Multi-agent-based transport planning in the newspaper industry

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ABSTRACT

In many cases of today's planning tasks, the synchronization of production and distribution is becoming increasingly important in order to minimize costs and to maximize customer satisfaction. This is especially the case if transport schedules are closely connected to production schedules, as it is in the newspaper industry—where perishable goods are distributed immediately after production. In order to achieve the above mentioned competing objectives, a special kind of vehicle routing problem, the vehicle routing problem with time windows and cluster-dependent tour starts (VRPTWCD), has to be solved. Moreover, the varying print and post-processing schedules due to unknown editorial deadlines lead to the need for a dynamic online control of the newspaper production and distribution process. In this contribution, the outlined dynamic transport problem is solved online under consideration of unforeseen changes in production schedules. The solution concept is based on a multi-agent system consisting of, amongst others, several Edition and Vehicle Agents. This system is exemplarily applied to a real life application case of one of the largest German newspaper companies. It is shown that a static (centralized) optimization of the underlying problem would even lead to worse results in comparison to the current situation and that the appliance of the multi-agent system is suitable in the newspaper industry.

1. Introduction

Analyzing recent trends in the transport sector, the following challenges become obvious: First, shippers are experiencing an *increase of transport costs*. The rapid oil price growth in recent years, launch of truck tolls on highways in several countries as well as costs for delay in delivery are just some reasons for higher transport costs. Second, distributors have to face the need for a *higher customer orientation*. The growing demand for individualized products, delivered with short service times and high delivery reliability, implicates the need for an improvement of delivery flexibility in order to increase customer service. Therefore, products have to be manufactured with shorter lead times and at the time of the order (Gunasekaran et al., 2008). Finally, in order to address the two challenges mentioned above, a decoupled consideration of the supply chain processes is no longer sufficient (Buer van et al., 1999). Hence, a combined consideration of production and distribution tasks is essential—especially if both tasks are closely connected to each other. This contribution considers transport planning (the main focus is on vehicle routing and production schedules are seen as a dynamic input) in a particular complex sector in which a perishable good has to be distributed immediately after production—the newspaper industry. A general workflow of this industry can be separated in mainly five processes as shown in Fig. 1 (the circles indicate the affiliation of a process to production (P) or distribution (D)).

Each announcement day, editorial departments create the content of different editions, depending on their area of circulation. Moreover, editorial departments define forecasts for the production process (production schedules). Next, editions are produced on one or more print presses. The print process is then followed by a post-processing step where pre-prints and advertising supplements (inserts) are added. Afterwards, the newspapers are allocated to trucks. Hereby, unpredictable delays due to latest news that have to be inserted or due to disturbances during production lead to strongly varying print completions and thus to strongly unpredictable tour starts. All vehicles start their tours at production site(s), delivering several (mostly heterogeneous) editions. Each truck executes its vehicle route in order to supply unloading points, where one or more newspaper carriers start the delivery of customers. The vehicle routes have to keep deadlines by which the newspaper carriers must receive their papers in order to supply all readers in time (one-sided time-windows). To avoid subscription cancellations, the in-time delivery of all editions is inescapable.

In recent years, several researchers have dealt with transport planning in the newspaper industry. The first paper, which defines the distribution of newspapers as a specific vehicle

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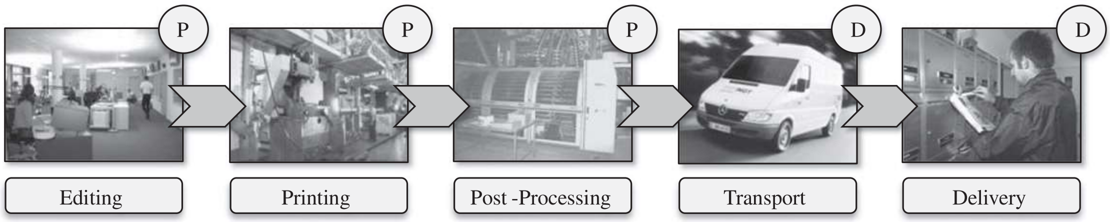

Fig. 1. General newspaper industry's workflow.

routing problem, was published by Golden (1975). Afterwards, a guideline for routing and scheduling in the newspaper industry was presented by Holt and Watts (1988). The first contribution with a mathematical formulation for the transport problem was proposed by Mantel and Fontein (1993). Ree and Yoon (1996) designed a two-stage heuristic for solving the newspaper delivery problem. The problem of synchronizing production and distribution of heterogeneous newspapers is described and formulated in detail by Buer van et al. (1999). Garcia et al. (1999) designed a simulation model for the analysis of newspaper printing, packaging and distribution processes. Song et al. (2002) considered an application case concerning one of the largest newspaper companies in Korea, which produces and distributes several different editions. Russell et al. (2008) presented a tabu search meta-heuristic to aid in the synchronization of the production and distribution of multi-product newspapers. The most recent contribution was presented by Chiang et al. (2009), which present a simulation/metaheuristic approach in order to face stochastic aspects. The majority of researchers defines and solves the problem of newspaper distribution based on a vehicle routing problem with time windows (VRPTW, see e.g. Bräysy and Gendreau, 2005a, b). In addition to a standard VRPTW, it is necessary to deal with the problem of *heterogeneous editions per truck under consideration of production schedules*. Truckloads with several different editions lead to an interdependence between production schedules and tour clusters (i.e. changing tour starts due to modified production schedules or tours). This problem was defined by Böhnlein et al. (2009) as a vehicle routing problem with time windows and cluster-dependent tour starts (VRPTWCD). The static version of this problem (based on production forecasts), can be solved by means of the hybrid meta-heuristic AntTabu (see Böhnlein et al., 2009).

However, the solely solution of a vehicle routing problem based on static production schedules (forecasts) is not sufficient anymore. Latest news being inserted as well as disturbances in production lead to strongly varying tour starts and thus to delays in supply. Hence, the vehicle routing problem has to be solved *under consideration of static (forecasted) and dynamic (online) production schedules*—what has not been faced by literature yet. Consequently, a simultaneous solution of both variants of the vehicle routing problem at hand, the consideration of static and dynamic production schedules, is introduced in this contribution.

2. Problem formulation and objectives

2.1. Formulation of the underlying newspaper industry's problem

In order to illustrate the complex underlying problem and the necessity of considering distribution in conjunction with production schedules, the example in Fig. 2 is used. Hereby, the effects of late allocations of editions to trucks as well as cluster-dependent tour starts are clarified. This example includes a post-processing schedule with four mechanical inserters and 19 editions as shown at the top. The box below contains an extract of vehicle *k*'s tour, which has to deliver the editions e_{13}, e_{16} and e_{19} to unloading points. The vehicle starts its tour at the production site (index 0), to which it returns after supplying all unloading points. Each unloading point has a demand for one or more edition(s) and a one-sided time window (due time) that should be kept in order to realize in-time customer supply. Arrival times and distances can be calculated by means of previously computed complete time/distance matrices. Due to the fact that most newspaper companies do not schedule the allocation of edition fragments to trucks (what is the only optimization in production being faced in this contribution and what has not been considered in literature yet), it might happen that vehicle *k* gets the last edition fragment of e_{19}. As this fragment is completed and allocated at 03:09, vehicle *k* starts its tour after its latest tour start (which has to be kept in order to reach in-time delivery). This results in two unloading points (22 and 23) being expected to be supplied with delay. A delayed delivery leads to additional costs (newspaper carriers have to be indemnified for the resulting waiting time, resulting in so-called newspaper carrier compensation costs) as well as to a decrease of customer satisfaction (as a result of the tardy supply). This out-of-time-delivery can mainly be resolved by means of the following two strategies: First, one or more unloading point(s), which have to be supplied before unloading point 23, could be moved from vehicle *k*'s cluster to another cluster, i.e. to another tour, in order to save the time being too late. Second, all unloading points, which have a demand for e_{19} (unloading points 20 and 22), could be moved to another tour, e.g. to a tour which already supplies e_{19} without any delay. This results in an earlier tour start of vehicle *k* at 00:00, i.e. when e_{13} is completed. This scenario reflects the strong dependency between production and distribution as well as cluster-dependent tour starts (VRPTWCD) occurring with respect to vehicle routing in the newspaper industry. This static problem can be solved before production start on the basis of forecasted schedules (see Böhnlein et al. (2009) for further information including a mathematical formulation of the static VRPTWCD).

