STELLINGEN

 behorende bij het proefschrift

 An Adaptive
 Trip Planning Support
 Environment

 Richard de Jong

 7 april 1992
I

Indien een organisatie de verschillen die zich voordoen tussen de geplande en de werkelijke uitvoering van het produktieproces wil verkleinen, dan ligt het niet voor de hand het model voor het voorspellen van planuitvoeringen te verfijnen door middel van het verzamelen en analyseren van een grote hoeveelheid gegevens. Het verhogen van de planbaarheid van het produktieproces middels organisatorische ingrepen heeft vaak een gunstiger effect. Dit proefschrift.

II

Voor het succesvol ontwerpen van informatiesystemen voor de ondersteuning van operationele planning kan de ontwerper niet volstaan met het afnemen van interviews en het observeren van het planningsproces, maar dient deze ook zelf de uitvoering van plannen van nabij mee te maken. Dit geeft inzicht in hetgeen gepland dient te worden en kweekt een begrip van de wijze waarop plannen worden uitgevoerd. Dit proefschrift.

III

Het toepassen van hedendaagse logistieke concepten binnen een organisatie, waarbij vaak logistieke samenwerking en keten-denken een rol spelen, vraagt in toenemende mate om inzicht in de procesgang in andere organisaties en de afstemming hierop van de werkzaamheden in de eigen organisatie. Dynamisch modelleren (1) voor het geven van genoemd inzicht en het beoordelen van veranderingsvoorstellen zal als gevolg hiervan in veel organisaties nuttig kunnen worden toegepast.


IV

De effektiviteit van geautomatiseerde ondersteuning voor het ontwerpen van informatiesystemen zal toenemen als - uitgaande van het feit dat het ontwerpen in ieder van de afzonderlijke ontwerpfasen een proces van probleem-oplossen is - de gereedschappen ondersteuning bieden in alle stappen waaruit dit proces bestaat, te weten beeldvorming en specificatie, het genereren van oplossingen en het kiezen van een oplossing (2).

V

Het Nederlandse verkeersbeleid dat gericht is op het afremmen en ombuigen van de verwachte groei van het personenautoverkeer tot in het begin van de 21e eeuw zou goede perspectieven bieden, ware het niet dat deze groei zich op verschillende plaatsen al heeft gerealiseerd en nog verder zal doorzetten. Een heroverweging van het beleid lijkt hiertoe op zijn plaats.

VI

Teneinde de prominente rol van Rotterdam als doorvoerhaven te waarborgen, is het gewenst om voor de lange termijn te werken aan een uitbreiding van het aandeel van de binnenscheepvaart en het treinverkeer, maar dient daarnaast op korte termijn een uitbreiding van de wegeninfrastructuur voor een congestie-vrije ontsluiting van het achterland te worden gerealiseerd.

VII

Het sterk uitbreiden van het aantal produkten door beleggingsinstellingen leidt binnen deze instellingen tot een verschuiving van de nadruk op beleggingsexpertise naar productmarketing. Bovendien verschuift de verantwoordelijkheid in het behalen van een hoog rendement meer naar de klant.

VIII

Gezien de complexiteit van problemen van maatschappelijke aard en de veelheid van disciplines die ingebracht dienen te worden om tot een goede afweging van keuzes te komen, moet het referendum meer worden gezien als een instrument dat bijdraagt aan een betere acceptatie van besluiten dan dat het tot betere oplossingen voor bovengenoemde problemen leidt.

IX

Het veelvuldig voorkomende probleem dat binnen een sportvereniging te weinig leden zich beschikbaar stellen voor een uitvoerende kaderfunctie kan opgelost worden door de verantwoordelijkheid voor het leveren van kader binnen de teams te leggen.
AN ADAPTIVE
TRIP PLANNING SUPPORT
ENVIRONMENT
AN ADAPTIVE
TRIP PLANNING SUPPORT
ENVIRONMENT

proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft
op gezag van de Rector Magnificus,
Prof. drs. P.A. Schenck,
in het openbaar te verdedigen
ten overstaan van een commissie
aangewezen door het College van Dekanen
op dinsdag 7 april, 1992 te 14.00 uur

door

Richard de Jong

informatica ingenieur

geboren te Rotterdam
Dit proefschrift is goedgekeurd door de promotoren:

Prof. dr. H.G. Sol
Prof. dr. ir. R. Hamerslag

en door de leden van de promotiecommissie:

Prof. ir. A.J.M. Beulens
Prof. drs. B.K. Brussaard
Prof. dr. A.R. van Goor
Prof. dr. ir. P. van der Veer
"Complete information is only possible within simplistic concepts of reality. That we are charmed and fascinated by it, should prompt questions about its feasibility, justification, and desirability" (Straub and Angell, 1991).

To my parents
Published and distributed by R. de Jong, P.O. Box 356, 2600 AJ Delft, The Netherlands

Cover design by J.C. Baris

CIP-GEGEVENS KONINKLIJKE BIBLIOTHEEK, DEN HAAG

Jong, Richard de

An adaptive trip planning support environment / Richard de Jong. - [S.l. : s.n.]. - Ill.
ISBN 90-9004903-7
Trefw.: logistiek ; informatiesystemen.

© 1992 R. de Jong

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the author.
Contents

Preface ................................................................................. ix

1 Background and Research Approach
   1.1 Introduction .............................................................. 1
   1.2 Planning Support Environments .................................. 5
   1.3 Research Questions and Research Approach ................. 10
   1.4 Outline of the Thesis .................................................. 14

2 Physical Distribution in Retail Trade Organizations
   2.1 Introduction .............................................................. 17
   2.2 Physical Distribution System ...................................... 19
   2.3 Transportation Characteristics ................................... 23
   2.4 Summary and Conclusions ......................................... 26

3 Vehicle Routing and Scheduling Support
   3.1 Introduction .............................................................. 29
   3.2 Modelling Vehicle Routing and Scheduling Problems .... 31
   3.3 Modelling Road Networks ......................................... 35
   3.4 Information Systems for Vehicle Routing and Scheduling . 38
   3.5 Summary and Conclusions ......................................... 42

4 Trip Planning: Perceived Situation
   4.1 Introduction .............................................................. 45
   4.2 RetailCo: A Retail Trade Organization ......................... 46
   4.3 Trip Planning at RetailCo ........................................... 52
   4.4 Trip Planning in Retail Trade Organizations ................... 58
5 Trip Planning: Proposed Situation
5.1 Introduction ........................................... 61
5.2 Layout of the Planning Support Environment .......... 62
5.3 Trip Execution Model .................................. 64
5.4 Construction of a Trip Execution Model ............... 72
5.5 Tactical Trip Planning ................................ 80
5.6 Operational Trip Planning .............................. 85
5.7 Summary and Conclusions .............................. 89

6 Prototype Implementations
6.1 Introduction ........................................... 91
6.2 Trip Execution Modeller ................................ 91
6.3 Trip Execution Simulator ............................... 99

7 Using the Planning Support Environment
7.1 Introduction ........................................... 107
7.2 Construction of a Trip Execution Model ............... 108
7.3 Validation of the Trip Execution Model ................ 123
7.4 Comparison of Trip Execution Models ................ 128
7.5 Evaluation of Tactical Trip Planning .................. 132
7.6 Evaluation of Operational Trip Planning .............. 136
7.7 Summary and Conclusions .............................. 138

8 Epilogue
8.1 Introduction ........................................... 141
8.2 Conclusions Related to Adaptive Trip Planning ....... 142
8.3 Conclusions Related to Planning Support Environments .... 145
8.4 Future Research ....................................... 146

References ............................................... 149

Index ......................................................... 159

Samenvatting ............................................. 163

Curriculum Vitae ......................................... 169

viii
Preface

When transporting goods, the punctuality of their delivery is becoming increasingly important in today’s business logistics. High levels of delivery reliability can only be achieved by valid planning models for the prediction of trip durations. This thesis concentrates on the feedback of trip data which are used to update the planning model. It also presents the application of trip execution simulation to assess the effects of changes in the transportation process. Both may contribute to improve the punctuality.

Many persons have supported me greatly in producing this thesis. I wish to thank my advisors, Henk Sol and Rudi Hamerslag, in the first place. I thank Henk Sol for the opportunity he has given me and for his continuous and inspiring advice. I owe Rudi Hamerslag for our regular discussions, and for raising my interest in applying information systems to traffic engineering. Acknowledgements are also due to the RetailCo company for offering me a case environment and hospitality for several years. Thanks go to Jan Verharen, Lou Peerdien, Boudewijn Caninus, and all the others involved. A number of students of the Information Systems department at Delft University of Technology assisted me enthusiastically in the research: Dennis Marck, Erwin Gravesteyn, and Peter Allemekinders. I would like to mention the Kongsj society, especially Remko Dur and Paul Motshagen, for demonstrating what colleagues can mean, and the Tipsy society where planning support ideas were discussed frankly and critically. Most of all, I wish to thank my parents and my brother for their great support and commitment.

Rotterdam
February 1992

Richard de Jong
1

Background and Research Approach

1.1 Introduction

A glance at the main roads of the Netherlands at any place and time definitely supports the statement that road transportation is a service industry of considerable economic importance. Several thousands of trucks make trips every day in order to transport goods. In 1989, about 7 thousand trucking companies owned a total of 50 thousand trucks, required for the transportation of 301 million tons of goods. Moreover, 154 million tons of goods were transported by company-owned trucking services (KNV, 1991). The above numbers indeed indicate quite a substantial service industry, although characterized by a large number of small companies and by a diversity of disjunct sub-markets ranging from local parcel post services to international full truckload services (Kamphuis, 1984, pp. 427-428).

