1 Introduction

The research presented has been developed at the Chair of Transportation Systems and Logistic[1] at the Department of Mechanical Engineering at the Technische Universität Dortmund and the Fraunhofer-Institute for Material Flow and Logistics[2]. The research project "Dynamic Tour and Trip Planning in Freight Forwarding Companies" was supported by the Graduate School of Production Engineering and Logistics[3] and funded by the state of North Rhine-Westphalia[4]. Within the scope of the project collaborations with forwarding agencies took place to improve the operative route planning operations. The objective is the development of approaches increasing service and vehicle utilization, which are applicable in practice. In the following background information about vehicle routing in general and the pickup and delivery problem specifically is given. Further, the motivation, the objective, and the approach as well as the structure of the thesis including it's relevance to science and practice are presented.

1.1 Background

Forwarding agencies transporting less-than-truckload (LTL) freight are subject to intense competition. The domestic LTL markets in many countries are mature markets, especially in Germany [KK07, p. 93]. Still, the volume of goods transported is growing due to the general growth of the economy, but a market concentration can be observed. Additionally, growing operating costs combined with low transport prices result in low profit margins. This is particularly challenging for small and medium-sized companies. Some companies and co-operations report operating margins of four percent and more, but other companies and co-operations do not appear that profitable at present [KK07, p. 93].

In practice, forwarding agencies try to lower the increasing pressure of the market conditions by gaining competitive advantages through methodical optimization of processes and by using cutting-edge technology. The focus in science and practice is on strategic areas, for example, the optimization of transport networks, and on operative areas, for

[1] Technische Universität Dortmund, Fakultät Maschinenbau, Lehrstuhl für Verkehrssysteme und −logistik, Leonhard-Euler-Straße 2, 44227 Dortmund, Germany

[2] Fraunhofer Institut für Materialfluss und Logistik, Joseph-von-Fraunhofer-Str. 2-4, 44227 Dortmund, Germany

[3] Graduate School of Production Engineering and Logistics, Leonhard-Euler Straße 5, 44227 Dortmund, Germany

[4] Staatskanzlei des Landes Nordrhein-Westfalen, Stadttor 1, 40219 Düsseldorf, Germany

2 Logistics of Forwarding Agencies

The following describes processes of forwarding agencies handling LTL freight or grouped freight. The chapters' purpose is to explain background, terms and operations of the industry handling LTL freight. Therefore, at first essential information about the freight forwarding industry are presented in Section 2.1. After stating some background information, the networks and operations of forwarding companies are described in detail in Section 2.2. At last Section 2.3 depicts planning tasks and problems encountered in route planning processes.

2.1 Information about the Freight Forwarding Industry

In the global economy, which is based on the division of labor, transport and logistics are essential for the international competitiveness. Without smooth logistic processes the globalization of markets would be limited. Logistic processes are increasingly complex and manifold due to spatial divided production processes. Additionally, the economic growth is responsible for an increased transport volume. For instance, the transport performance will grow by approximately 30 percent to the year 2030 [VDAb]. The bigger part of the increasing transport volume will affect the road. In 2000 about 65 percent of all freight traffic has been transported on the road and this portion is assumed to increase even more [Gie01]. Especially the development of the turnovers in e-commerce in business to business (B2B) and business to customer (B2C) are growing, though the focus is still on B2B [SPJ01, pp. 232]. As more and more physical articles are sold electronically or online, these goods have to be distributed physically as well [SPJ01, pp. 241].

In only 10 years, from 1995 to 2005, the road transport in Europe increased by about 40 percent. Alone in the years from 2000 to 2005 the transport performance in Germany increased by about 14 percent (Figure 2.1 [VDAa], [VDAb]). Against the background of this increasing transport volume, efficient vehicle routing gains importance. Changes in the shipment structure result in smaller amounts to be sent with each shipment, less bulk articles and, therefore, higher frequencies of deliveries to customers. For example, a growing number of customer orders in the Internet and the articles are directly delivered to their homes (e-commerce) [Rom05].

Germany is a transit land within Europe and has with 12,000 km the longest interstate network in the European Union [Wal06, p. 20]. About one quarter of all transports of the European Union is conducted within Germany [Wal06, p. 36]. In 2006 the freight traffic

3 State of the Art of Science and Technology

Optimal or near-optimal solutions can be computed for small or medium-sized static instances of the traveling salesman problem or the vehicle routing problem. One reason for this is the increased computational power, but far more important are the considerable algorithmic advances in this field. Yet, new challenges from practice emerge regarding stochastic and dynamic optimization, but still the number of contributions to static routing problems, like the vehicle routing problem, is by far greater than those dealing with stochastic or dynamic problems.

