science, economy, and psychology have studied the area of coordination, which can be viewed as "managing the interdependencies among activities" (Malone et al. 1994). In any environment where software agents participate, the agents need to engage in cooperative and/or competitive tasks to effectively achieve their design objectives. From the multi-agent systems perspective coordination is a process in which agents engage in order to ensure that a community of individual agents acts in a coherent manner (Nwana et al. 1996). A variety of mechanisms have been developed to manage coordination problems. On one side are organizational structures and social laws (Shoham et al. 1992), long-term rules that govern the behavior of the society of agents. At the other end are the black board model (Erman et al. 1980) and the one-shot protocols, e.g., contract net (Smith 1980). In between are techniques such as partial global planning (Durfee et al. 1991) and various negotiation techniques, e.g., market-based (Clearwater 1995) and game theoretic (Axelrod 1984) negotiation. Several researchers have shown that there is no single best organization or coordination mechanism for all environments (Decker et al. 1995). Coordination techniques are classified here according to the three dimensions.

We capture the authority relationships between agents in the dimension of *control*, which is either centralized or distributed (decentralized). The *MAS structure* corresponds to the set of agents constituting the MAS, their roles, and the communication paths between agents. The structure is either predetermined, i.e., static (the set of agents or their roles do not change during the execution), or is changing dynamically. Finally, the *agent attitude* dimension captures the behavior of agents, which is classified as either benevolent (cooperative), i.e., they will comply with social laws and global goals, or selfish (competitive), where the agents' individual goals, e.g., in a market-based economy, will govern their behavior.

3.3 Results

The main classification of the result of the approaches will be in terms of maturity of the research. However, we will also try to assess the performance and the limitations of the approach.

3.3.1 Maturity An agent application can have varying degree of maturity, i.e., how complete and validated an application is. According to Parunak (2000), the description of the maturity of an agent application helps the users to assess how much work that remains to implement agents for their applications. Furthermore, Parunak has suggested a number of degrees of maturity which formed the basis for our refined classification.

The lowest degree of maturity in the classification is *conceptual proposal*. Here the idea or the principles of the proposed application is described with its general characteristics, e.g. if the model is simple or complex. In the literature the term *conceptual model* is quite well-established and well-defined. However, we prefer the more open term conceptual proposal since it otherwise could be more difficult to fit in all applications according to the classification.

The next level in the classification is *simulation experiments*. Here the application has been tested in a simulation environment. The experiment can be either an *implemented* MAS or a *simulated* MAS. The data used in the simulated experiment can either be real data, i.e. taken from existing systems in the real world, or data that is not real, i.e. artificial, synthetic or generated. Further, the type of data has been divided into limited/partial or full-scale data. The full-scale data represents data for a whole system, while the limited/partial data only covers parts of the system.

The *field experiment* indicates that experiment with the application has been conducted in the environment where the application is supposed to be applied. As in the simulated experiment, the field experiment is also divided into limited/partial and full-scale.

The final level, *deployed system*, indicates that the system has been implemented in the real world and also is in use. This is the most mature type of agent applications.

3.3.2 Evaluation comparison If a new approach is developed to a problem which has been solved previously using other approaches, the new approach should be compared to those existing approaches. Such an evaluation could be either *qualitative*, by comparing the characteristics of the approaches, or *quantitative*, by different types of experiments.

3.4 Summary of Framework

The table below summarizes the framework for describing and assessing the agent-based approaches to logistics.

	Aspect	**Categories**
Problem description	Domain	1. Transport 2. Traffic 3. Terminal
	Mode of transportation	1. Air 2. Rail 3. Road 4. Sea 5. Intermodal
	Time horizon	1. Operational 2. Tactical 3. Strategical
Approach	Usage	1. Automation system 2. Decision support system
	Control	1. Centralized 2. Distributed
	MAS structure	1. Static 2. Dynamic
	Agent attitude	1. Benevolent 2. Selfish
	Agent architecture	1. Reactive 2. Deliberative 3. Hybrid
Results	Maturity	1. Conceptual proposal 2. Simulation experiment 2.1. artificial data 2.1.1. limited/partial 2.1.2. full-scale 2.2. real data 2.2.1. limited/partial 2.2.2. full-scale 3. Field experiment 3.1. limited/partial 3.2. full-scale 4. Deployed system
	Evaluation comparison	1. None 2. Qualitative 3. Quantitative

In the Appendix, there is a table where the published work in the area of agent-based approached to transport logistics that we have encountered is classified according to this framework. The papers are sorted first according to domain and then according to mode of transportation.