Transportation in general is not only significant if totals on the transported tons of goods are presented, but also if the relative share of transportation costs in product costs is taken into account. A frequently quoted breakdown of product costs reports that 22% of these costs are related to distribution, and that 23% of the distribution costs represent transportation (Van Goor, 1986, p. 16 and p. 31). These percentages are only averages, so the values in certain businesses are even higher.
Besides, the costs for transportation cannot be considered in isolation from the other distribution costs (e.g. inventory costs) due to trade-off relationships existing between these costs categories (Ballou, 1985, pp. 16-17 and p. 29).

Vehicle routing and scheduling

A company owning trucks must control the usage of its fleet: transportation orders have to be assigned to trucks, and a route along the customers and a time schedule for the trip must be specified for each truck. This planning task is called vehicle routing and scheduling, in literature. According to Frowein (1990, pp. 60-61) it should be regarded as a principal task, often recurring daily, in trucking services because truck fleet performance depends heavily on the quality of the plans.

During the last three decades, vehicle routing and scheduling has proven to be a fruitful field for scientific research. The report by Bodin et al. (1983) provides a comprehensive survey of the historical developments in this area. The initial attention was concentrated on finding optimal mathematical solutions for pure routing problems. Later on, algorithms were developed which could handle more realistic problems by taking several real world aspects into account, for instance, maximum trip duration. Nowadays, interactive planning systems are being developed and used. The support of vehicle routing and scheduling is described in more detail in chapter 3.

The task specify time schedules is a primary task in vehicle routing and scheduling. A time schedule defines the times at which activities during a trip must start and finish, such as arrival and departure times at customer locations. The purpose is to specify time schedules meeting the time constraints, such as the earliest arrival and latest departure times at customer locations. Time constraints exist, for example, due to customer requirements or local ordinances (EVO, 1986). Meeting time constraints not only requires that the planning system - whether computerized or not - can deal with these, but also that the planning system contains a model of the trip execution calculating the trip durations correctly. If such a trip execution model is unavailable, deviations between the time schedule and the real trip duration are likely to occur, which may cause the scheduling efforts to be worthless.

Specifying adequate time schedules is difficult but important, as illustrated by the discussion between Tilanus and Tichelaar. Tilanus (1989) argues that estimating trip durations and therefore fine planning is hardly possible because of the large number of factors which can disturb the trip execution. He describes a day
of piece-goods distribution, and indicates a 3 hour delay on a trip of 14 hours, caused by customers requiring extra unloading time, customers refusing to accept goods, and traffic congestion. Eventually, some customer visits had to be canceled at the end of a day. Tijchellaar (1990) finds that calculating trip durations is necessary, however. He not only mentions fine planning as a reason, but also trip costing, and the required social policy towards the drivers.

The following two trends demonstrate the importance of time schedule specification within vehicle routing and scheduling. We will describe both briefly here, and in more detail in chapter 2. Firstly, there is a trend towards putting higher demands on delivery reliability in business logistics, which is defined as the conformity between the planned and the real delivery time. Many companies are striving to reduce their inventory levels, and consequently require deliveries at higher frequency and reliability rates (Ruijgrok, 1991, pp. 18-25). The measurement of delivery reliability used to take place in units of weeks or days. It is becoming general practice nowadays to allow a slack in delivery time of only a few hours in order to streamline the product flow through the organization. For this reason, trucking services are faced with many time constraints. Although difficult to accomplish, these constraints have to be met, as "repeated surveys have shown that average delivery time and delivery time variability rank at the top as important transportation performance characteristics", cf. Ballou (1985, p. 181).

Secondly, there is the manifest trend towards more traffic congestion on the road network in the Netherlands. Due to traffic growth and the limited road network capacity, the frequency of congestions increases, and so does the resulting average delay. Unless radical and widespread measures are taken, traffic - and hence traffic congestion - will boost in the next decades (McKinsey, 1986; SVV2, 1990). Delays caused by traffic congestion have a negative influence on the delivery reliability of trucking services. Therefore, the impact of traffic congestions should be anticipated during vehicle routing and scheduling as far as possible.

Putting high demands on the specification of time schedules is especially poignant for the supply of retail food stores. According to Van Vlerken (1989), in food retail trade organizations, the distribution to the stores is essential, and advanced distribution systems are required. Time constraints for visits to the stores are usual in this business (Kok, 1988b, p. 257). Furthermore, the above trends do relate to this business. We will confine our research to food retail trade organizations, of which the characteristics will be described in detail in chapter 2.
Time constraints for supplying retail stores are usually expressed in quarters of an hour rather than hours. For this reason, we prefer to differentiate between delivery reliability and delivery punctuality. We define delivery reliability as the likelihood of goods being delivered during a certain trip, and delivery punctuality as the agreement between the planned and real times of a store visit. A punctual delivery takes place in accordance with the planned times. We will also call a time schedule punctual if it agrees well with the real trip duration.

We can conclude that the time schedule specification in vehicle routing and scheduling for retail food trade organizations is increasingly important. An adequate model for calculating trip durations as well as support for the specification of time schedules meeting the time constraints are required to carry out this task effectively. However, this requirement is often not fulfilled.

Opportunities for computerized planning support

There are many directions for conducting research if we take the above discussion as a starting point. We could study alternative logistic structures in order to relax the need for time constraints, but we could also study the way to reduce traffic congestion, so that the specification of punctual time schedules is made easier. Following our background in the information systems discipline, we will seek enhancements by making use of computerized information systems.

The above description on vehicle routing and scheduling suggests two areas in which computerized information systems in retail trade organizations could be worthwhile. Firstly, trip execution monitoring and replanning is impossible while the stores are replenished. Passino and Antsaklis (1989, pp. 19-21) define such situations as open-loop planning, generally requiring a detailed model of the problem domain in real world planning situations. Detailing of the model is meant to reduce the uncertainty about the future state of the problem domain, in order to keep deviations between plan and reality small. Following this line of argumentation, a detailed model for calculating trip durations could be valuable. The construction of a detailed trip execution model requires insight into the executed trips, with historic trip data and computerized analysis support.

Secondly, once a detailed trip execution model is available, it can be used for time schedule specification. This task in vehicle routing and scheduling includes the calculation of store visit durations, followed by a check whether the time
constraints are met. Interactive planning systems for vehicle routing and scheduling are available (see chapter 3). However, the trend towards high demands on punctuality certainly requires additional computerized planning support.

Personal conversations indicate that the idea of using historic trip data to improve the performance of vehicle routing and scheduling is widely accepted in the road transport industry, but that it is only rarely applied. We suggest that making appropriate computerized planning support available to vehicle routing and scheduling, based on historic trip data, is helpful in overcoming the constraints effectively.

We shall introduce the theoretical starting points in the remainder of this chapter, and describe the organization of the research project. Section 1.2 gives an overview of the computerized planning support theory. The research questions and the research approach are presented in section 1.3. Finally, the thesis is outlined in section 1.4.

1.2 Planning Support Environments

We used the phrase computerized planning support in the previous section, without providing a proper definition. It was used to indicate that computerized applications can support planning problems, such as vehicle routing and scheduling. In this section we postulate our theoretical starting points by discussing parts of the theory dealing with computerized planning support. We shall introduce the concept of a Planning Support Environment (PSE) by addressing the subjects of planning, decision support, and environment.

Planning

Planning is defined in many ways in literature, varying from a limited to a broad set of tasks. We follow Takkenberg (1983, p. 28), who defines planning as executing tasks leading to a plan which specifies a coherent set of decisions, aimed at the execution of certain activities and the realization of certain objectives. Hence, planning deals with altering the future state of a problem domain.

We will discuss the aspects of organizational planning relevant to the concept of
a PSE below. To clarify these aspects, we will apply the information paradigm as described by Brussaard and Tas (1980, p. 822) to vehicle routing and scheduling. The information paradigm states that a dynamic system (e.g. an organization) can be abstracted to a Real System (RS) and an Information System (IS), where the purpose of the IS is to plan and control the behaviour of the RS. The environment of the RS/IS combination comprises matters not managed by the IS. An IS manages by monitoring the state of the RS as well as the relevant parts of the environment (the problem domain as we call it), processing the information received, and sending messages to the RS causing its state to change. The IS describes the problem domain in the past, present, and/or future. The information paradigm includes the recursion principle, which stipulates that it is also valid for subsystems, i.e. RSs and ISs can be described as RS/IS combinations themselves. The recursion principle can be applied both inwardly and outwardly.

Figure 1-1 shows the way the information paradigm can be applied to vehicle routing and scheduling. The real system (TRIP EXECUTION) consists of trucks transporting goods from origin to destination locations. Vehicle routing and scheduling takes place in the information system (OPERATIONAL TRIP PLANNING). The information system receives transportation orders, plans truck exploitation, and sends trip instructions to the real system. Figure 1-1 is discussed further below to clarify aspects of organizational planning.

Organizational planning usually takes place within a hierarchy of planning levels. Anthony (1965) mentions, for example, strategic, tactical, and operational planning. Planning levels differ with regard to the organizational level of responsibility, scope of issues addressed, degree of detail, and the planning horizon. Higher planning levels provide objectives and constraints for lower planning levels. Figure 1-1 shows a higher planning level (TACTICAL TRIP PLANNING), which is obtained by applying the recursion principle outwardly.

The lowest planning level in a planning hierarchy specifies the framework for the execution of the operational activities. At this planning level, indicated as scheduling and dispatching by Hirshfeld (1983, p. 74), the specific activities or sequence of activities to be performed with existing facilities are determined, to meet specific output requirements in the next operational period. We will call the lowest planning level operational, and the next higher planning level tactical. Vehicle routing and scheduling is an instance of operational planning. In developing a PSE for an operational planning situation, the tactical planning level should also be taken into account.
Figure 1-1 RS/IS-combinations of vehicle routing and scheduling.

