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A decision support system for cooperative transportation planning: Design, implementation, and performance assessment

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ABSTRACT

In this paper, we describe a decision support system for cooperative transportation planning in the German food industry where several manufacturing companies share their fleets to reduce transportation costs. Besides using vehicles of their fleets, there are different outsourcing options offered by logistics service providers, but these are much more expensive. The decision-making kernel of the decision support system is implemented as a multi-agent-system (MAS). The kernel provides a distributed hierarchical algorithm for cooperative transportation planning and an on-line data layer that contains all the information for decision making. We sketch the distributed hierarchical transportation planning algorithm and identity the required software agents. The MAS interacts via web services with a commercial tour planning system that persistently stores the resulting tour plans, orders, and customer data. Moreover, the tour planning system is used to offer graphical user interfaces to interact with the users. The data layer is updated by order and customer data from the ERP systems of the different manufacturing companies. We describe the architecture and the implementation of the MAS and the overall coupling framework. Furthermore, we discuss the simulation-based performance assessment of the resulting decision support system when the system is applied in a rolling horizon setting and present some computational results. The results demonstrate that the MAS approach is appropriate for the cooperative transportation planning domain.

1. Introduction

According to Toth and Vigo (2002) vehicle routing problems (VRPs) are very important in real-world environments. From a computational point of view, these problems are NP-hard. Some MAS approaches are suggested in the literature to solve VRPs, because frequent disturbances occur in this domain (cf. Mahr, Srour, de Weerdt, & Zuidwijk, 2008) and the decision making is often based on distributed data. In the present paper, we describe a decision support system for a cooperative transportation planning scenario in the German food industry. Manufacturers with complementary food products but overlapping customers use together their vehicle fleets. Rich VRPs with time windows for delivering the orders to the customers, maximum operating times for the vehicles, capacity constraints for the vehicles, and outsourcing options are obtained after a hierarchical decomposition of the transportation problem into appropriate subproblems. The researched cooperative transportation planning problem is at the same time academically challenging and highly relevant from a practical point of view because large cost savings can be obtained when the manufacturers cooperate. At the same time, besides a pure algorithmic perspective, new requirements arise for a corresponding decision support system from the fact that several companies and decision makers are involved in the solution of the cooperative transportation planning problem. In this paper, we describe important steps towards the design and the implementation of a decision support system for cooperative transportation planning that allows for a parallel computation of the resulting VRPs. Optimization problems in vehicle routing are prospective candidates for recent parallel computing efforts because of their complexity and relevance (cf. Schulz, Hasle, Brodtkorb, & Hagen, 2013). In addition, we assess the performance of the implemented prototype in a rolling setting fully considering the stochasticity of the transportation network. It is an important stream in recent VRP research to take into account the stochastic behavior of the network (cf. Pillac, Gendreau, Guéret, & Medaglia, 2013).

Several heuristics for cooperative transportation planning problems are proposed by the present authors (cf. Sprenger & Mönch, 2012). However, this paper focuses on the design of appropriate decision support systems. The iCoMAS prototype is proposed. We will show that a MAS approach for the researched cooperative

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transportation planning problem allows for an efficient computation of the subproblems. In addition, the MAS is able to work with the local data that is available for each of the partners of the cooperation. Software agents can be used to represent the objectives of the different decision-making entities. Our research effort goes in line with the strong need for autonomy and decentralized decision making in current logistics systems as shown by Kopfer and Schönberger (2011). The structure of the resulting decision support system is decoupled from the planning algorithms applying the ideas of decision-making and staff agents from the Product Resource Order Staff Architecture (PROSA) (cf. Van Brussel, Wyns, Valckenaers, Bongaerts, & Peeters, 1998).

The contribution of this paper is two-fold. From a theory-related point of view, this paper applies and refines the general-purpose principles of distributed hierarchical decision making to the cooperative transportation planning domain. We present a two-level distributed hierarchical approach. This approach includes a novel exchange procedure for orders among the different entities of the base level to ensure an ex post coordination.

From a more practical point of view, we contribute to the literature by presenting design principles for the related decision support system. To the best of our knowledge, there is no decision support system described in the literature that deals with cooperative transportation planning situations. The rare exception is (Sprenger & Mönch, 2011) where the decision-making kernel for a corresponding decision support system based on software agents is briefly sketched.