4. Analysis of Survey

The survey shows that agent technology has been applied to many different problem areas within transport logistics. Often these are distributed and very complex by nature, such as: planning and scheduling, fleet management, transport scheduling, traffic management, and traffic control. In the work reviewed, there was an even distribution between the three domains (transport, traffic, and terminal), whereas the modes of transportation were dominated by air, road and intermodal. It is worth noting that very little work has been done studying strategic decision making. In addition, only a few of the publications concerning air and rail deal with transport-centered issues.

Most of the *rail*-related publications address problems of allocating slots for the railway network, i.e., timetabling. This is a problem seldom found within the other modes of transport besides air traffic (even though railway slot allocation differs significantly from air traffic slot allocation). Market-based approaches (Clearwater, 1996) have appealed to several of the researchers, which makes the coordination mechanism very similar to the negotiation that takes place in practice. In addition, some publications study resource allocation for specific rail transports, but these problems are not modal-specific to the same extent as the slot allocation problem. Several of the approaches have been evaluated experimentally, but no deployed system has been found. Methods that are alternative to agent technology for these kinds of problems are often centralized optimization and simulation technologies.

Regarding the publications that relate to *air* traffic and transportation, the studies on air traffic management is dominating and agent technology seems to have been applied to this problem area for more than a decade. The main topic addressed is distributed air traffic management using free flight, i.e., the aircrafts are allowed to choose their speed and path in real-time and air traffic restrictions are only applied when air space separation is required. No application focusing on airport slot allocation for a tactical setting has been found, which is surprising as many railway scheduling applications exist. Only a few publications in the air domain deal with transport related issues, of which one, is claimed to be implemented.

In the papers on *road transports*, most of the problems concern transport scheduling, i.e., allocating transport tasks to vehicles. The approaches are distributed and include negotiation in various manners, such as the contract net protocol, and sometimes are market-based. However, also Multi Agent Based Simulation (MABS) is used in some applications. The agents in these applications represent different roles, e.g., a company, a truck, a customer etc. The transport applications are on a tactical level and mostly the purpose is to serve as a DSS to a transport operator since the problem is complex and need some human supervision before the final transport task allocation. Alternative methods to agent technology in road transport are classical mathematical methods, operations research, and centralized approaches.

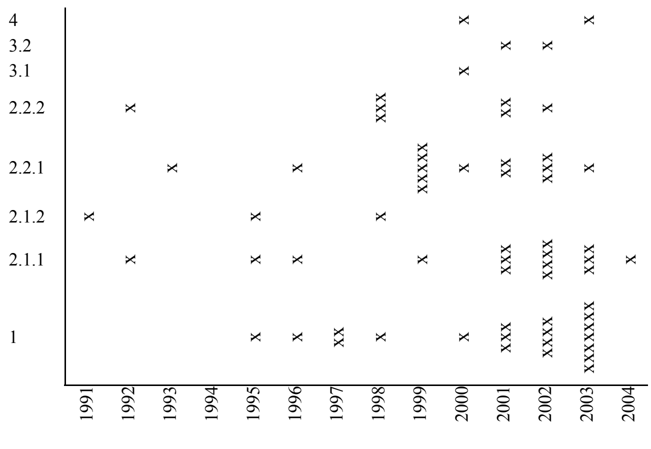
In the *road traffic* domain most of the problems concern traffic management and control to deal with for example congestion of the roads. They are designed to inform drivers about the traffic situation and give recommendations, regulate the traffic with signals and messages, and so on. A couple of the applications deal with public transport management where the actual status of the vehicles is compared to the planned status, e.g. a timetable. The majority of the systems are on the operational level and most of the applications function as a DSS, but some are designed to serve as automation systems. Alternative methods mentioned in the papers, are evolutionary algorithms, knowledge-based systems, neural networks, fuzzy theory, and genetic algorithms.

Most applications of agents concerning the *sea* mode of transportation has been trying to increase the efficiency of the container terminal operations. Many papers tend to focus specifically at the marine-side interface whilst disregarding the other processes in the terminal that determine overall terminal performance, e.g., the stacking of containers. The terminals are characterized as complex and dynamic systems and researchers find the relationships between the many actors involved (having both common and conflicting goals) where vast amounts of information are not processed adequately to encourage the use of agents. Several papers focus exclusively on the operational processes of communication between the gantry cranes and the straddle carriers in order to reduce idle time and the number of times that a container is handled, whereas a couple of papers deal with tactical and strategic decisions. Unfortunately, the majority of the papers reviewed do not state clearly the type of agent approaches used or how their agents are able to communicate and make decisions. It is interesting to note that so much work has been done on terminals, but so little on traffic and transport.