The problem domain of an organizational planning situation is not stationary. Nowadays, organizations are faced with a turbulent environment, which means that the environment of the organization changes rapidly, and with a low predictability, as pointed out by Huber and McDaniel (1986, p. 577). Both changes in the organizational environment and the higher planning levels responding to these changes result in the problem domain of an operational planning situation transforming over time. Maintaining the usefulness of a PSE requires adaptation to these transformations. For this reason, a PSE for operational planning should be easy to adapt. We will concentrate on the adaptation of the problem domain model within a PSE.
Organizational planning is strongly related to the organizational function control. We follow Davis and Olson (1984, p. 300), who define control as measuring deviations from the plans, and initiating corrective actions. Figure 1-1, for example, shows flows with trip data and management information, both meant to exert control. We identify two types of control: direct feedback and adaptive feedback. Direct feedback consists of measuring deviations from the plan, followed by initiating corrective actions affecting the plan execution, for instance by replanning. Direct feedback is a means for handling uncertainty about the future state of the problem domain. Adaptive feedback is complementary to direct feedback, and includes initiating modifications in the way of planning or even remodelling the real system. The purpose of adaptive feedback is to adapt to transformations in the the problem domain. The above-mentioned adaptation of the problem domain model is an example hereof. If feasible, a PSE for operational planning should support both types of feedback.

Decision support

Organizational planning can be regarded as solving ill-structured problems. According to Sol (1982, pp. 5-6), a problem is ill-structured if it fails on one or more of the following properties:

- the set of action alternatives or solutions is finite and limited;
- the solutions are consistently derived from a model of the problem situation corresponding well to reality;
- the effectiveness and/or the efficiency of the action alternatives can be explicitly (e.g. numerically) evaluated.

Applying information technology to solve ill-structured problems is known as the research field of Decision Support Systems (DSSs). Research efforts relating to DSSs have been immense in the last few decades.

In the early 1960s, many organizations started to use computerized information systems. The first Transaction Processsing Systems (TPSs) were built in order to automate massive routine administrative tasks. A TPS typically gathers, updates and presents large amounts of data according to strictly predefined procedures with a high degree of efficiency.
Sec. 1.2 Planning Support Environments

In the late 1960s, Management Information Systems (MISs) emerged with their ability to generate information enabling management to exert regular control. MISs are aimed at aggregating information contained in TPSs, and making the resulting information available throughout an organization for review and control purposes. Today, instances of TPSs and MISs exist simultaneously in organizations.

When the development of interactive software became feasible both technically and economically in the early 1970s, Gorry and Scott Morton (1971) were the first who defined Decision Support Systems (DSSs) as "interactive computer based systems which help decision makers utilize data and models to solve unstructured problems". Although many attempts have been made to redefine the definition, it is still appropriate for a common understanding of what DSSs are about.

The definition of Gorry and Scott Morton can be illustrated as follows. Classifying a problem as unstructured (i.e. ill-structured) is a main criterion for identifying the need for a DSS. A DSS should help the decision maker by supporting him, instead of replacing him, during the process of problem solving. The reasoning is that ill-structured problems cannot - by definition - be captured in a model according to a predefined procedure in order to solve them satisfactorily. The decision maker should be supported by giving him interactive control over data and models. This is also reflected by the technical view of DSSs by Sprague and Carlson (1982, pp. 28-33), who distinguish subsystems for dialogue management, data base management, and model base management. Keen and Scott Morton (1978, p. 1) add to the above that decision support should improve the effectiveness of decision making rather than its efficiency.

Considering DSSs as computerized systems exclusively intended to support ill-structured problem situations is often too limited. There is a growing awareness that structured and ill-structured problems cannot be separated strictly when developing information systems, as illustrated by the following.

Firstly, the performance improvement in organizations can be considered at three levels (Bots and Sol, 1988; Sol, 1988). At the micro level, the emphasis is on the task improvement of the employees in their workplace. At the meso level, improving the performance of an organization as a whole is paramount. Attention is paid to the co-ordination of tasks performed by employees. At the macro level, the scope is extended by including several organizations, with the aim of improving the overall performance.
A PSE for operational planning supports primarily at the micro level. However, according to Van Weelderan (1991, p. 45), decision support at the micro level depends on how the problems at the meso level are resolved. Planning support should therefore also be available for solving problems in the co-ordination of tasks. Note that the macro level does not apply to our research because we chose to study a single retail trade organization.

Secondly, the employees in an organization perform type I and type II work in problem solving (Panko, 1984). Type I work consists of numerous transactions at a low cost for well-defined problems, while type II work is characterized by fewer but more costly transactions without definite procedures. Sol (1991) argues that information systems supporting decision processes, such as PSEs, should offer integrated support for both type I and type II tasks.

Planning Support Environment

After having explained planning and decision support, a brief discussion of the term environment completes our introduction to a PSE.

Following Bots (1989, p. 51) and Verbraeck (1991, p. 90), when referring to planning support, we prefer the word environment over system, because planning support comprises more than just a computerized system consisting of hardware and software. Instead, an environment supports a large number of (planning) tasks, ranging from communication with other people to generating plans, by not only providing a computerized system but also access to other information systems, a telephone, etcetera. Besides, a PSE for operational planning is not necessarily restricted to a single workplace.

1.3 Research Questions and Research Approach

In section 1.1, we characterized time schedule specification as a vehicle routing and scheduling issue requiring more attention, and we indicated opportunities for computerized planning support. In section 1.2, we introduced the concept of a Planning Support Environment (PSE), which will be used as a starting point for elaborating the planning support for vehicle routing and scheduling. The research questions and the research approach are expressed in terms of a PSE.
Research questions

The research questions are:

1. What are the characteristics of a PSE for vehicle routing and scheduling if time constraints play a major role?

2. What are the effects of using such a PSE for vehicle routing and scheduling?

The research will be confined to supplying retail food stores. Furthermore, we shall concentrate on the components of a PSE which are innovative to the currently available planning support for vehicle routing and scheduling.

Finding an answer to the research questions is practically and scientifically relevant. The practical relevance follows directly from section 1.1, in which the position of the road transportation industry in the Netherlands was discussed, together with the trends emphasizing the importance of specifying adequate time schedules in vehicle routing and scheduling.

The scientific relevance follows from the fact that information systems as a discipline lacks the robust design principles for constructing and evaluating effective DSSs, see e.g. Elam (1989, p. 5). Sol (1991, pp. 116-117) states: "Although DSS enjoy an enormous popularity, the results so far have not lived up to expectation", and he adds: "Information systems as a discipline is finding its way through buzzwords and unsolved problems. The discipline is in search of a broader base of theories and experience". Gaining an understanding by means of experience is a premise for establishing theory on DSS development. Our research can be regarded as a case study which delivers experience to the important factors in effective DSS development.

Choosing a research approach

The above research questions set the requirements for the research approach. Firstly, there is a definite need to study the subject in a natural setting. Secondly, we are unaware of previous studies in this particular direction. According to Benbasat et al. (1987, p. 370), these points are indicative for a case study approach. We do not wish to restrict ourselves to a case study in which the observer simply
records existing matters, but we prefer an active participation in the development process.

We choose a research approach derived from the inductive-hypothetical model cycle (Sol, 1982, p. 4). The research approach is organized around the construction of four model types, as shown in figure 1-2.

![Diagram showing models in the research approach]

**Figure 1-2** Models in the research approach

In the first place, one or more *descriptive empirical models* are constructed, each describing the perceived situation of a specific area of interest. Analyzing the perceived situations provides an insight into problem causes, and into factors affecting the problem situations. Besides, the descriptive empirical models serve as yardsticks for the evaluation of alternatives.

A single *descriptive conceptual model* is constructed next, which is an abstraction of the descriptive empirical models, and describes the essential aspects
of the perceived situations. The generic character of the model should relate to a sufficient number of similar areas of interest, so that the external validity of the research is assured.

Applying the proposals from literature to the descriptive conceptual model and a design theory, brings the prescriptive conceptual model into existence. This model is still an abstraction of the specific areas of interest, but contains normative elements. The model explicitly indicates the changes to be applied to the perceived situations in order to solve the observed problems.

Finally, the above-mentioned prescriptive conceptual model is worked out into one or more prescriptive empirical models, comprising an implementation of the proposed changes in a specific area of interest. The models should confirm that implementation of the changes is possible, and are used for a comparison with the corresponding perceived situation.

Both research questions can be answered if the four model types are elaborated. The prescriptive conceptual model should describe the characteristics of a PSE for vehicle routing and scheduling if time constraints play a major role. Comparing a prescriptive empirical model with the corresponding descriptive empirical model should deliver a statement about the effects of using such a PSE for vehicle routing and scheduling.

**Applying the research approach**

We shall now discuss the application of the above-mentioned research approach to our research project. The project can be divided into the following phases.

1 - **Orientation**
The research is initiated with the idea that historic trip data can be used to improve the performance of vehicle routing and scheduling. Starting as a layman in this domain of business logistics, the first phase is dedicated to gaining common domain knowledge. A literature study is performed, and employees are interviewed in several organizations.

2 - **Learning from a case**
In the second phase, we co-operate with a retail trade organization selling food and other consumer goods, which we shall call RetailCo. Due to the limited time and the need for an exhaustive exploration, RetailCo is the only case we will study. The
second phase is mainly spent on an observational study of the trip execution and planning processes at RetailCo, which should generate the information for the construction of the descriptive empirical model. Also, the descriptive conceptual model is constructed.

3 - Design
The third phase is dedicated to designing the components of a PSE for vehicle routing and scheduling, which support the handling of the time constraints. Based on the literature study and the knowledge of RetailCo and other organizations, the opportunities for computerized planning support, as indicated in section 1.1, are worked out. We first formulate ideas about the way the planning support should be provided, and then elaborate these ideas in a design. The design brings the prescriptive conceptual model into existence, and gives an answer to the first research question.

4 - Implementation
Prototype systems are implemented at RetailCo, after freezing the design. We restrict ourselves to prototype implementations, as the research objective is to determine the feasibility of the design (see also the research questions). The prototypes represent the prescriptive empirical model.

5 - Evaluation
In the final phase of the research, the prototypes are used at RetailCo for evaluation purposes, the outcome of which should provide an answer to the second research question.