The above mentioned problems are emphasized by the fact that editorial departments insert latest news even during production in order to create up-to-date newspapers. Furthermore, disturbances due to, e.g., paper disruptions lead to unforeseen changes in the production process. By means of the box-and-whisker plot in Fig. 3, an extract of the strong varieties concerning post-processing start as well as completion times is presented. Hereby, the upper part of each row represents the distribution of start times and the lower part illustrates the corresponding completion times of the edition concerning 40 exemplarily evaluated days (these days are also considered in the evaluation of the solution concept). Consequently, a strongly varying print and post-processing execution can be recognized, i.e. possible delays have to be absorbed by the distribution processes in order to supply customers in time. This leads to the

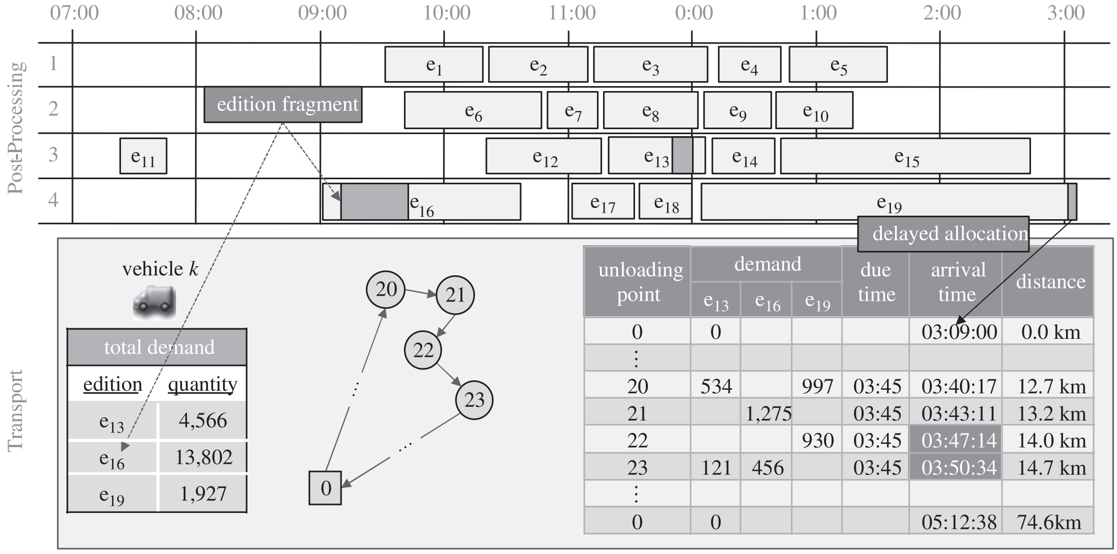

Fig. 2. Strong dependency between production and distribution schedules.

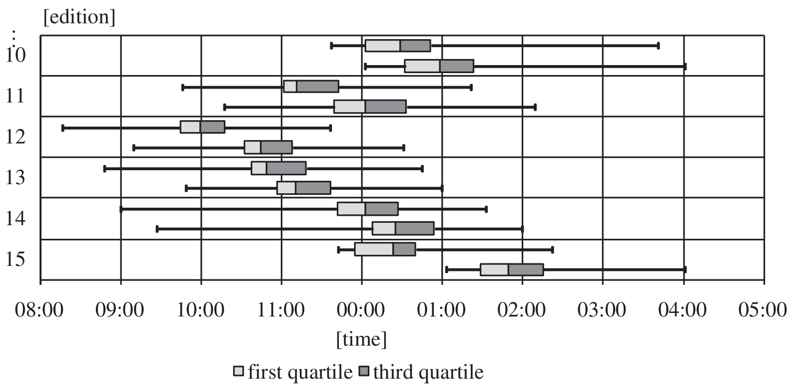

Fig. 3. Strongly varying post-processing start and completion times per edition.

necessity of a dynamic consideration of the underlying VRPTWCD (see Böhnlein (2008) for a mathematical formulation of the dynamic problem with regard to a standard VRPTW).

2.2. Objectives

The following two objectives have to be achieved in regard to the problem context formulated above. On the one hand, a *minimization of costs* has to be faced. This objective can be subdivided into the sub-objectives of minimizing travel distances, minimizing carrier compensation costs and minimizing the number of vehicles in use. Concerning travel distances and carrier compensation costs, calculations can be established, whereas the evaluation of the costs for the number of vehicles in use turns out to be more complicated, as the vehicle fleet of most newspaper companies consists of a pre-defined number of vehicles and drivers. Hence, the reduction of the number of vehicles on a specific distribution day does not necessarily result in a reduction of costs. However, saving vehicles in a pre-optimization step leads to a high flexibility as these vehicles can be used online to realize in-time supply and thus to maximize customer service (when e.g. a disturbance in production happens). On the other hand, a *maximization of customer satisfaction* has to be addressed. The increase of customer service distinguishes between the delivery reliability of editions and the topicality of newspapers. This differentiation includes the natural conflict between production and distribution functions in the newspaper industry. The focus in this contribution is, besides the minimization of costs, on the maximization of customer satisfaction in the distribution process. Hereby, production schedules are seen as an input for the vehicle routes and thus the topicality of newspapers is taken for granted (editorial departments may insert latest news even if production already started). To measure the customer service in the distribution process, a ratio, the so-called level of service, is required. The two variants of this index define the delivery reliability of one particular tour (1) and of all tours (2), respectively:

$$ls_k = \frac{\sum_{i=1}^{N}\sum_{e=1}^{E} d_{i,e}tw_i}{\sum_{i=1}^{N}\sum_{e=1}^{E} d_{i,e}} \forall i \in tour_k \tag{1}$$

$$ls = \frac{\sum_{i=1}^{N}\sum_{e}^{E} d_{i,e}tw_i}{\sum_{i=1}^{N}\sum_{e=1}^{E} d_{i,e}} \tag{2}$$

Hereby, tw_i is a binary variable indicating if unloading point i is supplied in time (then 1 else 0), $d_{i,e}$ indicates the demand (number of newspapers) for edition e at unloading point i, E the total number of editions and N the total number of unloading points. Consequently, ls_k indicates the ratio between the number of in-time delivered newspapers and the total number of newspapers on tour k. In contrast to this, ls denotes the ratio between the total number of newspapers supplied in time and the total number of newspapers.

The two objectives of decreasing costs and increasing customer satisfaction have different interdependencies. On the one hand, a delayed supply of newspaper carriers could either be compensated by re-planning the vehicle routes (which might result in higher distances) or by using additional vehicles. Both options result in higher transport costs that have to be paid in order to achieve a high customer satisfaction—these objectives are competing. On the other hand, there is also a complementary aspect between the two objectives: If levels of service are increased, carrier compensations costs can be saved as delays at the unloading points are reduced. Thus, eliminating delays and therefore increasing customer satisfaction mostly, but not necessarily, results in higher transport costs. Consequently, it is necessary to balance the level of service with the costs of providing that service (Rushton et al., 2007). Therefore, the presented solution concept includes a parameter for the adjustment of a minimal level of service that should be reached by vehicle k if possible, ls_k^{min}.

