INVESTIGATIONS ON OBJECT-CENTERED ROUTING IN DYNAMIC ENVIRONMENTS: ALGORITHMIC FRAMEWORK AND INITIAL NUMERICAL RESULTS

Support for Distributed Decision Making in Transport Systems

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Abstract: Dynamics in logistics are a subject of increasing importance in logistic processes. The more detailed dynamics are considered, the more complicated it becomes to handle them in centralized planning. Therefore, decentralized approaches with autonomous cooperating entities might become more efficient.
This paper introduces some aspects of decentralized approaches, mainly focusing on the process of information acquisition which enables the autonomous entities to decide about the handling of routes and orders.

1 INTRODUCTION

The consideration of so-called *dynamics* which are process relevant up-to-date and so far not known information appearing consecutively and unpredictably with ongoing time, is of increasing importance for the management of transport processes in today's logistic systems.

Two aspects of dynamics are recognized. At first, transport networks are formed temporarily and by independent parties each providing an own subnetwork. A centralized knowledge about the complete network is typically not available. Secondly, a very huge amount of up to date information that is exploited in the management of the transport processes requiring frequent process updates and adaptations in order to keep the transport quality on a maximum efficient level.

The application of centralized planning approaches is impossible. Decision support systems have to be able to support an object-centered planning, in which several autonomous objects have to be coordinated instead of determining the exact process for each vehicle.

In Section 2, an example of such a scenario is introduced. Section 3 is about the configuration of generic algorithmic support for the decentralized routing and the proposed decision support is assessed within a simulation study in Section 4.

2 CHALLENGE OUTLINE

This section is dedicated to the outline of the decision situation we are dealing with. Subsection 2.1 provides a short survey about the relevant streams in the scientific literature. The investigated network is introduced in Subsection 2.2. An explicit scenario is shown in Subsection 2.3.

2.1 Literature

Two general approaches for coping with dynamics in routing have been discussed in the scientific literature.

In *a-priori optimization* a set of a-priori-paths is determined in advance that visits all possible customer sites (Powell et al., 1995). The a-priori-paths have the least expected costs among all possible paths. If determining the paths, probability distributions about the need for visiting a particular customer site are exploited. The a-priori-routes are then updated and adapted to the real need, e.g. if it turns

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out that a customer site does not need to be visited, it might be skipped from the a-priori-route but the visiting order of the remaining requests is not subject to alternation. A-priori-optimization-based approaches require the knowledge about a suitable probability distribution.

In *reactive routing* approaches, only known problem data about customer sites and the network structure are considered during the generation of routes. After an event has been detected that corrupts the realization of the so far followed routes, a new route generation is carried out. Route-update times are determined in advance in *rolling horizon planning* (Bitran and Tirupati, 1993), but in *online planning* (Irani et al., 2004; Fiat and Woeginger, 1998), a new planning is executed every time a new event appears that contradicts the execution of the so far valid routes. (Langer et al., 2007) investigate different algorithmic paradigms for their ability to support a quick and reliable decision making in dynamic routing.

Impacts of autonomously made decisions in a network are analysed and evaluated in (Roughgarden, 2005).

2.2 Dynamic Network Routing Challenge

A transport system is considered that is used to fulfil transport demands using a collection of vehicles. The demand is expressed by customer requests which are specified consecutively over time. Since the vehicles are allowed to decide autonomously about their operations, a centralized planning model/solver combination cannot be deployed to tackle the problem.

As soon as a new request r is waiting to be scheduled, the existing autonomously deciding vehicles check whether and how they are able to fulfil this request. In case that the vehicle v is interested to fulfill this request it generates a route proposal $r(v) = (n_{v_1}, \ldots, n_{v_{N(v,r)}})$ satisfying the following constraints.

1. Neither the vehicle capacity is exceeded nor request associated time windows are violated and
2. the vehicle returns to its home base not later than a given time.

It is specified that a vehicle does not formulate a proposal for request r when it is not able to fulfil this request satisfying the two conditions mentioned above.