1.4 Outline of the Thesis

The chapters 2 and 3 describe the outcomes of the orientation phase. Chapter 2 gives an overview of the physical distribution in retail food trade organizations, whereby special attention is given to road transport. Chapter 3 is dedicated to planning support for vehicle routing and scheduling.

Chapters 4 to 7 provide an elaboration of the four model types in the research approach, and contain the answers to the research questions. Chapter 4 describes the trip execution and planning processes as they take place at RetailCo, followed by an abstraction hereof (descriptive empirical and descriptive conceptual model).
Chapter 5 introduces the components of a Planning Support Environment (PSE) for vehicle routing and scheduling which offer planning support if time constraints play a major role (prescriptive conceptual model and answer to research question 1). Chapter 6 describes the prototypical implementation of the above components for RetailCo (prescriptive empirical model). In chapter 7, the effects of the use of the prototypical implementation are discussed (answer to research question 2).

In chapter 8, a summary of findings is given and directions for future research are suggested.
2

Physical Distribution in Retail Trade Organizations

2.1 Introduction

In the previous chapter, we indicated that the research will be confined to the supply of retail food stores. Furthermore, we mentioned the trends requiring more attention to the specification of adequate time schedules in vehicle routing and scheduling: a trend in business logistics towards putting higher requirements on delivery reliability, and a trend towards more traffic congestion.

In this chapter we will discuss the general characteristics of the physical distribution system in a food retail trade organization, among which (the effects of) the above trends. The organization of the physical distribution forms a context for the way in which vehicle routing and scheduling can be performed. This chapter contributes to the descriptive conceptual model, and is based on literature, interviews in several organizations, and personal observations.

Physical distribution management, together with materials management, covers the field of business logistics. "Business logistics deals with all move-store activities
that facilitate product flow from the point of raw material acquisition to the point of final consumption, as well as the information flows that set the product in motion for the purpose of providing adequate levels of customer service at a reasonable cost", cf. Ballou (1978, p. 9). Materials management controls the logistic chain from the raw material acquisition to the end of the production process. Physical distribution management controls the remainder of the logistic chain, to deliver products at customer locations. Retail trade organizations operate within the physical distribution part of a logistic chain. Figure 2-1 shows an overview.

![Diagram of business logistics with nodes labeled: raw material acquisition, production plants, distribution centres, stores, customers, materials management, and physical distribution management.]

Figure 2-1 Scope of physical distribution in retail trade organizations

Van Goor (1986, p. 32) identifies three subsystems within a physical distribution system: facilities, inventories, and transport. The facilities subsystem, amongst others, deals with decisions about the location and function of warehouses, and thus determines the structure of the physical distribution system. Inventories are mainly buffers between supply and demand, so that a timely availability of products and an efficient product flow can be combined. Transportation is a means to ship products to the right place, at the right time.

Section 2.2 describes general characteristics of the physical distribution system in food retail trade organizations. The transportation subsystem, which includes vehicle routing and scheduling, is described in section 2.3. Finally, the aspects of physical distribution which are highly relevant to our research, are summarized in section 2.4.
2.2 Physical Distribution System

Retail stores can be regarded as customers in the logistic chain controlled by a retail trade organization. The distribution to stores, especially in the super market branch, is aimed at a high customer service level at limited operational cost, as illustrated below.

According to Ballou (1985, pp. 52-55), customer service can be defined as the transaction-satisfying activities which usually begin at order entry and end at the delivery of products to customers, and which are continued as activities for post-transaction support in some cases. Retail stores often require a delivery reliability of more than 97% at a lead time of only 24 hours for the majority of the assortment (Van Vlerken, 1989). Other elements of the customer service required by retail stores are, for example, facilities for automatic order entry and rush order entry (Kok, 1988a, pp. 12-13). Of course, meeting the time constraints for product delivery to stores is also an element of customer service.

Logistic costs can be broken down to transportation, handling, storage, and inventory costs (Van Goor et al., 1989, pp. 350-355). The food retail business is characterized by a substantial share of logistic costs in the business costs, and by small profit margins. A net profit margin after taxes of about 1% is usual, see for instance Van Vlerken (1989). Super market organizations have been convinced of the profound role of logistic costs for a long time, and much attention has been paid to the development of efficient physical distribution systems in which the integration of the logistic chain is basic.

In the remainder of this section, general characteristics of the above-mentioned physical distribution systems will be described. We will discuss both the structure and the operation of such a system, followed by recognizable trends. For analogous discussions, see Van Vlerken (1989) and Van der Lans (1990).

Structure of the physical distribution system

Figure 2-2 shows the typical structure of the physical distribution system in a retail trade organization. The logistic chain between the suppliers and the stores is controlled by the retail trade organization. There are many suppliers, and they are located over a wide geographic area. These two conditions are also valid for the retail stores. Stocks can be found at the suppliers, at distribution centres, and at stores. Retail stores usually have a low storage capacity, due to the combination of
limited floor space, sizable assortments, and high turnover rates.

The distribution centres are intermediaries between the suppliers and the stores, and have two main functions with both a customer service and a costs aspect. The first function is to have the inventory close to the stores, to be able to reach a high delivery reliability and to take advantage of an economy of scale in building up stocks. The second function is to collect large shipments from the suppliers and to assemble these into orders for stores, to release the stores of a large number of deliveries, and to take advantage of the economy of scale in transportation.

Figure 2-2 Structure of a physical distribution system (abbreviated)
Within the above structure, several distribution channels exist next to each other. The majority of the assortment flows from the suppliers through one distribution centre - or more distribution centres in a multi-level system - to the stores. A distribution centre can be specialized in the handling of a single sub-assortment only. Small parts of the assortment are shipped directly from the suppliers to the retail stores.

The main reason for the existence of separate distribution channels is the diversity in product characteristics, such as the sales volume for which a distinction can be made between what we call slowmovers and fastmovers. Another important product characteristic is the required conditioning (e.g. deep-freezing). According to Våhl (1989) and Brands (1989), a direct delivery from the suppliers to the stores is standard for bulk products, fresh products, and complete sub-assortments.

**Operation of the physical distribution system**

Large volumes of thousands of articles flow rapidly from the suppliers to the stores in daily operation. The information flow setting the product flow in motion follows the opposite direction.

Articles not shipped directly to the stores are transported from the supplier to a distribution centre. These articles are stored and assembled into orders for stores later. To keep inventory costs low, to maintain speedy reactions, and to preserve the keeping qualities of food products, it is customary to have less than 1 week throughput in stock at a distribution centre, see e.g. Schaafisma (1986, p. 33). Articles are transported to the stores from one or more distribution centres, and directly from suppliers (see also section 2.3). The logistic chain continues in the stores. Due to the limited storage capacity, the inventory level in a retail store is almost restricted to sale stocks, and deliveries are often worked up directly.

The information flow setting the product flow in motion starts at the stores. The stores insert orders for articles at the retail trade organization, based on historic sales and anticipating future sales. Orders and forecasts are the ingredients for controlling the inventory level in a distribution centre. The retail trade organization regularly purchases articles from the suppliers, to replenish the inventory in the distribution centres.

Ballou’s statement (1985, p. 15) about the progress in information technology being a key condition for the creation of business logistics, definitely applies to the physical distribution system in food retail trade organizations. Managing the
product flow is impossible without computerized information systems.

Some typical applications are indicated below. Barcode readers are used for automatic order entry in retail stores. More and more point-of-sale terminals are becoming available. The stores insert orders at the retail trade organization by means of Electronic Data Interchange (EDI). This is also being used increasingly for inserting orders at suppliers, for which the Transcom-standard has been developed. In the distribution centres, information systems are used for inventory control and for planning the assembly of orders for stores. It is interesting to note that the first applications of vehicle routing and scheduling systems can be traced back to the late 1960s.

**Trends in physical distribution**

In retail trade organizations, especially in the super market branch, several trends can be recognized which put higher requirements on the product flow management. We will discuss these trends briefly, together with the consequences for the physical distribution system. Background information on this subject can be found in Van der Velden (1990).

The number of articles flowing through the logistic chain will grow in the next decade because of:

- smaller packing quantities, amongst others, due to the increase in the number of single households;
- a diversification of the existing assortment, as illustrated by the introduction of the so-called *light* products;
- the upgrade of the fresh product assortment.

The available space in retail stores will probably be insufficient to process the increase in the number of articles. Food retail trade organizations are looking for solutions for this problem, such as enlarging the sales floor area by reducing the warehouse floor area, or reducing the inventory level in the stores, which requires a higher delivery frequency, i.e. the product flow becomes more continuous. Both solutions require a better mutual co-ordination of the transportation process and the handling of the goods in the stores. As a consequence, meeting time constraints will be more important in the future.
2.3 Transportation Characteristics

We characterized the transportation of goods to retail stores as a link of an integrated logistic chain in the previous section. For this reason, not only the transportation costs, but also meeting time constraints is an important performance indicator. In this section, we will concentrate on the transportation of goods to stores, and discuss characteristics relevant to our research. We will subsequently comment on the transportation process and traffic congestion.

Transportation process

According to Kamphuis (1984, pp. 428-429), the transportation process consists of the preparation, the execution, and the settlement of trips, see figure 2-3.

![Diagram of transportation process]

Figure 2-3 The transportation process
Trip execution
Trip executions consist of the following sequence of activities: a truck starts at a
distribution centre or at a supplier location, visits one or more stores, and
eventually returns to its point of origin. When a truck returns to the distribution
centre, goods are sometimes picked up at a supplier location, to reduce the costs
of driving without load. This is called backhauling.