3. Multi-agent-based solution concept

As the VRPTWCD can be separated into a problem with static and dynamic production schedules, it is not sufficient to only have a solution method for the static problem. A desirable solution concept is able to solve both problems within one system. Hereby, the solution for the problem with pre-defined production schedules can be calculated in the first step—the *pre-optimization step* (on the basis of production schedule forecasts). In the next step, the focus is on solving the more complex problem with unforeseen erratic production schedules. This dynamic problem implies, besides a *high solution quality*, the need for an *efficient* solution concept as presented in this work. Efficiency (computing performance of the solution concept) is the decisive aspect as the optimization has to be restarted iteratively every time an incident in production occurs. All "traditional" solution methods, which are suitable for the static VRPTWCD, i.e. for instance any (meta)heuristic, do not have the ability to solve the dynamic VRPTWCD in an adequately efficient manner. Consequently, an approach which is able to solve the dynamic problem *online* needs to be designed, i.e. time passes during optimization and thus the solution method has to react on changes even during optimization. As such a method cannot be implemented as a centralized solution because of too high computing times (Bräysy and Gendreau, 2005b), the usage of a distributed solution method becomes obvious. This solution methods needs to have the ability to be applied to a *multitude of newspaper companies*.

In order to tackle these challenges, agent-based technologies represent one of the most promising technological paradigms for designing distributed systems (Ahmad, 2002). The suitability of a multi-agent system for an integrated consideration of supply chain tasks is confirmed by several researchers (see e.g. Akanle and Zhang, 2008; Anosike and Zhang, 2009). Within this context, there are several reasons for the suitability of applying a multi-agent-based solution method to the static and dynamic VRPTWCD: First, the underlying problem itself is subdivided (mainly in production and distribution tasks), leading to an easier implementation and understanding through applying a multi-agent system. This allows a higher flexibility when taking the modularity of the real system into account. Next, the decomposition through agents is very important in order to manage complexity (Jennings, 2000). The ability to model, design and build complex, distributed systems is enabled by the decomposition into multiple agents and thus the decentralization of control. Moreover, the isolation of system capabilities into independent processing units provides the possibility to distribute agents over a network of computers, resulting in considerable computing power (Kohout and Erol, 1999). Hereby, it is possible to enable one agent per vehicle using on-board units and navigation software which informs drivers about their vehicle route. Because of the fact that autonomous agents act concurrently, problem solving can be accelerated and thus the required efficiency to solve the problem online can be achieved. Furthermore, the high-level interactions of agents make the engineering of complex systems easier (Jennings, 2000). By providing abstraction levels through message exchange and coordination, multi-agent systems enable the analysis, design and implementation of large and complex systems (Burmeister et al., 1997). Multi-agent systems are, compared to standard approaches, more suitable for varying contexts where frequent re-programming is needed. Thus, an adaptation of the system is easier when a multi-agent-based solution concept is applied. Finally, Kohout and Erol (1999) show that the significant advantages of distributed, agent-based systems can be used to obtain high-quality results in an online control system. Summarizing these arguments, a multi-agent system seems, being consistent with the opinion of several researchers, adequate as an online-solver for the stated problems.

3.1. Multi-agent systems

The term *agent*, i.e. the basic and fundamental element of a multi-agent system, has its background in the early work on artificial intelligence, when researchers concentrated on trying to create artificial entities which mimicked human abilities (Hewitt, 1977). It is common to describe it as a computer system, situated in an environment, which is capable of flexible, autonomous action in order to achieve its goals (Jennings et al., 1998). Agents include four important capabilities (compare Wooldridge and Jennings, 1995): First, they are able to *act autonomously*, i.e. they decide *independently* for *themselves* what to do in order to satisfy their objectives. Second, they are capable to *interact* with other agents by engaging *social ability* (in order to reach global objectives), as for example coordination, negotiation and communication (Wooldridge, 2006). Third, agents are *reactive*, i.e. they perceive their environment and respond timely to changes that occur in it. And fourth, they are *proactive*, i.e. able to exhibit goal-directed behavior by taking the initiative.

Against the background of the definition of an agent, *multi-agent systems* are defined as a network of agents which solve problems that are beyond their individual capabilities (Jennings, 2000). These systems may consist of homogeneous or heterogeneous agents which perform a set of tasks or satisfy a set of goals (Lesser, 1999). They have the abilities to solve problems that might be too large for a centralized single agent, to provide solutions to inherently distributed problems, to offer conceptual clarity and simplicity of design and to tolerate uncertain data knowledge (Green et al., 1997). *Coordination* is a central aspect of intelligent agency, i.e. the capability to decide on its own actions in the context of activities of other agents (Durfee, 2001). A group of agents is coordinated by means of *negotiation*, which is basically defined by Bussmann and Müller (1993) as the communication process of a group of agents in order to reach a mutually accepted agreement. Negotiation can be *cooperative* or *competitive* depending on the behavior of the agents involved. Cooperative agents will collaborate in order to achieve a common goal for the best interest of the system as a whole, whereas competitive agents try to maximize their own profit (Rosenschein and Zlotkin, 1998). To achieve coordination, agents must, besides negotiation, interact and exchange information, i.e. they need to *communicate*. Therefore, agents need to apply a common language to understand each other (Genesereth and Ketchpel, 1994).

3.2. Solution concept

On the basis of the analysis of agents and multi-agent systems, the design of the multi-agent-based solution concept for the newspaper industry is considered. To the authors' knowledge, a multi-agent system has not been designed and implemented for the newspaper industry yet, yielding the innovation of the proposed solution method.

The design (and implementation) of a multi-agent system involves the necessity of reflecting on the questions (following Dyke Parunak, 2001) of *what becomes an agent*, *how many agents* being used as well as how agents are *structured internally* and how each agent models its *environment*. Moreover, the design has to consider how agents *coordinate their actions* as well as the *communication channels* and *protocols* used by the agents. Based on these questions, the design of agents and the multi-agent system is presented in the following sections (these sections also focus on agents' design choices as presented by, e.g. Mes et al. (2008)). Hereby, the different types of agents, their actions and coordination are specified. In doing so, the questions formulated above are tackled.

3.2.1. Different types of agents: Internal structures, tasks and actions

The multi-agent system consists of the different types of agents as shown in Fig. 4: An *AntTabu Coordination Agent*, coordinating the solution of the static VRPTWCD, i.e. administering several *AntTabu Agents* which are responsible for creating vehicle routing plans in the pre-optimization step (based on production forecasts). Hereby, the focus is especially on saving vehicles in order to increase flexibility for the agents of the dynamic problem. However, the objectives of minimizing costs through distances traveled and maximizing customer satisfaction through keeping time windows have to be reached. Furthermore, several *Vehicle Agents*, which are substitutes for a vehicle in the distribution process, and *Edition Agents*, representing editions in the production (i.e. post-processing) process, are in use. *Emergency Agents* are necessary for the resolution of disturbances which occur in the dynamic production process and lead to delayed tour starts. The figure also depicts the coordination between the agent types of the static and dynamic VRPTWCD, whereat AntTabu Agents as well as Vehicle Agents communicate with agents of the same type.

In order to achieve their objectives, the agents execute several tasks (or actions) autonomously. The main sequence of these tasks is illustrated by means of activity diagrams, which answer the questions of how the agents are structured internally and how they model their environment. These figures also contain information about different agents' behaviors. Behaviors are special kinds of tasks with the ability of being executed in parallel to other tasks and thus enable coordination. Coordination, negotiation and communication between agents are presented in detail in Section 3.2.2.