Of the reviewed publications regarding *intermodal* transportation, primarily the combination of road and rail has been considered. The problem studied is usually to coordinate several tasks for a specific transport, such as, slot request, terminal handling and allocating transport services. The approach is typically to identify a set of different roles, similar to the real-world functions, and allocate agents for each of these. Although only a few publications were found, the work in this area seems to be extensive at the moment and rapidly developing. Some alternative methods for this problem are discrete-event simulation and optimization. In practice, however, it is more often dealt with in an ad-hoc manner with a mix of human-intervention and spread-sheet analysis. For this domain, as for the other domains, the benefits of using agent-based approaches are not explicitly discussed.

The main reasons mentioned in the papers for adopting an agent-based approach are: facilitates distributed control, ability to cope with partial and noisy data, and ability to model complex problems. Although the ability to distribute control is the most cited reason, it is interesting to note that 35% of the work surveyed make use of centralized control. Also, only half of the applications utilize the possibility of dynamic MAS structures, which is an often cited strength of agent technology. A majority of the work (63%) concerns the use of agent technology in decision support systems.

Regarding the maturity, the vast majority of the approaches surveyed have just reached the level of conceptual proposal (33%) or simulation with limited or artificial data (48%). An obvious danger with simulation experiments based on artificial or partial data is that abstractions are made that simplifies the problem to a point where the results are not relevant for real-world problems. The diagram below illustrates how the maturity of the papers has developed through the years.



In two thirds of the approaches surveyed, agents are applied to solve problems without considering current or alternative approaches to solve these problems. Of those that actually are making comparisons, the majority make only qualitative comparisons. The alternative approaches regarded in the papers are, e.g., for traffic management: evolutionary algorithms, knowledge-based systems, neural networks, fuzzy systems, and for transport scheduling: classical mathematical and OR methods, i.e., mainly centralized approaches.

5 Conclusions

While producing the survey we have identified a number of positive aspects of the current state of agent-based approaches to logistics:

- Many different approaches has been suggested and investigated.
- Many of the logistics problems that have been studied have characteristics that closely match those of an ideal agent technology application very well.
- Especially in the areas of air and road traffic management agent technology seems to have contributed significantly to the advancement of state-of-the-art.

However, there are also some things that can be improved:

- The maturity of the research; few fielded experiments have been performed and very few deployed system exists.
- The suggested agent-based approaches are often not evaluated properly; comparisons with existing techniques and systems are rare. Both qualitative assessments explaining the pros and cons of agent technology compared to the existing solutions, and quantitative comparisons to these solutions based on experiments, are desired.
- Some problem areas seem under-studied, e.g., the applicability of agent technology to strategic decision-making within transportation logistics.

References

Allo, B., Guettier, C., Lébucin, N., A demonstration of dedicated constraint-based planning within agent-based architectures for autonomous aircraft, *IEEE International Symposium on Intelligent Contro*l, pp. 31-38, 2001.

Axelrod, R., *The evolution of cooperation*, Basic Books, 1984.

Balbo, F., Pinson, S., Toward a Multi-agent Modelling Approach for Urban Public Transportation Systems, *Engineering Societies in the Agents World II*, , LNAI 2203, pp. 160-174, Springer, 2001

Ballou, R.H., *Business Logistics Management*, 4th Ed. Prentice Hall International, 1999.

Blum, J., Eskandarian, A., Enhancing intelligent agent collaboration for flow optimisation of railroad traffic, *Transport Research Part A*, 2002.

Bouzid, M., On-line transportation Scheduling using Spatio-Temporal Reasoning, *10th International Symposium on Temporal Representation and Reasoning and Fourth International Conference on Temporal Logic*, IEEE, 2003.

Brewer, P.J., Plott, C.B., A binary conflict ascending price (BICAP) mechanism for the decentralized allocation of the right to use railroad tracks, *Int. Journal of Industrial Organisation*, Vol. 14: 857-866, 1996.

Brooks, R.A., New Approaches to Robotics. *Science*, Vol. 253: 1227-1232, 1991.

Buchheit, M., et al., MARS: Modeling a multiagent scenario for shipping companies. *European Simulation Symposium*, Society for Computer Simulation, 1992.

Budenske, J., Newhouse, J., Bonney, J., Wu, J., Agent-based schedule validation and verification", *IEEE International Conference on Systems, Man, and Cybernetics*, Vol. 1: 616-621, 2001.

Bürckert, H-J., Funk, P., Vierke, G., An intercompany dispatch support system for intermodal transport chains, *33rd Hawaii International Conference on System Science*, 2000.

Burstein, M., Ferguson, G., Allen, J., Integrating agent-based mixed-initiative control with an existing multi-agent planning system, *Fourth International Conference on MultiAgent Systems*, pp. 389-390, 2000.