The vehicles' proposals then are compared and the best proposal (according to current decision criteria) is executed.

Beside additional requests, varying transshipment or pickup as well as unloading times might be considered as a source of dynamics. Furthermore, traffic congestions influence the travel time required for using a connection between two adjacent locations.

Let t denote the time in which an event becomes known that requires a new route determination. The underlying graph in which a route has to be determined is defined as $\mathcal{G}(t) := (\mathcal{N}(t), \mathcal{A}(t), \mathcal{D}(t))$. The node set $\mathcal{N}(t) := \mathcal{N}^f \cup \mathcal{N}^V(t)$ consists of the static set of network locations $\mathcal{N}^f$ and the current vehicle positions collected in $\mathcal{N}^V(t)$. The nodes are connected by the arcs collected in $\mathcal{A}(t)$ (some arcs might also represent roads that are temporarily closed). The evaluation of a route proposal is done by applying the evaluation function $\mathcal{D}(t)$ to the nodes and arcs involved in the considered route. The evaluation has to be performed for each route proposal individually as the travel times are not constant, but may vary with ongoing time t due to traffic congestions and high workload in the pickup or delivery nodes.

The request r released at time t requires the transport of a good of a certain capacity c_r from a pickup location $p_r^+ \in \mathcal{G}(t)$ to a delivery location $p_r^- \in \mathcal{G}(t)$. A route proposal has to start at the current vehicle position, passing p_r^+ and afterwards p_r^- and terminating at a node in $\mathcal{G}(t)$. Therefore, for each vehicle a constrained shortest path problem in $\mathcal{G}(t)$ has to be solved (Köhler et al., 2005).

2.3 Scenario Description

The scenario used here for the investigation of dynamic logistic networks is based on a map of Germany. 18 major german cities have been selected as nodes in the network, and edges are defined according to main highway connections as depicted in Figure 1. At each of the nodes, transport orders for goods of unit size are generated randomly during runtime, and the generation rate is dependent on the size of the city, ranging from 2 orders per hour in Kassel to 34 orders per hour in Berlin. A basic version of this scenario has been described in (Wenning et al., 2007), the version used here has some slight modifications, which are a different amount and distribution of vehicles and the occurence of traffic jams which is described in section 4.2.

The vehicles in this scenario have a capacity of 60 size units and a travel time limit of 8 hours before returning to their home location. This implies they cannot cross the whole map, and transshipments are required for transport orders that have to cover a long distance. The amount as well as the distribution of vehicles is subject to alteration between simulation runs in order to increase the efficiency of transport processes.

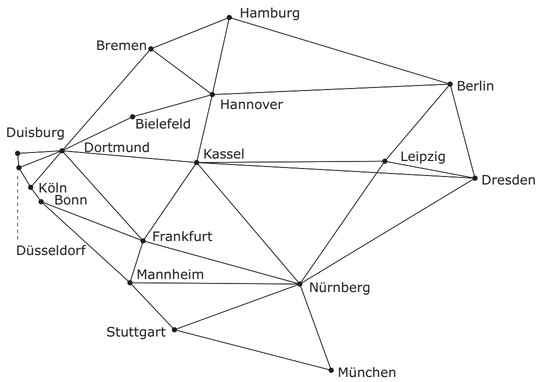

Figure 1: The simulated transport network.

3 ALGORITHMIC APPROACH

The configuration of a reactive route finding procedure is subject of this section. Since the events that cause the update of the routes and the generation of new proposals do not follow any known probability distribution, an a-priori-optimization is far away from applicability so that only a reaction on a route-corruption event remains as a remedy.

The application of existing shortest path detecting algorithms is compromised by the different constraints that restrict the set of realizable routes in the considered scenario. In order to apply for example Dijkstra-based methods to identify a feasible route, a network pre-processing has to be carried out that requires the knowledge of the complete network. As stated in the introductory section, this assumption is not valid and consequently, another approach has to be used.