3.2.1.1. Agents for the static pre-optimization. The multi-agent system consists of one *AntTabu Coordination Agent* (see Fig. 5 on the right), which has the intention to construct an optimized vehicle routing plan while considering the forecasted production plan which is provided by the editorial department(s)—the pre-optimization step based on AntTabu (Böhnlein et al., 2009) is operated. This agent starts its lifetime with loading the parameter settings specified by the user of the system. Next, it initializes all variables. After this initialization procedure, it creates a colony of AntTabu Agents which are responsible for the computation of valid vehicle routing plans and sends them their configuration according to the parameter settings. The AntTabu Agents now calculate their vehicle routing plans. The AntTabu Coordination Agent has to wait for the completion of the Ant Colony Optimization (ACO) run of each AntTabu Agent and then receives a vehicle routing plan from each AntTabu Agent. After all plans have been received, it evaluates the results of each plan (transport costs, number of vehicles and level of service) and determines σ elitist AntTabu Agents. Next, it instructs each elitist AntTabu Agent to perform Tabu Search (TS) in order to post-optimize its vehicle routing plan. Non-elitist AntTabu Agents are authorized to terminate. After all vehicle routing plans were received from the elitist AntTabu Agents, the AntTabu Coordination Agent evaluates their resulting vehicle routing plans and updates the pheromone trails. The next colony of AntTabu Agents is created and the procedure is repeated unless a maximum number of iterations it_{max} is reached. Otherwise, it creates Vehicle Agents according to the best result of the optimization and notifies them about their vehicle route, i.e. about the unloading points they have to supply. Hereby, each Vehicle Agent gets one vehicle route from the resulting best vehicle routing plan.

AntTabu Agents (see Fig. 5 on the left) are responsible for the construction of valid vehicle routing plans and possibly for the post-optimization with TS (solution of the static VRPTWCD). Each AntTabu Agent starts its lifetime with receiving its configuration by means of a message sent by the AntTabu Coordination Agent. Then, each AntTabu Agent starts the construction of a vehicle

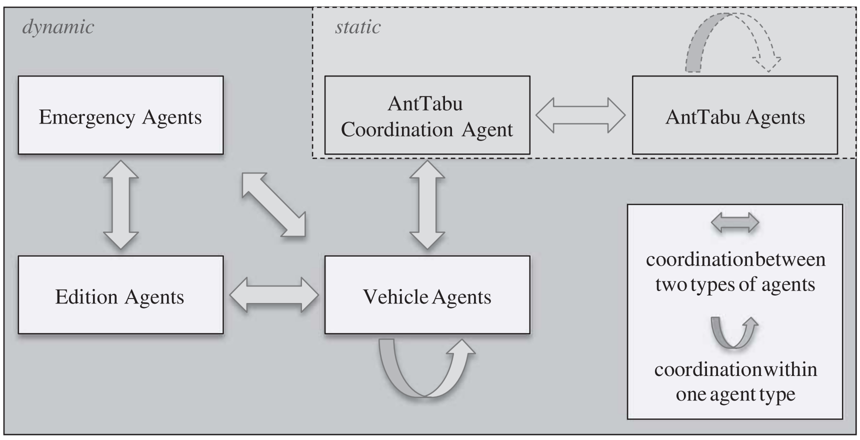

Fig. 4. Different types of agents and their coordination.

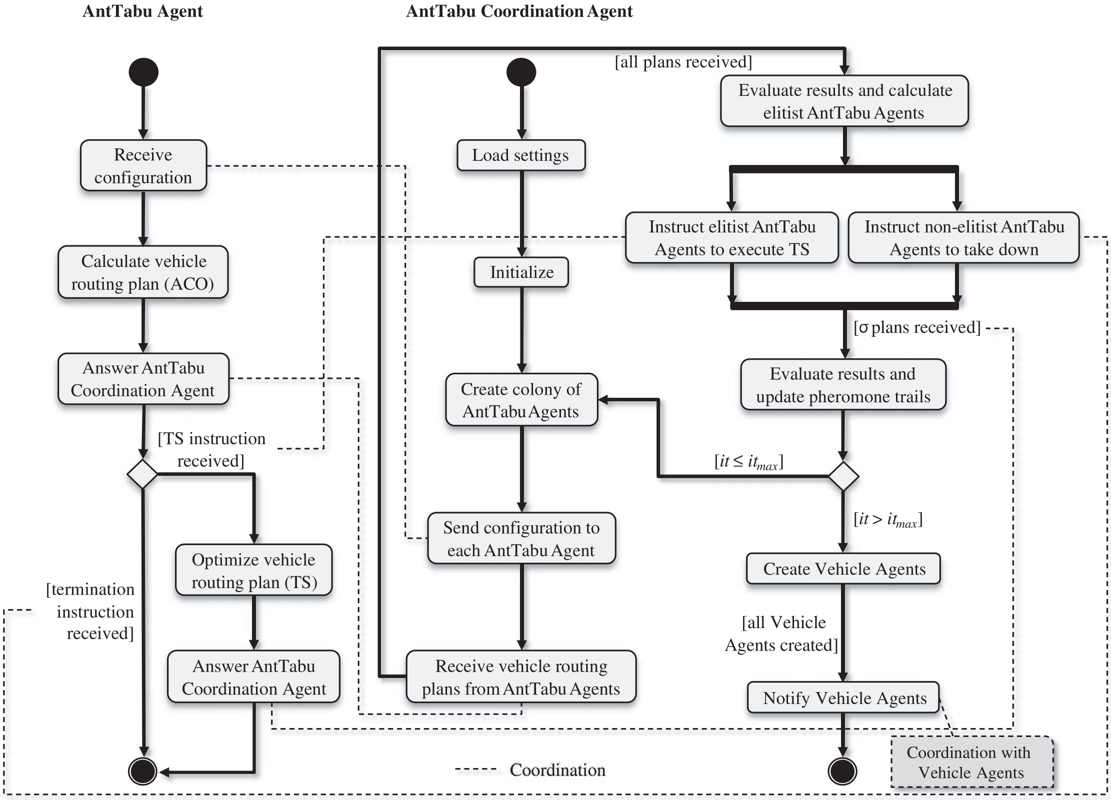

Fig. 5. Activity diagrams—AntTabu Agent/AntTabu Coordination Agent.

routing plan by means of ACO, whereat new solutions are built by visiting all unloading points based on tour starts that can be calculated by means of the predicted post-processing completion times. Afterwards, it sends the results of its optimization to the AntTabu Coordination Agent, which is responsible for the evaluation of all resulting vehicle routing plans. If an AntTabu Agent's resulting vehicle routing plan is among the best results and thus belongs to the group of elitist ants, it is informed by the AntTabu Coordination Agent and post-optimizes its vehicle routing plan with TS. After each iteration, AntTabu Agents indirectly communicate with each other via pheromone trails (dotted arc in Fig. 4). Their lifetime ends after sending the resulting vehicle routing plan (possibly after the execution of TS) to the AntTabu Coordination Agent.