At first, the issue of obtaining reliable traffic data is introduced (Section 3.1). Thereafter, a general introduction to routing problems is given (Section 3.2). In the following two types of models are differentiated. On the one hand, these are models based on data known in advance, including probabilistic and stochastic models. Problems dealing with such information conduct the route planning prior to the route execution, thus, the problems are referred to as a priori models. On the other hand, real-time optimization models are able to process new information every time it becomes available and, therefore, are able to handle dynamic data and to evaluate situations in real-time. Thereafter, the integration of time dependent travel times (Section 3.3), dynamic customer orders (Section 3.4), and of both (Section 3.5) are depicted. These sections describe existing approaches as well as problem specific challenges in modeling.

3.1 Technology and Traffic

Usually the travel times between two points in congested areas are not constant. Especially fluctuations in travel speed result in varying travel times. The subsequent paragraphs introduce the state of the art to supply routing systems with travel times. For a better understanding different traffic states are presented and then contents of traffic notices are evaluated. Helling differentiates four groups influencing the effect of travel times and information advantages: Market relevant conditions (e.g., consumer acceptance, distribution, compliance of driving instructions), technical conditions (e.g., digital maps, locating, dynamic sampling, route calculation), traffic conditions (e.g., network load: obstructions or slow-downs, network density: alternative routes), effects by notice quality and dynamic sampling (e.g., loss of time) [Hel06, pp. 36].

4 Formulation of the Mathematical Optimization Model

Scheduling tasks in forwarding agencies are complex and challenging. Section 4.1 gives detailed information about the aspects, which have to be considered in a model realistically representing the scheduling task. Section 4.2 describes generally aspects considered for the derivation of the model. Further, the evaluation of time dependent models (i.e., travel times on the edges are time dependent) and the measurement of different degrees of dynamism also in terms of customer location and the daytime of arrival are of interest. Thereafter, Section 4.3 gives the discrete formulation of the model. The formulation is developed with the objective to consider a priori data and forecasts for pickup locations and traffic development.

4.1 Optimization Task

The scheduling problem of forwarding agencies is best represented in a directed graph. Therefore, it is helpful to consider the different problem specific attributes. These and their parameter values are relevant for the solution process (i.e., they are influencing the selection of the solution strategy). The parameter specifications colored in Table 4.1 are the ones used in the model. Individual input data (e.g., customer orders or travel times) can be stochastic or deterministic. In the former case orders are, for example, only known with a certain probability or not known at all at the beginning of the planning. Dynamic planning situations have the characteristic that the tour end often is open, requiring a different direction of optimization. It is also possible that the demand of existing orders changes. In this context it is neither reasonable nor practicable to reschedule every order, if the majority of vehicles already travels to customers. Independent of the data type this problem can be solved with different numbers of depots. Forwarding agencies usually have a fixed customer depot assignment with one depot.

PDPs of forwarding agencies might depend on the vehicle type (e.g., special loading and unloading equipment) and it is advantageous that such restrictions can be integrated later on. The number of vehicles as well as the capacity is typically limited, thereby "fuzzy" means that each additional vehicle or the driving time violations are allowed, but penalized with a certain factor. The transition matrix may be symmetrical or asymmetrical as well as two or more dimensional. In the latter case there is more than one

5 Development of an Integrated Solution Approach

The general procedural method developed to solve the dynamic pickup and delivery problem rests upon a concept presented by Kolb also known as the Kolb Cycle. In-depth examination of learning processes led to the concept of the Kolb Cycle, which is basically a four-stage cycle: Concrete experience is followed by observation and reflection, which is succeeded by the formation of abstract concepts and by testing implications of these concepts in new situations, which in turn leads to new experiences. This process is a continuous spiral, that is, the learning cycle is continuously recurring [KOR95, pp. 49]. Generally, the learning cycle can begin at any one of the four steps (Figure 5.1).[1] A modified version of the learning cycle is used for the development of a solution approach due to good personal experiences with the application of the learning cycle. After creating a general concept and model, experiments or actions are performed. The resulting experience will be used to understand and reflect what happened in the particular instance. This allows performing adjustments at theory and model.