As it is assumed that probability distributions for the considered events are not known to the components of the dynamic scenario, routes have to be determined reactively. Therefore, a reactive two-step route proposal generation is carried out. In the first step, possible routes to the designated termination node of the vehicle's route are identified using a network broadcasting method. In the second step, all route options are evaluated and the highest valued route is selected as the proposal of the considered vehicle (Subsection 3.1). For the explicit scenario introduced in 2.3, a special configuration for this algorithm idea is proposed (Subsection 3.2).

3.1 Route Request / Route Reply - Methods

In the approach proposed here, a distributed routing based on reactive mechanisms from communication networks is transferred to the application in logistics. The vehicles need to collect information on the current network structure in order to make reasonable and sensible routing decisions. Here, each node in the network only knows its adjacent nodes but other information is not available (cf. Section 1). In particular, this is information about the links (arcs) to the adjacent nodes and available waiting packages at the nodes corresponding to so far unserved requests.

The access to this information is similar to the route discovery mechanisms in ad hoc networks, for example in Dynamic Source Routing (DSR) (Johnson and Maltz, 1996): The initiator (in this case a vehicle) sends a request to its adjacent node. From there, this request is propagated to the neighbour nodes. Each node adds some of its local knowledge about the current status to the request so that the request is accumulating information as it propagates. When it has reached a termination node, a reply is generated containing all information that was collected on the way and is sent back to the initiator. The initiator compares the identified routes and selects the most appropriate one as its route proposal.

In the example illustrated in Fig. 2, the vehicle waiting at node S needs a route to node T through the current network $\mathcal{G}(t)$ (which, in this example, is specified by the solid arcs and the nodes S, 1, 2, 3 and T). It starts the route discovery process by sending a route request to S, which broadcasts it to its neighbours. In the considered example, it sends the request to node 1 (dotted line) and to node 2 (dashed line). Neither 1 nor 2 coincide with the target node T so that 1 as well as 2 forward the request to their neighbour 3. Again, 3 is not the target node and both incoming requests are proceeded to the next neighbour now reaching the target node T. Two routes from S to T are found: route A (S-1-3-T) and route B (S-2-3-T). T now sends a reply to each of the requests, integrating information that was added by the intermediate nodes during the request forwarding phase.

The numbers in brackets represent the evaluation values $\mathcal{D}(t)$ for passing the associated arc or node. Therefore, route A is evaluated by 5+0+2+0+7=14 and route B is evaluated by 6+0+4+0+7=17. Route A would become the proposal of the considered vehicle if the evaluation values represent costs.

3.2 Configuration

In the simulation experiments described in the next section, the vehicles in the scenario apply a routing method that is derived from source routing approaches in communication networks, such as the aforementioned DSR. The knowledge about transport

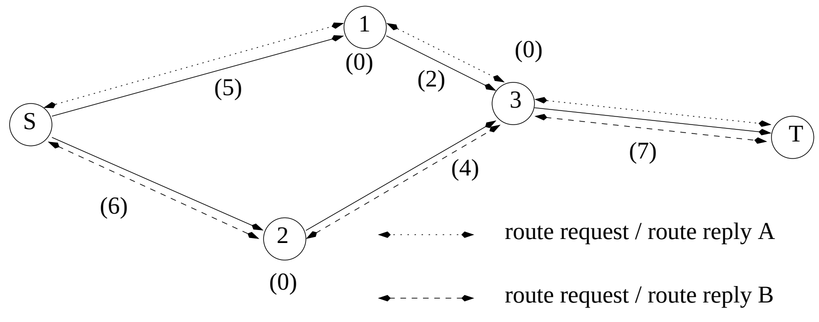

Figure 2: Example for route request / route reply.

orders is limited to the locally available orders, and knowledge about the network, especially estimated travel times, are collected from distant nodes using the described route request/route reply methods.

Before starting the routing process, a destination node has to be found. The determination of this destination node is done by counting the destinations of the local transport orders and selecting the node as destination that is most frequently requested. After having obtained a route by receiving route replys, the vehicle evaluates whether it is possible to cover the route completely within its time constraints. If this is not possible, the route is shortened up to a length that does not violate the vehicle's time constraints. The most distant node then becomes a transshipment location for the transport order.