3.2.1.2. Agents for the dynamic optimization. *Vehicle Agents* (see Fig. 6 in the center) have two intentions: On the one hand, they try to supply all of their unloading points in time in order to maximize their level of service and thus the global level of service. Their other intention is to minimize transport costs by optimizing their routes. Vehicle Agents start their lifetime after the pre-optimization step (the number of Vehicle Agents may not exceed the number of vehicles in the fleet). They initially calculate their demands according to their delivery list which was sent by the AntTabu Coordination Agent. Afterwards, each Vehicle Agent registers its interest in required editions at the Directory Facilitator (DF; as agents principally do not know each other, the DF provides yellow pages) to be able to communicate with the responsible Edition Agent. Next, Vehicle Agents optimize their delivery list by means of the route improvement heuristic 3-opt (Lin, 1965) under consideration of time windows in order to minimize costs. Based on this optimized vehicle route, Vehicle Agents calculate a deadline (latest possible tour start time) for their tour start. In the next step, they use the *cooperative Buyer*—as well as the *competitive CoverDemand-Behavior* in parallel. The CoverDemand-Behavior is the Vehicle Agents' counterpart to the *NewspaperAllocation-Behavior* used by the Edition Agents. This behavior involves the negotiation between Edition and Vehicle Agents (see Section 3.2.2). Based on the deadline, each Vehicle Agent checks its truckload iteratively and compares the current (real) time with the latest tour start time. If a delay occurs (i.e. if the minimum level of service ls_k^{min} cannot be reached), its current vehicle route is optimized by the 2-opt heuristic (Croes, 1958) with the objective of minimizing the total travel time under consideration of time windows (at this time the agent changes its objective). Note that the minimum travel time route is not necessarily congruent to the minimum distance route (Kohout and Erol, 1999) and hence the Vehicle Agent possibly can reduce its expected travel time and thus realize an earlier tour start. The aim of this optimization is that delays might be resolved by lower travel times, whereas possibly higher costs have to be accepted. If no resolution of the delay is possible, Vehicle Agents leave the Buyer-Behavior and use its counterpart, the *Seller-Behavior*. These behaviors are used to 'sell' or 'buy', i.e. transfer/accept unloading points to/from other Vehicle Agents in order to realize delivery in time (coordination takes place). If the sale of unloading points cannot resolve delays, Vehicle Agents use the *Emergency-Behavior* that enables coordination with the responsible Emergency Agent. Finally, Vehicle Agents start their tour if the truckload is completed and all delays are resolved or no delays occurred.

Each edition in the production process is represented by one *Edition Agent* (see Fig. 6 on the left). As print schedules are not optimized and the allocation of edition fragments to vehicles (represented by Vehicle Agents) can be executed at post-processing start at the earliest, Edition Agents are representatives for the editions in the post-processing step. The Edition Agents' intention

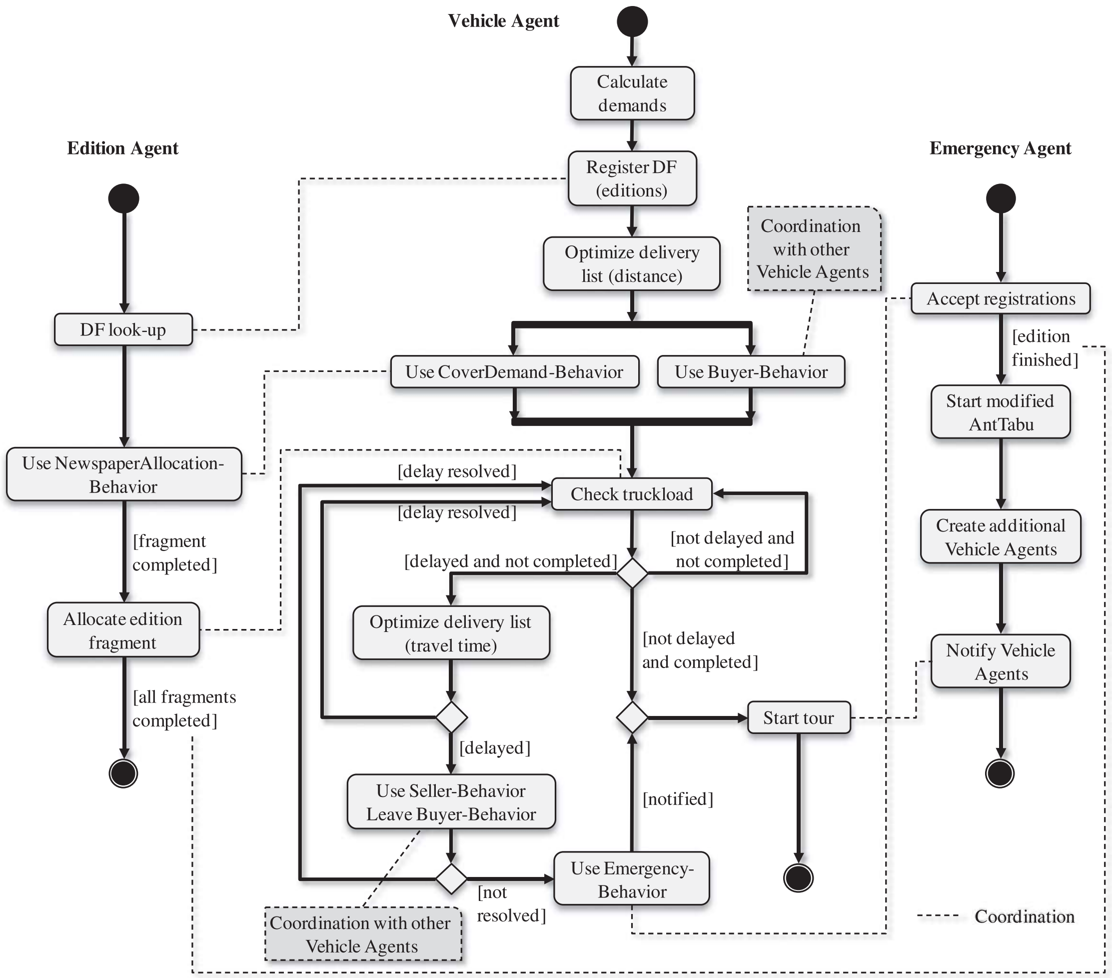

Fig. 6. Activity diagrams—Edition Agent/Vehicle Agent/Emergency Agent.

is the cooperative allocation of fragments to Vehicle Agents to realize early tour starts. As illustrated in Fig. 6, Edition Agents start with a look-up at the DF for all Vehicle Agents that require a fragment of their edition. This look-up is necessary for each Edition Agent in order to have knowledge about the existence of other agents. Next, the Edition Agents use the NewspaperAllocation-Behavior for the coordination with Vehicle Agents. Hereby, an Edition Agent communicates with all registered Vehicle Agents in order to optimize the allocation of edition fragments to them. The allocation has the aim of realizing earlier tour starts in order to maximize the Vehicle Agents' levels of service, whereupon a priority rule is used for scheduling the allocation of edition fragments (see Section 3.2.2 for a detailed description). After the computation of such a schedule, each Edition Agent sends the expected time of the allocation to the interested Vehicle Agent. This time can vary because of faster or slower production durations and disturbances, but gives the Vehicle Agents a rough point of time and therefore the chance to estimate tour starts if this is the last edition required to complete their truckloads. However, additional synchronization (see Section 3.2.2) between these two types of agents is necessary in order to maximize customer satisfaction. After an edition fragment is completed in the post-processing step, it is allocated to a Vehicle Agent (the associated vehicle is loaded) without the possibility of reversing the allocation. Edition Agents terminate when all edition fragments were allocated, i.e. when post-processing of the associated edition is finalized.

Emergency Agents (see Fig. 6 on the right) support Vehicle Agents, which are not able to supply their unloading points in time (i.e. which are not able to hit a minimal level of service ls_k^{min}). This support is realized by the use of flexibility (remaining vehicles after pre-optimization step). Hereby, the number of additional vehicles to be used has to be calculated, whereupon a careful utilization is necessary due to the limited total number of vehicles in the fleet. Each Emergency Agent is associated to one edition in the post-processing process and accepts registrations from Vehicle Agents which use the Emergency-Behavior (i.e. which want to start their vehicle route but still have to wait for the edition fragment the Emergency Agent is responsible for). The registration process ends when the associated edition is finished in post-processing. Therefore, the associated Edition Agent informs its Emergency Agent about its completion. After this message is received, the Emergency Agent uses one or more additional vehicle(s) in order to realize a higher service level for the registered Vehicle Agents and computes new vehicle routes with a modified version of AntTabu taking the registered vehicles' current routes and the additional vehicles into account. Hereby, the control parameter ls_k^{min} indirectly controls the number of additional vehicles to be used (the lower ls_k^{min}, the fewer vehicles have to be used). If this minimum level of service cannot be realized with the number of vehicles still available, the Emergency Agent has to use less additional vehicles and possibly fails to reach ls_k^{min} for each vehicle route. As the multi-agent system has the objectives of maximizing the level of service, minimizing transport costs and minimizing the number of vehicles, the Emergency Agents construct new vehicle routes following these objectives regarding this order. Hereby, the primary focus is on the minimization of the number of vehicles under consideration of ls_k^{min} in order to retain flexibility for all Emergency Agents which optimize vehicle routes at a later point of time. After the creation of vehicle routes, new Vehicle Agents are created and all participating Vehicle Agents are informed about their resulting vehicle routes and edition fragments are allocated. Finally, Vehicle Agents can start their tours.