Böcker, J., Lind, J., Zirkler, B., Using a multi-agent approach to optimise the train coupling and sharing system, *European Journal of Operational Research*, Vol. 134:242-252, 2001.

Callantine, T., Prevôt, T., Battiste, V., and Johnson, W., Agent-based support for distributed air/ground traffic management simulation research, *AIAA 2003-5371*, Reston, VA, U.S.A, American Institute of Aeronautics and Astronautics, 2003.

Carrascosa, C., M. Rebollo, et al., A MAS Approach for Port Container Terminal Management: The Transtainer Agent. Proceedings of *SCI, IFSR* (ISBN 980-07-7543-9), 2001.

Choy, M.C., Srinivasan, D., Cheu, R.L., Hybrid Cooperative Agents with Online Reinforcement Learning for Traffic Control, *IEEE International Conference on Fuzzy Systems*, 2002.

Clearwater, S.H. (ed.), *A paradigm for distributed resource allocation*, Xerox PARC, 1995, ISBN 981-02-2254-8.

Clearwater, S.H. (ed.), *Market-Based Control: Some early lessons*, World Scientific, 1996.

Cuppari, A., Guida, L.,Martelli, M., Mascardi, V., Zini, F., Prototyping freight trains traffic management using Multi-Agent Systems, *IEEE International Conference on Information, Intelligence and Systems*, 1999.

Decker, K.S. and Lesser, V.R., Designing a Family of Coordination Algorithms. In Proceedings of the *First International Conference on Multi-Agent Systems*, 1995.

Degano, C., Di Febbraro, A., Fornara, P., Fault diagnosis in an intermodal container terminal.. *8th IEEE International Conference on Emerging Technologies and Factory Automation*: 433-440, Vol. 2, 2001.

Degano, C., Pellegrino, A., Multi-Agent Coordination and Collaboration for Control and Optimization Strategies in an Intermodal Container Terminal, *IEEE International Engineering Management Conference,* 2002.

Dong, J-W., Li, Y-J., Agent-based design and organization of intermodal freight transportation systems, *Second*

International Conference on Machine Learning and Cybernetics, pp. 2269-2274, 2003.

Durfee, E.H., Lesser, V.R., Partial Global Planning: A coordination framework for distributed hypothesis formation, *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 21(5), 1167-1183, 1991.

Erman, D.L., Hayes-Roth, F., Lesser, V.R., Reddy, D.R., The HERSAY-II speech understanding system: Integrating knowledge to resolve uncertainty, *ACM Computing Survey*, Vol. 12:213-253, 1980.

Fernández, A., Alonso, E., Ossowski, S., A multiagent architecture for train fleet management, *Fifth UK Workshop on Multi-Agent Systems*, 2002.

Fernández, A., Alonso, E., Ossowski, S., A multiagent architecture for bus fleet management, *Integrated Computer-Aided Engineering*, Vol. 11(2), 2004.

Findler, N.V., Lo, R., Distributed artificial intelligence approach to air traffic control, *Control Theory and Applications*, Vol. 138(6): 515-524, 1991.

Findler, N.V., Elder, G.D., Multiagent coordination and cooperation in a distributed dynamic environment with limited resources, *Artificial Intelligence in Engineering*, Vol. 9(3): 229-238, 1995.

Fischer, K., Müller, J.P., Pischel, M., Schier, D., A model for cooperative transportation scheduling, *First International Conference on Multi-Agent Systems*, 1995.

Fischer, K., Müller, J.P., Pischel, M., Cooperative Transportation Scheduling: An Application Domain for DAI, *Journal of Applied Artificial Intelligence*. Vol. 10(1), 1996

Fischer, K., Chaib-draa, B., Müller, J. P., Pischel, M., Gerber, C., A Simulation Approach Based on Negotiation and Cooperation Between Agents: A Case Study, *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, Vol. 29(4): 531-545, 1999

France, J., Ghorbani A.A., A Multiagent System for Optimizing Urban Traffic, *International Conference on Intelligent Agent Technology*, IEEE, 2003.

Funk, P., Vierke, G., Bürckert, H-J., A Multi–Agent Systems Perspective on Intermodal Transport Chains, *Logistik-Management-Tagung LMT-99*, 1999

Gambardella, L. M., Mastrolilli, M., Rizzoli, A. E., Zaffalon, M. (2001). An optimization methodology for intermodal terminal management. *Journal of Intelligent Manufacturing*, Vol. 12(5-6): 521-534.

Gambardella, L.M., et al., Simulation and planning of an inter-modal container terminal. *Simulation* 71(2): 107–116, 1998.