4 NUMERICAL EXPERIMENTS

Results achieved from numerical experiments are reported in this section. Initially, the experimental setup is stated (Subsection 4.1). Afterwards, some numerical results are presented and discussed (Subsection 4.2).

4.1 Experimental Setup

The simulation is done with the help of a simulation environment developed for the simulation of autonomous controlled logistics. This environment is based on the Communication Networks Class Library (CNCL), which is a discrete-event simulation library originally intended for simulation of communication networks and, with some extensions, is now also used for the simulation of logistics. A more detailed description of the simulation environment is given in (Becker et al., 2006).

The simulation scenario is specified as described in section 2.3, the vehicles are selecting their routes, according to the description in 3.2, by determining the most requested destination and discovering a route with the aforementioned route discovery scheme.

4.2 Presentation and Discussion of the Results

This section presents results of simulations of three different variations of the scenario with respect to dynamics, especially traffic jams:

1. Free traffic flow, i.e. no traffic jams are present for the whole simulation time.
2. Traffic jams appear randomly between Hannover and Kassel with a jam probability of 0.2 and an average vehicle delay of 1.5 hours when being stuck in a traffic jam. The vehicles have no knowledge about the traffic jams.
3. Same as 2. except for the vehicles having knowledge about the traffic jams.

Figure 3 graphically shows the traffic flow in the first case. No traffic jams are present, and some main connections can be identified. 20 vehicles are the minimum amount which is necessary to handle the transport demand in this case, and their average capacity utilisation is 57.5%.

In the second case, traffic jams are introduced on a central and highly utilized part of the road network, the connection between Hannover and Kassel. As the vehicles had no knowledge of the traffic jams, they were planning their routes as if all roads were free. The effect was that, when the number of vehicles was not changed, some locations in the network were not served frequently enough any more, causing the complete scenario to become unstable with continuously growing package stocks and delivery delays. To counteract this effect, the number of vehicles in the scenario had to be increased to 23, while their capacity

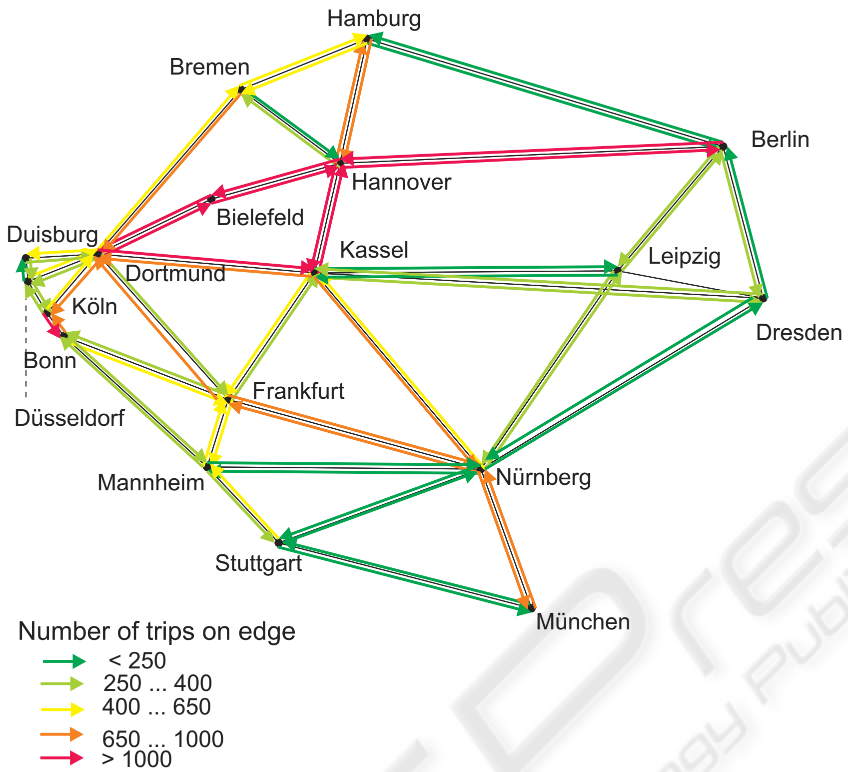

Figure 3: Usage of edges without appearance of traffic jams.

utilisation went down to 50.1%. Figure 4 shows the traffic flow in this scenario. It can be seen that there is more traffic in the northern/northwestern part of the map, which matches the fact that all additional vehicles were added to the Hamburg node.