3.2.2. Agents' behaviors and coordination between the agents

Coordination, including negotiation and communication, is an outstanding ability of multi-agent systems. Hereby agents' behaviors play an important role, representing tasks an agent can execute concurrently to other tasks (Bellifemine et al., 2007). As the tasks for the sale of unloading points to other agents, the allocation of editions to vehicles and the usage of additional vehicles are main components of the solution concept that have to be executed in parallel to other tasks, the related behaviors are described in detail as follows. Hereby, the questions concerning the coordination of agents' actions, communication channels and protocols are answered.

The objective of the *Seller-* and *Buyer-Behavior* is the sale of one or more unloading points from one Vehicle Agent to another suitable Vehicle Agent in order to realize higher service levels. In doing so, the Vehicle Agent selling an unloading point attempts to pass it to a Vehicle Agent which can supply it with minimum costs and in-time. Therefore, the Vehicle Agent, which wants to assign an unloading point, has to find another Vehicle Agent being able to supply it. This coordination is accomplished by means of the Contract Net Interaction Protocol (the main course of action is shown in Fig. 7 on the left). Before starting the coordination, the initiator/seller (Vehicle Agent using the Seller-Behavior) asks the DF for all Vehicle Agents that are interested in buying unloading points (participants with Buyer-Behavior). Next, the initiator calculates the most expensive unloading point (first unloading point to be sold) according to the antonym of the savings idea (Clarke and Wright, 1964). So, it sends a call for propose (cfp) message, including this unloading point, to all participants. Next, the participants check whether this unloading point can be inserted without violating capacity or time restrictions. If this is the case, a propose message including the costs for the exchange (again, the savings formula is used to calculate costs—the agents' "virtual currency") is sent to the initiator (if not, a refuse message is sent). The initiator then accepts the proposal with the lowest costs by sending an accept-proposal message, whereas all other proposals are rejected. Finally, the participant either transmits a failure notification (for instance if other unloading points were accepted in the meantime) or an inform announcement that the unloading point is accepted. The initiator restarts the protocol with the next most expensive unloading point if the sale could not solve the out-of-time problem, or with the same unloading point in case of a failure notification.

Both *NewspaperAllocation-* and *CoverDemand-Behavior* are used for negotiation between Edition and Vehicle Agents in order to realize an optimized allocation of edition fragments to vehicles. Hereby, the allocation faces the objective of maximizing the level of service. Therefore, each Edition Agent starts the negotiation with all Vehicle Agents registered at the DF at its post-processing start. At the beginning, the Edition Agent calculates its expected post-processing end and sends it to the Vehicle Agents. The Vehicle Agents are then capable to calculate their resulting ls_k (the agents' "virtual currency") and send this, as well as the number of editions they need to fulfill the demands and their latest possible tour starts, to the Edition Agent. Moreover, they tell the Edition Agent if this is the last edition to complete their truckload (critical edition). Next, the Edition Agent schedules allocations by comparing the Vehicle Agents' levels of service (i.e. delays), while also considering criticality as well as latest possible tour starts. As Vehicle Agents can start their tour immediately after allocation, critical demands are preferred. If several edition fragments are critical, a priority rule concerning levels of service is used—the Edition Agent privileges an allocation schedule which leads to a better over-all level of service. Hereby, the levels of service related to different allocation time proposals are calculated by the Vehicle Agents and communicated to the Edition Agent (which is then able to compute the best allocation schedule concerning ls by comparing the results). Finally, the Vehicle Agents are notified about the expected allocation time and the demanded edition fragments are allocated after their completion in the post-processing step. In addition to that, Vehicle Agents have the possibility to request an earlier allocation of an edition fragment

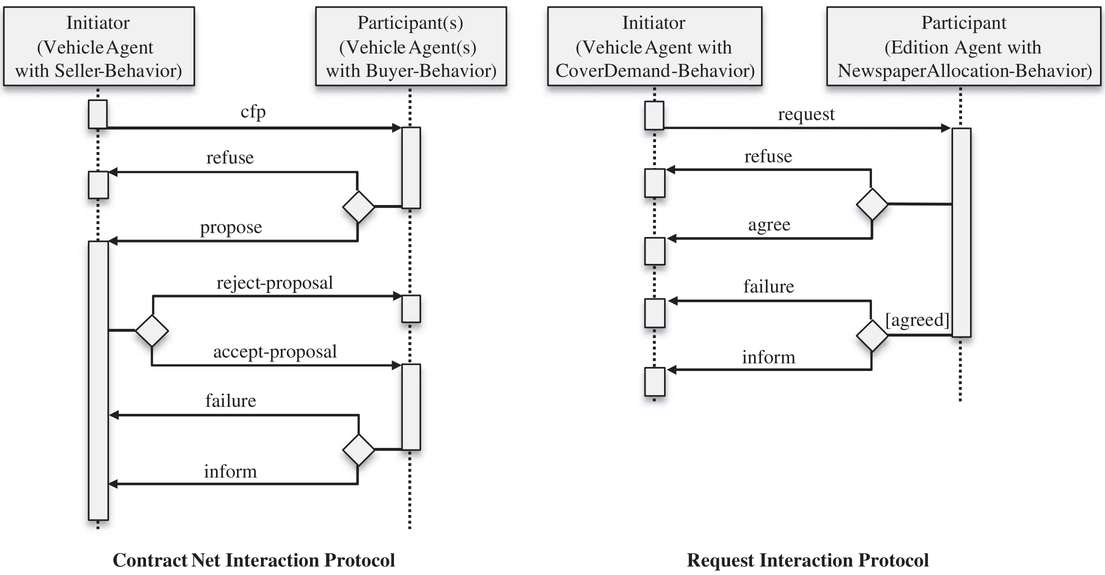

Fig. 7. Coordination between agents by means of protocols.

in order to start their tour earlier and thus to reach a higher ls_k. This is especially necessary as their tour start might change. Thus, coordination between the Vehicle Agent asking for an earlier allocation and the associated Edition Agent is necessary. This coordination uses the so-called Request Interaction Protocol and is shown in Fig. 7 on the right. First of all, the Vehicle Agent (the initiator of the coordination) sends a request message to the Edition Agent. This message contains the allocation time which is essential for the Vehicle Agent. Next, the Edition Agent reviews its allocation schedule, i.e. it checks whether other Vehicle Agents are able to accept a later allocation or not (on the basis of their latest tour starts). If this is not the case, it sends a refuse message to the Vehicle Agent. Otherwise, the Edition Agent agrees to the earlier allocation. In doing so, it has to inform other Vehicle Agents with a demand for its edition about the new expected allocation time. Finally, it either sends a failure message or informs the Vehicle Agent about the earlier (but still expected) time of the allocation.