When a store is visited, the store volume is unloaded, trip forms are filled in, and
mostly also some return packing is loaded. The duration of a store visit is a
substantial part of the total trip duration: about 2 hours are required for unloading
a full palletted truckload. For this reason, some organizations use fast unloading
devices, such as put-down containers or truck docks, see e.g. Jongenotter (1988)
and Ruijgrok and Machielse (1986, pp. 95-98). Using put-down containers implies
that an empty container is exchanged for a loaded one during a store visit, which
is unloaded by store personnel later. Floors of truck docks and trailer floors are
equally high, which makes unloading elevators superfluous.

Retail stores are usually located in shopping centres or in town centres, and truck
length restrictions and time windows are therefore sometimes imposed, as pointed
out by Kaiser (1988). The length restrictions are due to the limited manoeuvring
space near stores, and require the use of small trucks. The time windows can
prescribe earliest arrival and latest departure times, and are imposed by the local
government to guarantee the night’s rest and to exclude store visits in busy areas
during the day. According to Rodenburg (1988), both truck length restrictions and
time windows can have a significant influence on the transportation costs.

Trip preparation and trip settlement
Trip preparation and trip settlement take place at a distribution centre or, in case
of a direct shipment, at a supplier. The trip preparation not only includes vehicle
routing and scheduling, but also recording of transportation orders, determining the
availability of trucks and drivers, and filling in trip documents. The trip settlement
comprises invoicing and the generation of management information.

Vehicle routing and scheduling, together with the accessory administrative tasks
for the trip preparation, are usually performed on a day-to-day basis by trip
planners, who also keep drivers and stores informed about the planned trips. Trip
planners are experts with detailed knowledge about planning and executing trips.
This knowledge is based on experience and often concerns exceptional situations,
see De Jong and Sol (1991, p. 282). Therefore, trip planners generally play a key
role in efficient and effective transportation processes. We already indicated that
retail trade organizations have used vehicle routing and scheduling systems since the late 1960s. Planning support for vehicle routing and scheduling will be discussed in detail in chapter 3.

Traffic congestion

The availability of the road network is important to the operation of integrated physical distribution systems. Punctual deliveries require that travel durations be calculated accurately. However, traffic congestion complicates the task as it not only causes delays but also increases the uncertainty about the travel durations. Following the same line of argumentation, several authors point at the need to manage traffic congestion in order to be able to guarantee punctual deliveries (Ruijgrok and Janssen, 1987; Roos, 1988).

Traffic congestion is defined as the road intensity/capacity ratio prohibiting free traffic flow, which implies that traffic congestion can have intensity or capacity reasons (Branston, 1976). The intensity on roads generally shows monthly, weekly, and daily cycles, and may also change due to incidental reasons such as a large exhibition. For example, the road capacity can fluctuate due to weather, road works, or accidents. Traffic congestion in the Netherlands is most tangible during the daily peak hours in the Randstad, the West.

Traffic congestion on the main road network in the Netherlands will increase appreciably in the next two decades because the capacity growth does not keep pace with the intensity growth. There are no plans for substantial extensions to the capacity of the network. On the other hand, the traffic intensity on the network has increased by 20% between 1986 and 1989 (DVK, 1990). This trend towards increased traffic will continue in the next decades, due to prosperity growth and demographic developments (Hamerslag, 1986). The prognosis for the year 2010 even indicates a 70% car usage increase, and doubling of road transportation, both compared to the base year 1986 (SVV2, 1990, pp. 5-6).

In order to reduce traffic congestion on the main road network or to evade congestions, several measures can be taken, of which some are being considered, and some already (partially) introduced by the government. The measures could concern traffic demand management, and dynamic traffic management, see also Hamerslag (1990), Haven (1990), and TVV (1990). Examples of traffic demand management measures are road pricing, car and van pooling, and the stimulation
of public transport. Dynamic traffic management deals with the control of traffic flows based on the current situation. Instruments consist of distributing current accurate information, especially delay information, and managing the usage of the road network (e.g. ramp metering, tidal flows). It should be clear that information technology is essential for realizing dynamic traffic management, both as part of the road infrastructure and as in-car systems.

The location of retail stores, i.e. in a shopping centre or in the centre of a town, implies that the accessibility of stores can be troublesome. A measure considered by government to reduce traffic congestion in towns is the construction of distribution centres in the outskirts of towns, from which small trucks take care of the distribution of goods (Silvester, 1991).

In spite of the above measures, traffic congestion will increase in the next decades, and so will the resulting uncertainty about travel durations. It is the responsibility of a retail trade organization to manage the effects of traffic congestion, in order to guarantee the level of customer service required by the stores.

2.4 Summary and Conclusions

Retail trade organizations, especially in the super market branch, have advanced physical distribution systems guaranteeing high customer service levels at limited operational cost. The transportation of goods to the stores is a link in an integrated logistic chain.

Vehicle routing and scheduling is a daily recurring activity, in which it is important to specify time schedules meeting the time constraints. These time constraints exist due to the following reasons:

- the distribution channels leading to a store have to be co-ordinated in such a way that trucks from different channels do not arrive simultaneously;
- the transportation of goods to a store and their handling have to be co-ordinated, so that the goods can be worked up directly;
- time windows are imposed by the local government to guarantee the night’s rest and to exclude store visits in busy areas during the day.
The growing number of articles flowing through the stores, combined with their limited stock capacity requires higher delivery frequencies. The product flow to the stores becomes more continuous, which implies that meeting time constraints will be even more important in the future.

In contrast with the above logistic trend, there is a trend towards more traffic congestion on the road network which causes the uncertainty about travel durations to increase. Guaranteeing punctual delivery will consequently become more difficult in the coming years.
Vehicle Routing and Scheduling Support

3.1 Introduction

We defined vehicle routing and scheduling in chapter 1 as assigning transportation orders to vehicles, and specifying a route along the customers and a time schedule for each vehicle. We indicated that the task specify time schedules within vehicle routing and scheduling is increasingly important. Furthermore, we stated that our research will concentrate on the planning support as yet unavailable in existing vehicle routing and scheduling systems.

We will now take a closer look at vehicle routing and scheduling problems. The purpose is to provide an insight into the relevant aspects of modelling these problems, and into the state-of-the-art of vehicle routing and scheduling systems. The contents of this chapter contribute to the descriptive conceptual model, and originate from literature and experiences with currently available vehicle routing and scheduling applications.

The basic problem type underlying all vehicle routing and scheduling problems is the classical vehicle routing problem (Bodin et al., 1983, p. 80). A vehicle fleet with known capacity is stationed at a central depot. In addition, there is a set of
customers with a deterministic demand. A solution consists of routes, which
together service all customers exactly once. The objective is to minimize the total
distance travelled. This problem type is represented graphically in figure 3-1.

![Vehicle Routing and Scheduling Support](image)

**Figure 3-1** The classical vehicle routing problem

Most real-world vehicle routing and scheduling problems are extensions to the
classical vehicle routing problem. The problem characteristics, with the objectives
and the constraints, are usually more complex than presented above.

Vehicle routing and scheduling problems have challenged the operations research
discipline since the 1950s. Many papers have been published on algorithms for the
solution of the classical vehicle routing problem and its derivatives. However,
practical computer applications were rare until the late 1960s. The initial
applications were mainly batch-oriented.
Interactive planning systems for vehicle routing and scheduling have been developed since the 1970s, and are now used in several organizations. The reasons for this evolution in vehicle routing and scheduling are that the problems cannot be solved in polynomial time (i.e. the problems are NP-hard, see Bodin et al. (1983, p. 76)), that it is cumbersome to accommodate real-world aspects in algorithms, and the emergence of Decision Support Systems (DSSs).

In this chapter, we will consider vehicle routing and scheduling problems from the viewpoint of an information systems practitioner. In section 3.2, the modelling of vehicle routing and scheduling problems is discussed. The modelling of road networks is discussed in section 3.3. Vehicle routing and scheduling systems are described in section 3.4. Finally, the issues in vehicle routing and scheduling, highly relevant to our research, are summarized in section 3.5.

3.2 Modelling Vehicle Routing and Scheduling Problems

Vehicle routing and scheduling problems exist in many organizations, manifesting themselves in many appearances. Several classification schemes have been set up for the comparison of problems and the selection of solution strategies, see for instance Weber (1985, pp. 16-17) and Desrochers et al. (1988). Some of the characteristics of vehicle routing and scheduling problems are discussed below. It is not our intention to present a comprehensive classification scheme, but to provide a general insight into real-world problems.

Problem type characteristics

The problem domain of a vehicle routing and scheduling problem includes entities of the following entity types: DEPOT, VEHICLE, CUSTOMER, and PRODUCT. A vehicle routing and scheduling problem can be described in terms of these entity types, constraints concerning the entities, and an objective function.

The classical vehicle routing problem is organized around a single depot, vehicles with a known capacity, customers with a deterministic demand, and one product. Following extensions are often found, see also Fleuren (1988, pp. 18-23). Customer supply may take place from more than one depot. Vehicles may have separate compartments for different products, and may have the capacity expressed in more than one dimension (e.g. volume and weight). Customers may place orders
for several products, have a stochastic demand, and require that goods are both delivered and collected.

The constraints relate to single entities in the problem domain or to entity relationships (Martens, 1986). Examples of constraints of the first type are the number of available truck loading docks at a depot, vehicle capacity, availability of vehicles, and time limits for visiting customers. Examples of constraints of the second type are depots unable of servicing all customers, vehicles unable of reaching all customer locations, and vehicles restricted in the types of product to be transported.

The objective function of the classical vehicle routing problem, which minimizes the total distance travelled, is often too simple. Schrage (1981) mentions that messy cost functions may occur in reality. According to Tomberg (1988, p. 50), basic elements for the determination of transport costs are the distance travelled and the trip duration. Other customary cost elements are initial costs for using a vehicle and extra costs for driver overtime.

The description of a vehicle routing and scheduling problem in terms of entity types, constraints, and an objective function can be used for a formal specification. However, in case of a real-world problem, organizational aspects must also be considered; we will provide some examples. Constraints can be soft, which means that a violation does not exclude the feasibility of a plan. The policy of the organization may raise additional constraints, such as a preference for an equitable workload among drivers. Additional to low transport costs, the customer service may also be important. Furthermore, the associated administrative tasks, such as order entry, may influence the vehicle routing and scheduling problem.