The complexity entails that the problem formulation given in Section 4.3 can only be solved optimally for small test instances with mathematical optimization software. Considering the recent literature this is not surprising (cf. Chapter 3). PDPs are as important and interesting from both a practical and a theoretical point of view as VRPs, but the latter are studied considerably more intensive in literature than pickup and delivery problems. Still, the experiments show that time windows complicate routing problems tremendously. Even finding feasible, let alone optimal, solutions is $\mathcal{NP}$-hard. Additionally, dynamic models are even more difficult to solve so that they are often solved as a sequence of static problems [SS95].

Therefore, new methods and measures are necessary to speed up the solving process. The recent developments of models and (meta-)heuristics for a priori and dynamic data often rest upon originally static methods, which are very sophisticated through intense research over the years. Some originate from the field of mathematics and operations research while others have their source in the field of computer science. For example,

[1] Remark: The direction that learning takes depends on the personal needs and objectives. For instance, a person might seek experiences related to the personal goals; therefore, the process of learning is inefficient when personal objectives are not clear. Moreover, learning styles are highly individual in both direction and process. Some emphasize abstract concepts whereas others favor observation or application; hence, each learning style has weak points and strong points.

6 Computational Experiments

The tabu search approach for time dependent and dynamic settings is tested by computational experiments. Appropriate instances for the dynamic pickup and delivery problem do not exist and are derived in Section 6.1. Thereafter, Section 6.2 gives the model parameters determined and fine tuned with the attention on the trade-off between computation time and solution quality. Subsequent tests to analyze the behavior of the tabu search are presented. Results and performance of different test scenarios are evaluated, before the same computational analysis is performed for the operational data.

6.1 Data Preparation

For the classical VRP numerous test instances exist (e.g., like [GDDS95]) and some data sets exist for pickup and delivery problems, but these are insufficient for evaluating either the PDP of forwarding agencies or dynamic problems. Therefore, new test instances are generated based on the well known Solomon instances including pickup and dynamic related characteristics. Solomon generated 6 sets of problems with 100 customers each, which give with different parameter settings 56 instances incorporating several factors affecting the behavior of routing and scheduling algorithms [Sol09]:

- Geographical data
- Number of customers serviced by a vehicle
- Percentage of time-constrained customers
- Tightness and positioning of the time windows

Within instances of type R (R1 and R2) customers are distributed randomly within the service region, in problem sets of type C (C1 and C2) the customer locations are clustered, and problem sets of type RC (RC1 and RC2) are a mix of random and clustered customers. The customer coordinates are identical for problems of the same type, except for C1 and C2. The data structure is visualized in Figure 6.1 revealing the characteristics of the geographical data. Problem sets ending on 1 have a short scheduling horizon and allow approximately only 5 to 10 customers per route. In contrast, the other sets ending on 2 have a long scheduling horizon permitting generally more than 30 customers in one route. The width of the time windows is different, that is, some have very tight time

7 Conclusion

Relevant processes and crucial problems of forwarding agencies are introduced and described (Chapters 1 and 2). Solving these problems requires a new approach, that is, models suiting pickup and delivery problems of forwarding agencies considering varying travel times and dynamic orders. Especially no work addressing the generalization and extension of pickup and delivery problems of forwarding agencies to integrate time dependent travel times and unknown customer orders is available (Chapter 3). Practical experiences and this lack of solutions addressing the problem motivate this research. At first an optimization model representing all important restrictions and requirements that solves the static problem optimally is introduced (Chapter 4), but the dynamic setting, applicability, and, most important, the solving time demands a faster method. A tabu search approach is developed and extended to include time dependent travel times using time zones and anticipating unknown orders using customer clusters (Chapter 5). Finally, the developed tabu search is tested successfully (Chapter 6). In this chapter the discussion and a summary of the results is given in Section 7.1 and some future research directions with the emphasis on forwarding agencies are highlighted in Section 7.2.

7.1 Discussion of Results

The enhanced definition of the degree of dynamism rather less reflects the development of lateness. The results are more influenced by the characteristics of the input data. By the majority the customer structure (e.g., randomly distributed or clustered), the capacity, the length of the planning horizon, and the width of the individual time windows dominate the performance. The degree of dynamism helps though to explain variances in the performance of similar data sets with different parameter settings, for example, identifying data sets with tight time windows and a greater risk of lateness.

Evaluation and critical acclaim of all results of the developed tabu search with realized travel times show that improvements with universally valid time zones are possible. It is appropriate to use a travel time factor to model increased travel times for all customer distributions, though the effects diminish the more the customers are clustered. Overall, time dependent travel times are advantageous even though occasionally more vehicles are needed and total travel times increase slightly, but the objective, the reduction of late deliveries, is almost always achieved and usually the additional costs are covered by the avoided late deliveries.