When, in case 3, the vehicles had knowledge about the jams, it was possible to reduce the number of required vehicles back to 20, resulting in traffic flows very similar to Figure 3 again, yet with a slightly higher vehicle capacity utilisation than without the traffic jams (58.1% vs. 57.5%). This proves the knowledge about current dynamics improves the performance of object-centric routing in the scenario. It enables the vehicles to adapt their routing to the changed road conditions, thus improving the efficiency of the overall system.

The results shown here are initial results for one approach to implement autonomous control into logistic components. There are other approaches which have been investigated (Wenning et al., 2006) or are currently under investigation, all of them based on the idea of transferring concepts from communication networks to logistics.

5 CONCLUSIONS AND OUTLOOK

This paper has introduced important aspects of a decentralized planning approach for logistics. This approach relies on a mechanism that collects information about the current state of the dynamic environment similarly to route discovery processes in communication networks. It has been shown in simulation results that knowledge about the current state improves the performance of the logistic system by utilising resources more efficiently.

The authors are currently continuing their research on object-centered routing in several directions: besides the further work on suitable algorithms, one focus is to achieve comparability to traditional logistical routing approaches, another is to even include the load as active participant with decision capabilities in the routing process.

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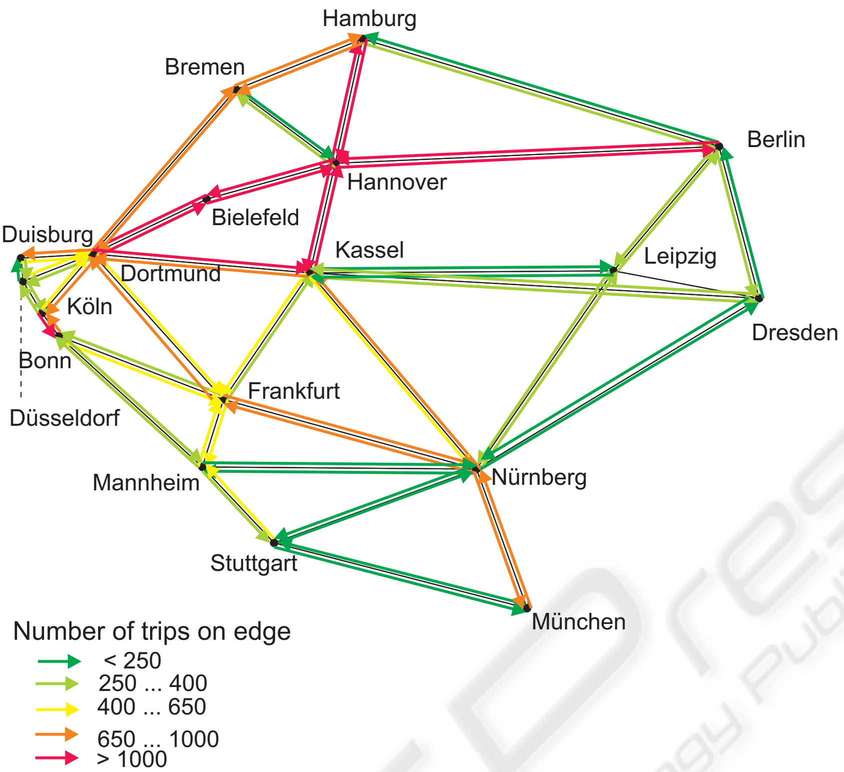

Figure 4: Usage of edges: occurance of jams, but not known by the vehicles.

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