Our research deals primarily with vehicle routing and scheduling problems in which time constraints are important. We indicated some reasons for the existence of time constraints at customer locations in section 2.4. These time constraints are usually modelled as time windows (Bodin et al., 1983, p. 72). A time window \([tb, te]\) restricts the service time of a customer to lie within the interval starting at \(tb\) and ending at \(te\). A special situation is a time window with \(tb=te\), indicating that the service time is definitive. A time window can be one-sided, that is to say, be defined as \((-\infty, te]\) or \([tb, \infty)\). Of course, time windows are not reserved for customer locations, but may also be defined for depots.

Time windows and other time constraints (e.g. maximum trip duration) form the basis for a fundamental extension to the classical vehicle routing problem: not only
are the spatial characteristics of the problem relevant, but also the times at which activities must be performed (Bodin et al., 1983, p. 117). The duration of activities such as loading, unloading, and driving must be modelled, to be able to calculate trip durations and to test the feasibility of planned trips against the time constraints. The duration of loading and unloading is usually modelled as a fixed duration and a duration for each unit load (Maltz, 1985, p. 484), while travel durations are mostly based on a representation of the road network.

A model for food retail trade organizations

The physical distribution system of food retail trade organizations was outlined in chapter 2. Below, a model of vehicle routing and scheduling problems in these organizations is described.

Stores have a fixed allocation to distribution centres and to suppliers, which implies that several vehicle routing and scheduling problems can be identified, each dealing with the transportation of goods from one depot. The stores can be regarded as customers with a deterministic demand. Split deliveries are sometimes allowed, which means that an order may be shipped to a store by several trucks.

The trips start and end at the same location, that is to say, at a distribution centre or at a supplier location. During the return to a distribution centre, backhaul may be collected at a supplier. As backhaul is loaded after the delivery of goods to the stores, it is not necessary to regard the vehicle routing and scheduling problem as a combined pick-up and delivery problem.

We will now review the main entity types found in the problem domain of a vehicle routing and scheduling problem for a food retail trade organization.

A vehicle routing and scheduling problem is defined for a distribution centre or for a supplier. Both can be regarded as a DEPOT whose location is required for the calculation of distances and travel durations. The number of truck docks at a depot sets the maximum number of trucks which can be (un)loaded simultaneously.

```entity type DEPOT
[
  attributes
    location
    truck docks
  location of the depot
  number of truck docks for (un)loading
]```
We define the entity type TRUCK, and assume that it belongs to a driver, as trucks normally have fixed driver assignments. A truck has a maximum capacity for carrying goods, and may be available during an interval of time only. Not all trucks are suitable for transporting conditioned goods. The properties of a truck are relevant for evaluating truck restrictions at addresses occurring in a plan.

The entity type TRUCK is the only entity type for which actions are identified. A truck is loaded at the depot, drives to stores where the store volume is unloaded and return packing is loaded, possibly visits a supplier to load backhaul, and eventually returns to the depot. Actions are loading, unloading, and driving.

```plaintext
entity type TRUCK
[ attributes
  capacity
  availability
  conditioning properties
  truck properties
  capacity expressed in a unit load (e.g. a pallet)
  interval of time when the truck is available
  properties for conditioning goods (e.g. deep-freezing)
  properties for evaluating truck restrictions

  actions
  load goods
  unload goods
  drive to location
  load the store volume, return packing, or backhaul
  unload the store volume, return packing, or backhaul
  drive to a store, a supplier, or the depot
]
```

Retail stores and - in the case of picking up backhaul - suppliers are visited during a trip. The stores and the suppliers are located at an ADDRESS. The location of the address must be known for the calculation of distances and travel durations. An address may have a time window and fast unloading devices. Not all truck types may be able to reach certain addresses.

```plaintext
entity type ADDRESS
[ attributes
  location
  time window
  unloading devices
  truck restrictions
  location of the address
  time window (see this section)
  devices for fast unloading
  truck types unable to reach the address
]
```

The ordered articles are not identified separately in solving a vehicle routing and scheduling problem. Instead, an aggregated quantity expressed in a unit load is used, for which the entity type ORDER has been defined. An order belongs to an address, and may require conditioning of the goods.
entity type ORDER
[
  attributes
  address
  quantity
  required conditioning
]

address to which the order belongs
quantity expressed in a unit load (e.g. a pallet)
required conditioning (e.g. deep-freezing)

The entity type TRIP is the building block of a plan for a vehicle routing and scheduling problem. Several orders are dispatched by a truck during a trip. A route and a time schedule must be specified for each trip.

entity type TRIP
[
  attributes
  truck
  orders
  route
  time schedule
]

truck used for the trip
orders to be dispatched
trip route
trip time schedule

We indicated that a representation of the road network is used in the calculation of travel duration, which is why we add the entity type ROAD NETWORK to our model. A road network consists of nodes, and links connecting the nodes. The locations of depots, stores, and suppliers refer to a node. Modelling road networks is discussed in more detail in the next section.

entity type ROAD NETWORK
[
  attributes
  nodes
  links
]

intersections between links
representations of roads

The above entity types are shown in the Bachman diagram of figure 3-2. The entity type road network is represented in terms of the constituting nodes and links.

3.3 Modelling Road Networks

Several authors indicate that it is important to calculate trip durations accurately for solving vehicle routing and scheduling problems, see e.g. Assad (1988, p. 39) and Van Wee (1989). Inaccurate calculations are unsatisfactory, as wrong distances and travel durations may lead to different - possibly less efficient - routes, while inaccurate calculations also impede the meeting of time constraints.
Kleindorfer et al. (1981, p. 31) suggest that modelling the problem domain is an often neglected - yet critical - aspect of a vehicle routing and scheduling problem. In particular, they mention the distance matrix containing the shortest distance between each location pair as an essential data set. In a test of computerized vehicle routing and scheduling applications in the Netherlands, it was found that some systems show deviations between the real and the calculated road distance of more than 10%, which is quite substantial (NEA, 1988, pp. 40-41).

An elementary basis for calculating the distance between two locations is known as the *euclidean* distance, requiring that the co-ordinates of the locations be known. Given two locations \( i \) and \( j \) and their co-ordinates, the euclidean distance \( d_{ei,j} \) is defined as the linear distance between the points (Assad, 1988, pp. 37-38).
The road distance $dr(i,j)$ can be obtained by multiplying the euclidean distance by a correction factor $\alpha$:

$$dr(i,j) = \alpha \cdot de(i,j) \quad (3-1)$$

Fildes and Westwood (1978) report a value for $\alpha$ between 1.07 and 1.52 in Great Britain, depending on the region. A regression analysis with data on actual road distances showed large values for the co-efficient of determination $R^2$, which supports the suggestion that the above approach can produce acceptable estimates. However, several shortcomings can be also indicated. Corrections of the calculated distance are necessary for different zones (e.g. downtown and suburban areas) and for obstacles (e.g. rivers). Besides, $\alpha$ is an average value depending on the distribution of distances travelled. Consequently, estimating road distances by euclidean distances requires few data and is easy to compute, but may produce insufficiently accurate outcomes. This also applies to the travel durations as these are strongly correlated with the road distances.

Nowadays, road network files can be used for calculating road distances and travel durations. A road network file contains an abstraction of the road network in terms of nodes and links. Nodes are intersections between two or more links. Links represent roads, generally with the attributes length and average speed. A road network representation usually consists of thousands of links. The travel duration for a link is the ratio between the length and the average speed. The road distance or travel duration between any pair of nodes can be computed by a shortest path algorithm. Such road distances are more accurate than the ones based on the euclidean distance. Several organizations produce and sell road network files on a commercial basis in the Netherlands. An example of a road network with a shortest path is shown in figure 3-3. A road network file can be used for vehicle routing and scheduling if the locations of addresses are matched to nodes. A general and often applied match coding scheme is the postal code system (Van Wee, 1989).

Matrices are often used instead of road network files in current vehicle routing and scheduling applications. Matrices contain the real distances or travel durations of the shortest paths for all location pairs. The matrices can be obtained from a road network file by calculating the shortest path between all possible origin-destination location pairs. Figure 3-3 shows the distance matrix corresponding to the road network shown.
Figure 3-3 Road network and distance matrix with a shortest path

Both Assad (1988, p. 40) and Stefanski et al. (1990, pp. 11-12) indicate differences in using road network files and matrices. A road network file needs less storage but requires that for each origin-destination pair of locations the time consuming shortest path algorithm is executed. It is more essential that in a road network file, in contrast with a matrix, detailed information on single roads can be stored conveniently. Amongst other things, this allows the modelling of time dependent travel durations for specific roads, which will become more important in the future. In a travel duration matrix this information must be linked to all origin-destination location pairs using that road.

3.4 Information Systems for Vehicle Routing and Scheduling

Vehicle routing and scheduling is suitable for computerized planning support. In section 3.1, we indicated that several organizations use interactive planning systems for vehicle routing and scheduling. Several systems have been described in literature, see e.g. Waters (1984), Belardo et al. (1985), Evans and Norback (1985), Robroeks (1985), and Savelsbergh (1988, pp. 56-85). Nowadays, about 15 computerized vehicle routing and scheduling applications are commercially
available in the Netherlands (Jol, 1987; Weenink et al., 1988, p. 287). We will discuss the characteristics of interactive vehicle routing and scheduling systems in this section.

**Why computerized planning support?**

The main argument for applying computerized planning support instead of manual planning is the expected decrease of transport costs. However, other arguments are mentioned as well, such as the increased level of customer service, the standardization of the planning policy among trip planners, and the faster planning process (Hooban, 1988, pp. 458-461; Huitink, 1988, pp. 215-216). Besides, if planning time is restricted and the number of transportation orders is high, computerized planning support may be necessary to keep pace with the speed of the product flow.

**Functional specification of vehicle routing and scheduling systems**

The input to vehicle routing and scheduling systems (in retail trade organizations) consists of instances of the entity types: TRUCK, ADDRESS, and ORDER. The output of all vehicle routing and scheduling systems is essentially the same: a route and a time schedule are provided for each trip. A route specifies the sequence of addresses to be visited, and a time schedule specifies the times at which activities are to be carried out. Management information, such as load rates and transport costs, can generally also be generated.

The above input and output constitute the interface with the other tasks of trip preparation, such as order entry and filling in trip documents (see section 2.3). Edit and print functions are usually available for manual input and variable format output in vehicle routing and scheduling applications. However, it is important that a vehicle routing and scheduling system is not considered in isolation, but that, for instance, orders can be read from an order entry system.

The current interactive planning systems for vehicle routing and scheduling show clear similarities. Below, we describe some functional characteristics of the planning support provided by these applications.

We will use the ROMC approach as the framework for describing planning support. According to Sprague and Carlson (1982, ch. 4), a planning system should
provide *Representations* to conceptualize and communicate a problem, *Operations* to analyze and manipulate with these representations, *Memory aids* to assist the planner in linking the representations and the operations, and furthermore *Control mechanisms* to handle and use an entire system.

*Representations*

Most vehicle routing and scheduling systems contain a graphical display of a map to represent a planning problem. Addresses, trips, and also geographical information (e.g. roads and rivers) can be shown on the map, while it may also serve as a screen on which operations are activated by direct manipulation.

The graphical display of a map is regarded essential for providing planning support. Hooban (1988, p. 462) even calls the map a *sine qua non* for vehicle routing and scheduling systems. Its importance can be explained in two ways. Firstly, the use of a map resembles the way of working before the introduction of computerized systems. Assad (1988, p. 33), for example, states: "if one walks into any dispatching station, one is apt to see the walls covered with maps". Secondly, a map representation resembles the way in which planners conceptualize a vehicle routing and scheduling problem.

*Operations*

We will now describe the typical functions of vehicle routing and scheduling applications. Following the overview by Verbeek (1991b, pp. 24-30), the functions are grouped into four categories:

- plan manipulation;
- plan generation;
- plan management;
- plan evaluation.

A function group is defined for each category, and can be regarded as a support component of a vehicle routing and scheduling application.

The plan manipulation includes the functions enabling trip planners to construct and edit plans interactively. The functions are intended to manipulate the attributes of a trip (e.g. the assignment of a truck), or to change complete trips.
function group PLAN MANIPULATOR
[
  functions
  assign truck
  assign order
  specify route
  relocate address
  specify time schedule
  combine trips
  split trip
]

toggles the assignment of a truck to a trip
toggles the assignment of an order to a trip
specifies the route of a trip
relocates an address in a trip
specifies the time schedule of a trip
combines two or more trips into one trip
splits a trip into two trips

The plan generation comprises the automatic construction of plans by the system. The functions are not restricted to the generation of complete plans from scratch, but can also be applied to single trips, routes, or time schedules. In some systems, the functions can be used for completing or improving (partial) plans.

Various algorithms are available for the generation of plans from scratch. An exhaustive survey hereof can be found in Bodin et al. (1983). There are also algorithms which are based on iterative route improvement (Waters, 1987). More recently, some progress has been made in the application of artificial intelligence approaches, such as expert systems, for vehicle routing and scheduling, see for instance Duchessi et al. (1988), Filman (1988), and Waters (1990). A discussion of the algorithms and the artificial intelligence approaches is beyond the scope of this thesis.

function group PLAN GENERATOR
[
  functions
  generate plan
  generate trip
  generate route
  generate time schedule
]
generates a complete plan
generates a trip for a set of orders
generates the route of a trip
generates the time schedule of a trip

The plan management includes the functions for managing a plan and for working with several plans simultaneously. Managing a plan is achieved by (un)freezing trips, and by saving and retrieving single trips. In order to be able to work with several plans, complete plans can be saved and retrieved.

function group PLAN MANAGER
[
  functions
  (un)freeze trip
  save (partial) plan
  retrieve (partial) plan
]
	toggles whether a trip can be changed
	 saves one or more trips of a plan
	 retrieves one or more trips into a plan
The plan evaluation aims at providing an insight into the quality of plans. The current vehicle routing and scheduling applications have functions for the evaluation of objective functions, and for the confirmation that the constraints are met. Note, however, that most systems are characterized by limited facilities for expressing complex objective functions.