The *Emergency-Behavior* is added to the Vehicle Agent's behavior list when the critical edition is allocated and neither travel time optimization nor Seller-Behavior can prevent delays in delivery. So, the Vehicle Agent registers itself concerning its critical edition at the responsible Emergency Agent. As described above, there is one Emergency Agent per edition being responsible for solving the conflict by adding one or more vehicles. In order to find out the optimal number of additional vehicles and to create new vehicle routes on the basis of the registered Vehicle Agents' delivery lists and the additional vehicle(s), an optimization is started when the post-processing step of the associated edition is finished. As there is little time for the computation of vehicle routes (vehicles have to leave the production site as early as possible and production is progressing), an efficient algorithm is needed. Therefore, a modified version of AntTabu is used for the online optimization of the vehicle routes to be considered. This version of AntTabu first of all calculates a vehicle routing plan by means of one ant in order to check if the number of vehicles still available at the current point of time is sufficient in order to reach ls_k^{min}. If this is not the case, ls_k^{min} is decreased (in order to guarantee supply, which is essential in practice) and another ant is used in order to calculate a vehicle routing plan. After computing a suitable ls_k^{min}, the main procedure of the modified AntTabu is executed. For efficiency reasons, this version consists of one ACO step (with only a few ants), a local search optimization step with TS (moves and swaps) and a post-optimization step with 2-opt. Hereby, ACO, TS and 2-opt are modified in order to react on the user's settings for ls_k^{min}, i.e. the algorithms allow vehicle routes which possibly do not keep time windows but have a service level equal to or higher than ls_k^{min} (if the number of vehicles available is sufficient). Moreover, the main objective of the modified AntTabu is to use additional vehicles as little as possible in order to gain a higher flexibility for vehicle routes that have a demand for editions which are still in the production process. The Emergency-Behavior ends with the notification of Vehicle Agents about their delivery list, i.e. when the associated Emergency Agent informs every Vehicle Agent about its vehicle route.

3.3. Software

To enable the utilization of the solution concept at hand, a software for the multi-agent-based solution concept for vehicle routing in the newspaper industry was implemented (see Fig. 8).

This application supports distribution planners in handling the complex problems with its underlying data and in solving the company's vehicle routing problem by means of the proposed solution method. It raises the claim to be used in a multitude of newspaper companies without high expenses for adaptation. This comprehensive software, which uses a multi-tier architecture, is named Newspaper Industry Distribution Optimization Software (*NIDOS*). It is implemented in Java and uses Hibernate for O/R-mapping as well as a MySQL-Server. The implementation of the multi-agent system is based on the Java Agent Development Framework *JADE* (by Bellifemine et al., 2007). This framework provides the possibility for implementing agent systems using the Foundation for Intelligent Physical Agents (*FIPA*) standard. Moreover, production and distribution schedules as well as the allocation of editions to vehicles are illustrated by means of Gantt

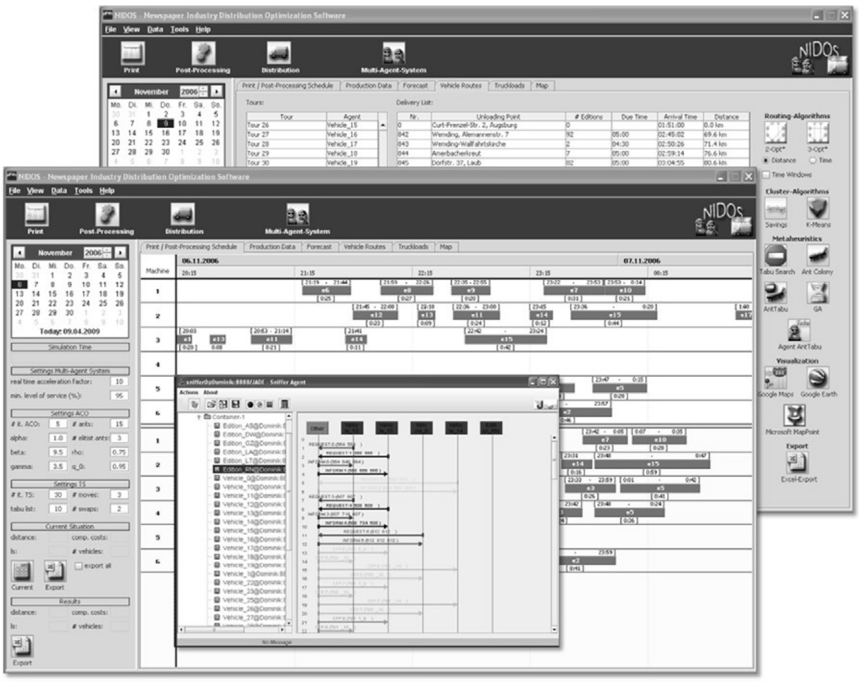

Fig. 8. Software NIDOS—graphical user interface.

charts. Vehicle routes can also be illustrated via a connection to *Google Earth*™, *Google Maps* or *Microsoft MapPoint*®. In order to provide an exact data basis for the optimization, the necessary distance and time matrices for the unloading points can be calculated by means of MapPoint. The main parameter for the multi-agent system is ls_k^{min}, which can be adjusted by distribution planners. The results concerning the application case, as illustrated in the following section, distinguish between three different settings for ls_k^{min}.

4. Application case and results

4.1. A German newspaper company

In this contribution, one of the largest German newspaper companies is considered as an example for the newspaper industry. It includes several editorial departments which are responsible for the content of 19 different editions. Moreover, the editorial departments account for the preparation of forecasts for the production schedules. Forecasts are arranged each production day depending on the quantity of topics the editorial departments wish to be included in the editions and past production schedules (e.g. midpoints for print durations and set-up times are known from the past). However, these forecasts are quite imprecise because in many cases latest news shall be included or print/post-processing problems inhibit production. The 19 editions are produced on six parallel rotary print presses located at one production site. The post-processing step, consisting of six mechanical inserters, is directly connected to the print process. After inserting pre-prints and advertising supplements, the newspapers are allocated to currently 61 homogeneous vehicles executing tours with altogether 1425 determined unloading points to supply newspaper carriers (several newspaper carriers per unloading point distribute a total of 325,000 newspapers each day). All vehicles start their tours at the production site, delivering several different editions on about 300 days per year. Additionally, capacity restrictions of 2.8 tons per vehicle and one-sided time windows have to be kept. The company assesses variable delivery costs of €1.00 per km and carrier compensation costs of €0.20 per minute of delay and per newspaper carrier. As the company uses the same vehicle routes each day, the current distance of 8540.7 km causes daily transport costs of €8540.70 (€341,628.00 in total concerning the 40 contemplated days). Moreover, current compensation costs range between €46.60 and €3065.40 on the days to be optimized (€29,890.20 in total). On these days, the level of service ls is between 82.22% and 99.76% (an average of 95.44%).

4.2. Results

The evaluation is accomplished by means of 40 representative production days, including days with early completion times, days with drastic delays as well as ordinary production days (compare Fig. 3). For that purpose, the resulting variable costs, the optimized levels of service as well as the required vehicles are compared to the newspaper company's current schedules on these production days.

A sole optimization of the 40 production days with AntTabu (static VRPTWCD) based on forecasts would lead to a reduction of variable costs of 28.5% and an increase of levels of service to 100% (+4.56 percentage points) on average (if the forecasts were accurate). Moreover, the number of vehicles in use could be reduced by on average 20 vehicles each day (−32.79%). However, these results are based on forecasts which are of low quality: If these resulting vehicle routing plans were accomplished, higher costs (+5.24%) and lower levels of service (−11.98 percentage points) in comparison to the current situation would arise. Due to the fact that the usage of the multi-agent system without pre-optimization step results in up to eight additional vehicles which are required for achieving a high customer satisfaction (see Böhnlein, 2008), the high flexibility (through saving vehicles) involved by AntTabu is inevitable in order to avoid an extension of the current vehicle fleet. Consequently, the usage of the considered multi-agent-based solution concept in combination with AntTabu as a pre-optimization step is inevitable. The optimization with the multi-agent system is subdivided into three different parameter settings for ls_k^{min}. In the following, the results associated to the settings $ls_k^{min} = 95\%$, 98% and 100% are denoted in exactly this order.