García-Serrano, A.M., Teruel Vioque, D., Carbone, F., Méndez, V.D., FIPA-compliant MAS development for road traffic management with a Knowledge-Based approach: the TRACK-R agents, *Challenges in Open Agent Systems '03 Workshop*, 2003.

Goldsmith, S. Y., et al., A Multi-agent System for Coordinating International Shipping. *Agent Mediated Electronic Commerce, First International Workshop on Agent Mediated Electronic Trading*, Springer, 1998.

Henesey, L., Notteboom, T., and Davidsson, P., Agent-based simulation of stakeholders relations: An approach to sustainable port and terminal management. *International Association of Maritime Economists Annual Conference*, 2003(a).

Henesey, L., Wernstedt, F., Davidsson, P., Market-Driven Control in Container Terminal Management. *2nd International Conference on Computer Applications and Information Technology in the Maritime Industries*, 2003(b).

Hernández, J.Z., Ossowski, S., García-Serrano, A., On Multiagent Co-ordination Architectures: A Traffic Management Case Study, *34th Hawaii International Conference on System Sciences*, 2001

Hernández, J.Z., Ossowski, S., García-Serrano, A., Multiagent architectures for intelligent traffic management systems, *Transportation Research Part C*, Vol. 10: 473-506, 2002

Ingrand, F.F. Georgeff, M.P. and Rao, A.S. An Architecture for Real-Time Reasoning and System Control. *IEEE Expert*, Vol. **7**:34-44, 1992.

Iordanova, B.N., Air traffic knowledge management policy, *European Journal of Operations Research*, Vol. 146: 83-100, 2003.

Itmi M., M. D., Pecuchet J.-P., Serin F., Villefranche L., Eco-problem solving for containers stacking. Systems, Man and Cybernetics, *IEEE International Conference on Intelligent Systems for the 21st Century*: vol. 4: 3810-3815, 1995.

Kohout, R., Erol, K., In-Time Agent-Based Vehicle Routing with a Stochastic Improvement Heuristic, *11th Conference on Innovative Applications of Artificial Intelligence*, 1999

Košecká, J., Tomlin C., Pappas, G., Sastry, S., Generation of conflict resolution maneuvers in air traffic management, *IEEE-RSJ International Conference on Intelligent Robots and Systems 97*, 1997.

Lee, T.-W., et al., Design of Simulation System for Port Resources Availability in Logistics Supply Chain, *International Association of Maritime Economists Annual Conference*, 2002.

Ljungberg, M., Lucas, A., The OASIS Air Traffic Management System, *Pacific Rim International Conference on Artificial Intelligence*, Seoul, Korea, 1992.

Lumsden, K., *Transportlogistik*, Studentlitteratur, Lund, ISBN 91-44-61041-6, 1995. (In Swedish)

Malone, T., Crowston, K.: The interdisciplinary study of coordination, *ACM Computing Surveys*, Vol. 26(1), 1994.

Mastrolilli M.F.N., Gambardella, L.M., Rizzoli, A.E., and Zaffalon, M., Simulation for policy evaluation, planning and decision support in an intermodal container terminal. *International Workshop on Modeling and Simulation within a Maritime Environment*, 1998.

McGraw-Hill Encyclopedia of Science & Technology, www.accessscience.com/server-java/Arknoid/science/AS (2003-03-25).

Müller, J.P. A Cooperation Model for Autonomous Agents, *Intelligent Agents III*, Springer, 1997.

Nguyen-Duc, M., Briot, J-P., Drogoul, A., An application of Multi-agent coordination techniques in air traffic management, *International Conference on Intelligent Agent Technology*, pp. 622-625, 2003.

Nwana, H.S., Lee, L., Jennings, N.R.: Co-ordination in software agents systems, *BT Technol J*. Vol 14(4), 1996.

Painter, J.H., Cockpit multi-agent for distributed air traffic management, *AIAA Guidance, Navigation, and Control Conference and Exhibit*, 2002.

Parkes, D., Ungar, L., An auction-based method for decentralized train scheduling, *AGENTS'01*, 2001.

Parunak, H.V.D. (1999). Industrial and Practical Applications of DAI, In *Multiagent Systems*, (ed.) G. Weiss. MIT Press

Parunak, H.V.D. Agents in Overalls: Experiences and Issues in the Development and Deployment of Industrial Agent-Based Systems, *International Journal of Cooperative Information Systems* 9(3): 209-227 (2000).