```
function group PLAN EVALUATOR
[
  functions
determine plan costs                  evaluates the objective function
determine plan feasibility           checks whether the constraints are met
]
```

**Memory aids and control mechanisms**

Several types of memory aids are available in the current vehicle routing and scheduling systems. A few examples are:

- record displays for providing detailed information about the trucks, addresses, and orders;
- list displays with the trucks (not) used in a plan, and the orders which have (not yet) been planned;
- summary statistics providing an insight into the quality indicators of planned trips, such as load factors and trip costs.

The control mechanisms support the trip planners in the use of the system functions to construct a plan. Customary control mechanisms are generic functions operating on a group of entities, instead of on a single entity.

Most vehicle routing and scheduling applications provide menus for function selection. Some applications explicitly support a process-oriented approach, for example the *cluster first - route second* heuristic.

### 3.5 Summary and Conclusions

There are many vehicle routing and scheduling problems, ranging from rather simple to very complex. The installation of a standard vehicle routing and scheduling system is often inadequate for the provision of effective planning support. The organizational aspects must be considered especially, such as the relation with the associated administrative tasks.
Several organizations use interactive planning systems for vehicle routing and scheduling. Important characteristics of the applications are the graphical display of maps, and functions for both the manual and the automatic construction of plans. Although progress can still be made in improving the usability of the systems, we conclude that a number of current applications adequately exemplify the state-of-the-art in DSS.

Two aspects are especially important if time constraints play a major role. Firstly, the representation of the road network is essential for the calculation of road distances and travel durations. The current vehicle routing and scheduling systems have a road network file or matrix. These, however, do not always contain accurate distances and durations. Secondly, most vehicle routing and scheduling applications mainly provide planning support for routing decisions, while there is little support for scheduling decisions.
Trip Planning: Perceived Situation

4.1 Introduction

In chapter 1, we adopted a research approach starting with the construction of one or more descriptive empirical models, and a descriptive conceptual model. These should give an insight into the problems and factors affecting the problem situations. Furthermore, we suggested to have a closer look at RetailCo: a retail trade organization selling food and other consumer goods.

In this chapter, we will present descriptive models providing an understanding of the trip execution and planning processes, both at RetailCo and in general. The information to set up the models was obtained by interviewing managers, reading reports, observing trip planners, and accompanying drivers on trips.

In order to describe the problem solving tasks in this chapter, we will use the task analysis technique developed by Bots (1989). A task is structured if a problem solving procedure for that task exists, and ill-structured otherwise. A task structure consists of a task hierarchy and a flow relationship. The hierarchy follows from the recursive definition of tasks in terms of subtasks and decisions, i.e. several levels of description can be identified. At the lowest description level, decisions can be
identified, together with the influencing and the affected information. The flow relationship indicates the order in which the tasks and the decisions are executed. The primitives of the task analysis technique are shown in figure 4-1. A bomb symbol in a task indicates the existence of subtasks.

![Diagram showing task analysis primitives](image)

Figure 4-1 Task analysis primitives

RetailCo's physical distribution system is outlined in section 4.2. A descriptive model of RetailCo is defined in section 4.3. A descriptive model for trip planning in food retail trade organizations is discussed in section 4.4.

### 4.2 RetailCo: A Retail Trade Organization

RetailCo is a large retail trade organization selling food and other consumer goods in the Netherlands (the name is imaginary). The organization owns chain stores and distribution centres. We have researched a distribution centre in the north-eastern part of the Netherlands. We will refer to this distribution centre as the distribution centre.

RetailCo's physical distribution system corresponds broadly to the system discussed in section 2.2. A brief overview should therefore be sufficient to characterize the product flow from the distribution centre to the stores.
Structure and operation of the physical distribution system

The distribution centre is mainly responsible for handling the fastmovers of the assortment. It serves more than 150 stores, all of which are located within a radius of 125 kilometers. Stores are supplied 2 to 5 times weekly.

The product flow from the distribution centre to the stores consists of two separate distribution channels: one for retail products and one for cooled products. The cooled products - in contrast with the retail products - have to be conditioned throughout the logistic chain.

The daily operation is subdivided into morning and afternoon batches. The trips of a batch are planned two batches before the trip. Order assembly and truck loading take place one batch in advance.

Transportation process

In section 2.3, we showed that the transportation process consists of the preparation, the execution, and the settlement of trips. Below, the perceived transportation process is described in terms of these functions.

Trip execution

Trips start and end at the distribution centre. Incidentally, backhaul is picked up when returning to the distribution centre. Trucks usually execute a trip in the morning batch and one in the afternoon batch.

Two truck types are used, both accommodating about 30 pallets. One truck type has a detachable trailer, and is used for the stores which can only be reached by a small truck. In such cases, the trailers are disconnected before, and reconnected after store visits.

The trips are carried out by professional trucking companies. The number of hired trucks varies from day to day. The trucking companies are responsible for providing a sufficient number of trucks and drivers. However, the number of detachable trailers is restricted.
Table 4-1 contains some trip execution key figures.

<table>
<thead>
<tr>
<th></th>
<th>retail products</th>
<th>cooled products</th>
</tr>
</thead>
<tbody>
<tr>
<td>trips / batch</td>
<td>± 30</td>
<td>± 5</td>
</tr>
<tr>
<td>store visits / trip</td>
<td>1 .. 3</td>
<td>6 .. 12</td>
</tr>
<tr>
<td>pallets / store visit</td>
<td>5 .. 30</td>
<td>1 .. 7</td>
</tr>
<tr>
<td>store visit duration</td>
<td>0.75 .. 2 hours</td>
<td>0.25 .. 0.5 hour</td>
</tr>
<tr>
<td>time window width</td>
<td>2 .. 4 hours</td>
<td>0.5 .. 1 hour</td>
</tr>
</tbody>
</table>

Table 4-1 Key figures of the trip execution

Trip preparation
The service management department is responsible for the product flow from the distribution centre to the stores. We will describe the tasks performed in this department. The organizational chart of the service management department is given in figure 4-2.

Figure 4-3 shows the task structure of PREPARE TRIPS. The subtasks will be explained briefly.

The task SPECIFY TIME WINDOWS is executed irregularly by the time window manager. Output of the task is a time window definition for store visits. A time window applies to one distribution channel, and imposes an earliest arrival and a latest departure time. A time window is usually fixed for a period of time, but may be changed temporarily on an ad-hoc basis. The purpose is to specify time windows such that the requirements of stores are met, that different distribution channels do not overlap, that it is possible to combine several store visits in a trip, and that the workload of the distribution centre is balanced. Computerized support is available for entering and displaying a time window definition.

The task PLAN TRIPS is performed in each batch by the trip planner. Output are a plan and trip forms. The plan containing a route and a departure time specification for each trip, does not only define trips, but also initiates order assembly and truck loading. Trips for retail products are planned from scratch in each batch, while trips for cooled products are based on a skeletal plan. The purpose is to specify plans meeting the time windows at a reasonable cost. The planner uses a computerized vehicle routing and scheduling system (see also the next section).
Figure 4-2 Organizational chart of the service management department

The task COMPLETE TRIP FORMS is performed by the trip forms controller after truck loading. The completeness of orders and the number of loaded pallets are checked. The actual number of pallets may differ from the planned number due to, for example, inefficient stacking of articles. The trucks are ready for trip execution after this task. Computerized support is not available for this task.

The task ISSUE TRIP FORMS is performed by the forwarding clerk. Backhaul orders are added to the trips and the trip forms are passed to the drivers. As the actual truck departure times are known while this task is executed, a list with the expected return times to the distribution centre is also produced, and trucks for the next batch are hired (the trips for that batch have already been planned). Computerized support is not available for this task.
Figure 4-3 Task PREPARE TRIPS