The *variable costs* are decreased by €64,067.57 (−17.24%), €59,109.30 (−15.91%) and €65,339.20 (−17.59%). Although deviations between the different settings are quite small, there are several reasons for these results. On the one hand, the usage of a higher ls_k^{min} leads, in most cases, to lower carrier compensation costs. This is due to the fact that Vehicle Agents are allowed to start their tours if ls_k^{min} can be realized, although not all unloading points are expected to be supplied in time. Moreover, the Emergency Agents create vehicle routes with a lower number of vehicles, but with higher carrier compensation costs when a lower ls_k^{min} is used. On the other hand, a higher ls_k^{min} has negative effects on the costs associated to the distance traveled. The reason for this difference is, e.g. the lower flexibility of the Emergency Agents at a late point of time when a high ls_k^{min} has to be achieved. This effect of the parameter ls_k^{min} on the variable costs can be identified by means of the chart (see Fig. 9 on the left): A high ls_k^{min} can lead to a bottleneck concerning the remaining number of

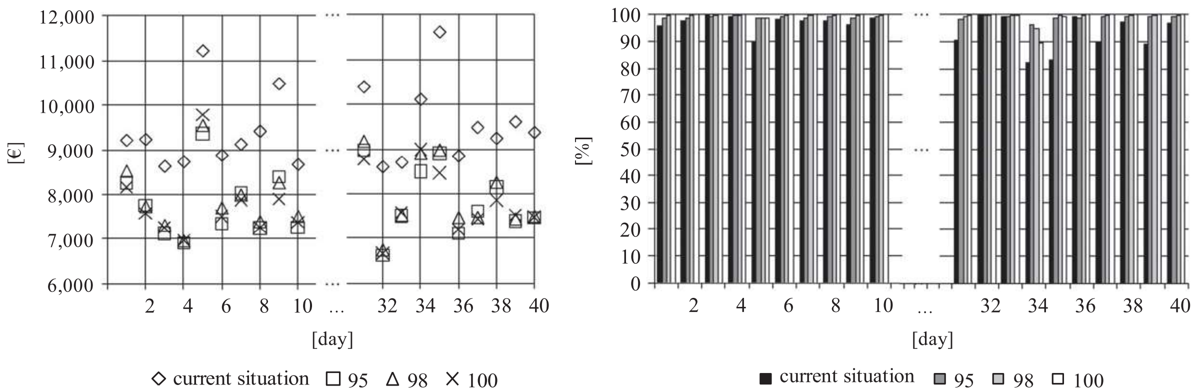

Fig. 9. Results—variable costs and levels of service.

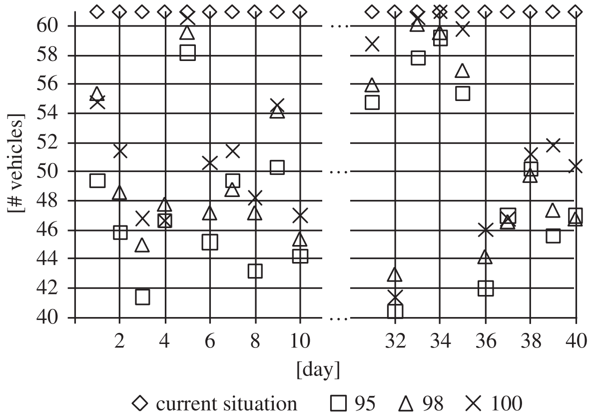

Fig. 10. Results—number of vehicles.

vehicles in the fleet. This can lead to high carrier compensation costs or high distances and thus to high variable costs as, e.g. shown on optimization days 5 and 34.

The current *level of service* of 95.44% is increased to 98.99%, 99.54% and 99.67% (see right chart in Fig. 9). However, the usage of a higher ls_k^{min} does not necessarily result in a higher level of service on every day because the number of vehicles in the fleet is restricted. This is for instance shown on optimization day 34 (see right chart in Fig. 9), on which levels of service of 96.30%, 94.64% and 89.51% can be reached. Hence, the bottleneck concerning the number of vehicles in the fleet is the reason for the suboptimal level of service associated to $ls_k^{min} = 100\%$. Editions are completed with a drastic delay on this day and Emergency Agents nevertheless try to reach $ls_k^{min} = 100\%$, resulting in an insufficient number of vehicles for Emergency Agents associated to editions which are produced at a later point of time.

The *number of vehicles* in use can be reduced to 47.51 (−22.12%), 49.45 (−18.93%) and 51.08 (−16.26%) vehicles. On almost each day, a higher value for ls_k^{min} results in a higher number of vehicles in use due to the necessity of realizing a higher service level. The flexibility through additional vehicles realized by a pre-optimization is especially needed on optimization days with a low level of service. For instance, on days 5 and 34 (see Fig. 10), which currently have a level of service of 89.94% and 82.22%, respectively, almost all remaining vehicles are required for increasing the level of service.

Summarizing, the results depend in each case on the settings of the parameter ls_k^{min}. A higher ls_k^{min} leads, in most cases, to better levels of service and to lower carrier compensation costs, whereas a lower ls_k^{min} results in lower distances as well as in fewer vehicles required. Consequently, the newspaper company using NIDOS needs to configure ls_k^{min}, depending on the focus of the company. If delays are expected in advance, it is recommended to use a lower ls_k^{min} to avoid the problems concerning scarceness of vehicles, which cause low service levels and high carrier compensation costs. Finally, a comparison with the sole optimization by means of AntTabu shows that the weakness of an optimization on the basis of pre-defined production schedules (forecasts) can be eliminated by the presented multi-agent system.

5. Conclusion

The described multi-agent-based solution concept and software NIDOS for the online optimization of transport processes under consideration of production schedules and delivery due times contributes to current research concerning the newspaper industry and transport problems. As production schedules in this industry are strongly varying and as distribution is directly connected to production, the sole solution with a metaheuristic based on production forecasts can even lead to worse results compared to the current situation. It becomes obvious that the development of a multi-agent-system involves an efficient solution concept for the newspaper industry's static and dynamic VRPTWCD. This solution concept comprises a distributed problem solver and thus higher flexibility as well as the opportunity of managing the complexity of the underlying vehicle routing problem with time windows and cluster-dependent tour starts. The capability of agents allows a synchronous pursuance of the objectives of minimizing variable distribution costs and maximizing customer satisfaction as well as the sensible use of vehicles in the fleet. Therefore, new techniques are designed within the multi-agent system, such as the negotiation between Edition and Vehicle Agents concerning the allocation of editions to vehicles as well as the sale of unloading points among Vehicle Agents to realize in-time delivery. Additionally, the online execution of a subversion of the meta-heuristic AntTabu by so-called Emergency Agents increases delivery reliability through the usage of vehicles which are saved by a static pre-optimization step. Besides the Emergency Agents, which are responsible for the administration of vehicles (flexibility), some other agents are designed: The AntTabu Coordination Agent and several AntTabu Agents realize the static pre-optimization with AntTabu. Edition Agents, which are representatives for an edition in the production process, coordinate the allocation of edition fragments with Vehicle Agents, which are themselves representatives for vehicles in the distribution process and are responsible for an in-time supply of newspapers with minimal costs. The application of this system to one of the largest German newspaper companies proofs adequate as the results are promising: variable costs are decreased by 15.91% up to 17.59% (depending on the chosen ls_k^{min}) concerning 40 optimized days. The level of service, an indicator for customer satisfaction, is increased by on average 3.55 to 4.23 percentage points and the number of vehicles in use can be reduced by 16.26% to 22.12%. As the results of this solution concept in the newspaper industry are impressive, future research should consider the adaptation to other industrial sectors, e.g. the automotive sector where just-in-time inventory implicates the need for a strong connection to suppliers (Kros et al., 2006).

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