Paulsson, U., Nilsson, C-H, Tryggestad, K., *Flödesekonomi*, Studentlitteratur, Lund, ISBN 91-44-00729-9, 2000. (In Swedish)

Perugini, D., Lambert, D., Sterling, L., and Pearce, A. A Distributed Agent Approach to Global Transportation Scheduling. *International Conference on Intelligent Agent Technology*, pp. 18-24, 2003

Proshun, S.-R.. et al., Container World: Global agent-based modelling of the container transport business, *4th International Workshop on Agent-Based Simulation*, Montpellier, France, 2003.

Rebollo, M., J. Vicente, et al. (2000). A Multi-Agent System for the Automation of a Port Container Terminal. *Autonomous Agents 2000 workshop on Agents in Industry*.

Rebollo, M., J. Vicente, et al. (2001). A MAS Approach for Port Container Terminal Management. *3rd Iberoamerican workshop on DAI-MAS*, pp. 83-94.

Rizzoli, A., Funk, P., Gambardella L., An architecture for agent-based simulation of rail/road transport, *International Workshop on Harbour, Maritime & Multimodal Logistics Modelling and Simulation*, 2002.

Rizzoli A.E., Fornara N., Gambardella L.M., A Simulation tool for combined rail/road transport in intermodal terminals, *MODSIM 1999*, Modelling and Simulation Society of Australia and New Zealand, 1999.

Rong, J., Geng, S., Valasek, J., Ioerger, T., Air traffic conflict negotiation and resolution using an on-board multi-agent system, *21st Digital Avionics Systems Conference*, Vol.2, pp. 69-80, 2002.

Sandholm, T., An implementation of the contract net protocol based on marginal cost calculations, *Eleventh National Conference on Artificial Intelligence*, 1993

Sawamoto, J., Koizumi, H., Tsuji, H., Distributed Cooperative Problem Solving in a Mobile Environment, *Twelfth International Conference on Information Networking*, pp. 375-380, 1998

Schneeweiss, C., *Hierarchies in distributed decision making*, Springer-Verlag, Heidelberg, ISBN 3-540-65585-9, 1999.

Shapiro, S. and Heskett, J.L., *Logistics Strategy*. West Publishing Co., 1985.

Shillo, M., Vierke, G., Multidimensional utility vectors in the transportation domain, *ECAI Workshop on Agent Technologies and Their Application Scenarios in Logistics*, 2001.

Shoham, Y., Tennenholtz, M.: On the synthesis of useful social laws for artificial agent societies, *Tenth National Conference on Artificial Intelligence*, pp. 276-281, 1992.

Sjöland, T., Kreuger, P., Åström, E., Danielsson, P., Coordination of scheduling and allocation agents, *2nd International Workshop on Constraint Programming for Time Critical Applications*, 1998.

Smith, R.G.: The Contract Net Protocol: High-Level Communication and Control in a Distributed Problem Solver, *IEEE Trans on Comput*, Vol. 29(12), 1980.

Stock, J. R. and D. M. Lambert (2001). *Strategic Logistics Management*. Boston, U.S.A., McGraw-Hill Irwin.

Thurston, T. and H. Hu (2002). Distributed Agent Architecture for Port Automation. *26th International Computer Software and Applications Conference*, IEEE Computer Society.

Tomlin,C., Pappas, G.J., Sastry, S., Noncooperative conflict resolution, *36th Conference on Decision & Control*, pp. 1816-1821, 1997.

Törnqvist J., Davidsson P., A Multi-Agent System Approach to Train Delay Handling, *ECAI-02 Workshop on Agent Technologies in Logistics*, 2002.

van den Bosch, A.T., Menken M.R., van Breukelen, M., van Katwijk, R., A Test Bed for Multi-Agent Systems and Road Traffc Management, *15th Belgian-Netherlands Conference on Artificial Intelligence*, pp. 43–50, 2003

van Katwijk, R., van Koningsbruggen, P., Coordination if traffic management instruments using agent technology, *Transportation Research Part C*, Vol. 10: 455-471 (2002)

Vilaplana, M. A., Goodchild, C., Application of distributed artificial intelligence in autonomous aircraft operations, *20th Conference on Digital Avionics Systems*, Vol. 2, 2001.

Wangermann, J., Stengel, R., Distributed optimisation and principled negotiation for advanced air traffic management, *IEEE International Symposium in Intelligent Control*, 1996.

Wangermann, J., Stengel, R., Principled negotiation between intelligent agents: a model for air traffic management, *Artificial Intelligence in Engineering*, Vol. 12: 177-187, 1998.

Weiss G., *Multi-Agent Systems*, MIT Press, Cambridge, 1999.

Wooldridge M., *An Introduction to Multi-Agent Systems*, John Wiley & Sons, London, 2002.

Yi, D.W., Kim, S.H., Kim., N.H., Combined Modeling with Multi-Agent Systems and Simulation: Its Application to Harbor Supply Chain Management. *35th Hawaii International Conference on System Sciences*. 2002.