The present paper, however, is a considerably extended version of this conference paper. It includes a rather complete requirement analysis. We derive distributed hierarchies in cooperative transportation from the general framework of distributed decision making proposed by Schneeweiss (2003). Based on this foundation, we present an extended version of the distributed hierarchical planning approach that is the main ingredient of the resulting decision support system. In addition, we describe the coupling architecture with a commercial tour planning system. While in (Sprenger & Mönch, 2011) only some very preliminary computational results are presented, we include the results of a full simulation study in the present paper. In addition, the findings from a simple field test are discussed.

The remainder of this paper is organized as follows. We describe the cooperative transportation planning problem in Section 2. In addition, requirements for the researched decision support system are derived. Related work is discussed in Section 3. The design and the implementation of the proposed decision support system for cooperative transportation planning situations are presented in Section 4. This includes a description of the distributed hierarchical transportation planning algorithm. Section 5 provides some simulation results with the MAS prototype.

2. Cooperative transportation domain

2.1. Domain description

In this research, a transportation network is assumed that consists of a set of customers $c \in C$, a set of food manufacturers, and intermediate distribution centers $i \in I$. Each food manufacturer runs a main manufacturing location $m \in M$. Express companies are utilized to operate the intermediate distribution centers. Far-away vehicles of the manufactures are possible at the intermediate transportation centers. If a differentiation between manufacturing locations and intermediate distribution centers is not important, we use the term distribution location $d \in DL$ for both types of locations, i.e. $DL := M \cup I$. Distribution locations can deliver orders to customers. The set of all locations $L := DL \cup C$ form the nodes of the transportation network. Weighted arcs are used to connect the nodes. The weights are given by the distance between the two locations that correspond to the two nodes of an arc.

Each manufacturer runs vehicles $v \in V$. They are located in the distribution locations that belong to the manufacturer. Each vehicle v offers a maximum available volume and a maximum operating time per day. A daily availability window is assigned to each distribution location. The vehicles can only operate within this time window.

We consider transportation orders $o \in O$. They are available for delivery at time r_o at the food manufacturer $m_o \in M$. A time window $w_o := [l_o, u_o]$ belongs to order o. The order o has to be served in w_o. This means that l_o and u_o is the earliest and latest point of time to finish the delivery of order o. The vehicle waits until l_o before the delivery can start if the vehicle arrives before l_o. The time window of the order has to be included in the availability window of the distribution location. Each customer order has a prescribed volume. Due to the time windows of the orders, there is some flexibility in the point of time when the transportation is started, denoted as transportation day σ.

We find three types of transportation in the non-cooperative setting (cf. Sprenger & Mönch, 2012) for a single manufacturer:

1. Deliveries that are carried out by own local vehicles at the main manufacturing location of the manufacturer form the first type.
2. The following two steps are used for the second type.
   (a) In a first step, orders are transported from the manufacturing location of the manufacturer to an intermediate distribution center by an express company $e \in E$. We assume that the manufacturer runs at least one far-away vehicle at the target intermediate distribution center. This transportation option is called indirect.
   (b) In a second step, orders are delivered to the customers utilizing far-away vehicles of the manufacturer.
3. The third type is given by directly transport orders from a main manufacturing location to a customer by an express company.

Transportation option 1 is the cheapest one due to the utilization of own vehicles. Express companies transport the orders overnight. Consequently, the customer orders arrive in the next morning before the distribution location starts to work. The third option, i.e. the direct transport by an express company, is the most expensive option. A direct transport is initiated in the evening after closing of the corresponding distribution location. When the arrival time is not within the availability window of the distribution location, the delivery can only start at the next opening. The non-cooperative transportation types are shown for a single manufacturer in Fig. 1.

We can distinguish two more cooperative transportation options for a given manufacturer:

4. A transport by an express company to a manufacturing location of a manufacturer different from the given manufacturer provides the first additional option. After this indirect transportation is performed, a type 1-transportation by vehicles of the second manufacturer is carried out.
5. The second additional cooperative option is an indirect transport by an express company to an intermediate distribution center. At least one of the manufacturers different from the given manufacturer has to operate vehicles at the target immediate distribution center. An additional type 2(b)-transport is carried out after this indirect transportation step.

The different cooperative transportation options are summarized for two cooperating manufacturers in Fig. 2. Analyzing the