Zhu, K., Bos, A., Agent-based design of intermodal freight transportation systems, *NECTAR Conference*, Delft, 1999.

Zhu, K., Ludema, M., van der Heijden, R., Air cargo transports by multi-agent based planning, *33rd Hawaii International Conference on System Science*, 2000.

Appendix Survey results

Paper	Problem Description			Approach					Results	
	Domain	Mode of transportation	Time horizon	Usage	Control type	MAS structure	Agent attitude	Agent architecture	Maturity	Evaluation comparison
Budenske et al (2001)	Transport	Air	Operational	Automation	Centralized	Dynamic	Selfish	Hybrid	1	None
Perguini et al. (2003)	Transport	Air, Rail, Road, Sea	Tactical	DSS	Distributed	Static	Selfish	Deliberative	2.1.1	Qualitative
Zhu et al. (2000)	Transport	Air	Tactical	DSS	Distributed	Static	Benevolent	Hybrid	3.1	Qualitative
Böcker et al. (2001)	Transport	Rail	Tactical	DSS	Centralized	Static	Benevolent	Hybrid	2.2.1	None
Sjöland et. al. (1998)	Transport	Rail	Tactical	DSS	Centralized	Static	Benevolent	Deliberative	1	None
Bouzid (2003)	Transport	Road	Tactical	DSS	Distributed	Dynamic	Benevolent	Deliberative	1	Qualitative
Fischer et al. (1999, 1996, 1995)	Transport	Road	Tactical	DSS	Distributed	Dynamic	Selfish	Hybrid	2.1.1	Quantitative
Kouhout et al. (1999)	Transport	Road	Tactical	DSS	Distributed	Dynamic	Selfish	Deliberative	2.2.1	Qualitative quantitative
Sandholm (1993)	Transport	Road	Tactical	Automation	Distributed	Dynamic	Selfish	Hybrid	2.2.1	Qualitative
Sawamoto et al. (1998)	Transport	Road	Tactical	DSS	Distributed	Dynamic	Benevolent	Hybrid	2.1.2	None
Buchheit et al. (1992)	Transport	Intermodal (road, rail, sea)	Operational	Automation	Distributed	Static	Selfish	Reactive	2.1.1	None
Bürckert et al. (2000)	Transport	Intermodal (road, rail)	Operational	DSS	Distributed	Dynamic	Selfish	Hybrid	2.2.1	None
Dong and Li (2003)	Transport	Intermodal (road, rail, sea, air)	Tactical and operational	DSS	Distributed	Static	Selfish	Hybrid	1	None
Funk et al. (1999)	Transport	Intermodal (road, rail)	Tactical and operational	DSS	Distributed	Dynamic	Selfish	Hybrid	2.2.1	None
Proshun et al. (2003)	Transport	Intermodal (road, rail, sea)	Strategic	DSS	Distributed	Dynamic	Benevolent	Hybrid	1	None
Burstein et al. (2000)	Transport Terminal	Air	Operational	Automation	Centralized	Dynamic	Benevolent	Hybrid	4	None
Rizzoli et al. (1999, 2002)	Transport Terminal	Intermodal (road, rail)	Tactical	DSS	Centralized	Dynamic	Selfish	Hybrid	2.2.1	None
Zhu and Bos (1999)	Transport	Intermodal (road, rail, sea, air)	All	Automation	Distributed	Dynamic	Benevolent	Hybrid	2.2.1	None
Allo et al. (2001)	Traffic	Air	Operational	Automation	Distributed	Dynamic	Benevolent	Reactive	2.1.1	None
Callantine et al. (2003)	Traffic	Air	Operational	DSS	Centralized	Dynamic	Benevolent	Reactive	2.1.1	Quantitative
Findler et al. (1991, 1995)	Traffic	Air	Operational	Automation	Distributed	Dynamic	Selfish	Hybrid	2.1.2	Quantitative
Iordanova (2003)	Traffic	Air	Operational	DSS	Centralized	Dynamic	Selfish	Hybrid	1	None
Košecká et al. (1997), Tomlin et al. (1997)	Traffic	Air	Operational	DSS	Distributed	Dynamic	Selfish	Reactive	1	None
Ljungberg and Lucas (1992)	Traffic	Air	Operational	DSS	Centralized	Dynamic	Benevolent	Hybrid	2.2.2	None
Nguyen-Duc et al. (2003)	Traffic	Air	Operational	DSS	Centralized	Dynamic	Benevolent	Reactive	1	None
Painter (2002)	Traffic	Air	Operational	Automation	Centralized	Dynamic	Benevolent	Reactive	2.1.1	None
Rong et al (2002)	Traffic	Air	Operational	DSS	Distributed	Dynamic	Selfish	Hybrid	1	None
Vilaplana and Goodchild (2001)	Traffic	Air	Operational	Automation	Distributed	Static	Selfish	Hybrid	2.1.1.	None
Wangermann and Stengel (1996, 1998)	Traffic	Air	Operational	DSS	Distributed	Dynamic	Selfish	Hybrid	1	Qualitative
Balbao and Pinson (2001)	Traffic	Road	Operational	DSS	Distributed	Static	Selfish	Reactive	2.2.1	Qualitative quantitative

Paper	Problem Description			Approach					Results	
	Domain	Mode of transportation	Time horizon	Usage	Control type	MAS structure	Agent attitude	Agent architecture	Maturity	Evaluation comparison
France and Ghorbani (2003)	Traffic	Road	Operational	Automation	Centralized	Static	Benevolent	Hybrid	2.2.1	None
García-Serrano et al. (2003)	Traffic	Road	Operational	DSS	Distributed	Static	Benevolent	Deliberative	4	None
van den Bosch and Menken (2003)	Traffic	Road	Operational	Automation	Distributed	Static	Benevolent	Deliberative	2.1.1	Qualitative
Blum and Eskandarian (2002)	Traffic	Rail	Tactical	DSS	Centralized	Static	Benevolent	Reactive, Hybrid	2.2.1	None
Brewer, Plott (1996)	Traffic	Rail	Tactical	DSS	Distributed	Static	Selfish	Reactive	2.2.1	None
Cuppari et. al. (1999)	Traffic	Rail	Operational	DSS	Centralized	Dynamic	Benevolent	Hybrid	2.2.1	Qualitative
Fernández et. al. (2002)	Traffic	Rail	Operational	DSS	Distributed	Dynamic	Benevolent	Reactive, Hybrid	1	None
Parkes (2001)	Traffic	Rail	Tactical	Automation	Distributed	Static	Selfish	Reactive, Hybrid	2.1.1	Quantitative
Törnquist and Davidsson (2002)	Traffic	Rail	Operational	DSS	Distributed	Static	Benevolent	Deliberative	1	None
Fernández et al. (2004)	Traffic	Road	Operational	DSS	Distributed	Static	Benevolent	Deliberative, Reactive	2.1.1	None
Hernández et al. (2001, 2002) TYRS	Traffic	Road	Operational	DSS	Centralized	Static	Benevolent	Deliberative	3.2	Qualitative quantitative
Hernández et al. (2001, 2002) $TRYSA_2$	Traffic	Road	Operational	DSS	Distributed	Static	Selfish	Hybrid	2.2.2	Qualitative quantitative
van Katwijk et al. (2002)	Traffic	Road	Tactical	Automation	Distributed	Static	Selfish	Deliberative	1	None
Choy et al. (2002)	Traffic	Road	Operational	DSS	Distributed	Static	Selfish	Hybrid	2.2.1	Quantitative
Goldsmith et al. (1998)	Terminal	Road	Operational	Automation	Distributed	Dynamic	Benevolent	Reactive	2.2.2	None
Carrascosa et al. (2001)	Terminal	Sea	Operational	Automation	Centralized	Static	Benevolent	Reactive	1	None
Itmi et al. (1995)	Terminal	Sea	Operational	Automation	Centralized	Static	Benevolent	Reactive	1	None
Lee et al. (2002), Yi et al. (2002)	Terminal	Sea	Tactical	DSS	Centralized	Static	Benevolent	Reactive, Deliberative	2.1.1	None
Rebollo et al. (2000, 2001)	Terminal	Sea	Operational	Automation	Centralized	Static	Benevolent	Reactive	1	None
Thurston and Hu (2002)	Terminal	Sea	Operational	Automation	Distributed	Static	Benevolent	Hybrid	2.1.1	None
Degano et al. (2002, 2001)	Terminal	Intermodal (road, rail, sea)	Operational	Automation	Centralized	Dynamic	Benevolent	Hybrid	2.2.2	Quantitative
Gambardella et al. (2001, 1998), Mastrolilli et al. (1998)	Terminal	Intermodal (road, rail, sea)	Tactical	DSS	Distributed	Static	Benevolent	Reactive, Deliberative	2.2.2	Qualitative
Henesey et al. (2003a)	Terminal	Intermodal (road, rail, sea)	Strategic	DSS	Distributed	Static	Selfish	Deliberative	1	None
Henesey et al. (2003b)	Terminal	Intermodal (road, rail, sea)	Operational	Automation	Distributed	Static	Benevolent	Reactive, Deliberative	1	None