The task FILL SERVICE DESK is performed continuously by the service desk employee during the preparation and the execution of trips. The task consists of several subtasks: firstly, the entry of rush orders, and secondly, undertaking action on complaints from stores. Furthermore, stores regularly contact the service desk to query the exact truck arrival times. The computerized support available for this task is the one for order entry.

Trip settlement
Figure 4-4 shows the task structure of SETTLE TRIPS. The subtasks will be discussed briefly.
The task RECEIVE TRIP FORMS is carried out by the forwarding clerk when trucks return to the distribution centre. Trip forms are collected, and the reported plan deviations (e.g. incidental waiting at stores) have to be approved. Plan deviations are registered by the drivers, and in case of waiting at a store also initialled by employees of the store. A deviation from plan may lead to a compensation for the trucking company. No computerized support is available for this task.

The task REGISTER TRIP DATA is performed after the return of the trucks to the distribution centre. Data on planned and realized trips are entered into a database management system. The trip data are used for the financial settlement with the trucking companies and for the generation of management information.

The task GENERATE MANAGEMENT INFORMATION is the last task of the trip settlement process performed in the service management department, and is executed in combination with the previous task. Its output are reports showing the deviations from the planned departure times of trips and the violations of time windows (see also section 4.3). The reports are produced by the above-mentioned database management system, and provide management information on the execution of trips.
Problems and developments at RetailCo

Meeting time windows is important in the perceived situation. Nevertheless, management reports indicate that 15% of the time windows in trips for retail products are violated, whilst in case of trips with cooled products, this number is even 40%. Furthermore, trucks have to wait during about 6% of the store visits. Although some violations of time windows are allowed, the above percentages require an investigation into the transportation process.

Meeting the time windows will become even more important in the future. The distribution centre has to deal with the trends in physical distribution as indicated in section 2.2. RetailCo is considering to subdivide the daily operation into more batches and to supply the stores more frequently. The future operation, which tolerates fewer disturbances, requires that the trip executions are punctual. This is the second reason for the need to investigate the transportation process.

RetailCo is considering several changes to the trip planning process to adapt the transportation process to the future. Firstly, the application of a skeletal plan for all trips, requiring only minor plan changes during the daily planning process. Secondly, the provision of additional interactive planning support for trip planning. Thirdly, the use of historic trip data to improve the accuracy of the calculation of trip durations.

Our engagement with RetailCo comprises a feasibility study to judge whether historic trip data can be used to improve the accuracy of the calculation of trip durations. Although the distribution centre is located in a region with little traffic congestion, it can serve as an appropriate case for our research.

4.3 Trip Planning at RetailCo

In this section, we will describe the way in which trips are planned at RetailCo. We will concentrate on the aspects of adhering to time constraints.

Trip execution model

The vehicle routing and scheduling system contains a model for calculating trip durations. The travel and store visit durations are calculated separately. Details of the trip execution model are described below.
The travel durations are based on a matrix with travel durations derived from a customized road network file owned by RetailCo. The road network file was set up by using standard road maps, and consists of 1900 nodes and 5700 links. The level of detail of the road network depends on the presence of stores. Link attributes are the distance and the speed category (10, 15, 40, 60, or 75 km/h). The travel duration of a link is the ratio of the distance and the speed category.

The store visit durations are calculated by a linear function of the store volume. The store volume is expressed in the number of pallet equivalents to be unloaded, and is an estimate based on the articles on order. The function for the calculation of the store visit durations for retail products is the same for all stores and has the following format:

\[
store\_visit\_duration (\text{minutes}) = 22 + 3 \cdot \text{pal\_eqs}
\]  \hspace{1cm} (4-1)

where \text{pal\_eqs} is the number of pallet equivalents of the unit loads.

The store visit durations for cooled products are always 15 minutes fixed. Furthermore, 20 minutes are added to the store visit duration if the trailer has to be disconnected to reach the store.

The extra duration required for backhaul orders is estimated from memory by the forwarding clerk, based on a list of standard loading durations.

**Information exchange between planning and execution**

Drivers receive a trip form from the forwarding clerk for each trip, with the following information:

- **general items**
  - week and day
  - trip identifier
  - truck identifier
  - driver name
  - planned departure time from distribution centre
  - planned return time to distribution centre
  - planned trip duration
  - planned trip distance
items for each store
store identifier
place
number of pallets to be unloaded
number of displays to be unloaded
time window
planned store visit duration

Planned arrival and departure times of store visits are not indicated on the trip form. The only timing indicators are the time windows and the total trip duration. Drivers should start a trip from the distribution centre at the planned departure time and execute the trip at a normal rate.

Drivers have to fill in the trip form during the trip. The departure from and the arrival at the distribution centre are clocked. Waiting durations at a store are initialised by employees of the store. The following information is added:

general items
actual departure time from distribution centre
actual return time to distribution centre
remarks on deviations from plan

items for each store
actual arrival time at store
actual departure time from store
amount of return packing loaded

After the trip, the trip forms are collected by the forwarding clerk, on which occasion the remarks on deviations from plan are coded in terms of cause, extra time, and extra distance. The trip forms are used for the payment of the trucking companies and for the generation of management information. Because the trips are carried out by trucking companies, the distribution centre has no insight into tachograph data.

Tactical trip planning

Tactical trip planning deals with the arrangement of the transportation process. This means that the way of planning and executing trips can be changed at this planning level. In our research, we only consider the issues related to the timing aspects of the trip execution. Examples are:
changing the width of the time windows for trips for retail products and for
cooled products;
starting a project in which drivers are encouraged to pay more attention to
a punctual trip execution;
the definition of planning rules indicating the circumstances under which
violations of time windows are allowed.

Management receives daily reports with the number of late departures from the
distribution centre, and the number of time window violations. The reports contain
data on single trips and totals per batch. The reports only provide information on
the current trip execution process; there is no formalized procedure for undertaking
action if plan deviations or constraint violations are signalled.

RetailCo has staff members participating in projects to solve complex problems.
They have an interactive vehicle routing and scheduling system at their disposal to
evaluate changes in the transportation process. This planning system, however, does
not provide detailed information on the effects of changes on the trip execution
process.

Operational trip planning

Vehicle routing and scheduling takes place at the operational planning level. The
purpose is to specify plans meeting the time windows at a reasonable cost.

In the task PLAN TRIPS (see figure 4-3), a provisional plan is generated by the
computerized vehicle routing and scheduling system, which can be adjusted
manually by the trip planner. The computerized system has no functions for
interactive planning. Figure 4-5 shows the task structure of PLAN TRIPS.

There are several reasons for manual plan adjustments. For example, the
computerized system cannot handle split deliveries, unless an order exceeds the
truck capacity. Also, the system sometimes generates a long trip for the morning
batch, which prohibits the truck from returning in time for a second trip in the
afternoon batch. Furthermore, only the planner is aware of special circumstances
in the distribution centre, the road infrastructure and the stores.
The task **SPECIFY TIME SCHEDULES** is the last subtask of **PLAN TRIPS**. The departure times of the trips are specified, and the feasibility of the trips is checked against the time constraints. The decision structure is shown in figure 4-6.

The vehicle routing and scheduling application calculates a time interval corresponding to the feasible departure times from the distribution centre for each trip. The earliest departure time is the limitation indicating that no left boundaries of time windows are violated, while the latest departure time does the same for the right boundaries. Hence, the system can check the feasibility of a plan against the time constraints.

There is a number of reasons for not adhering to the time interval computed by the system. Firstly, the system schedules split deliveries at the same arrival time, causing two trucks to arrive simultaneously. Secondly, deliveries early in the morning have to be scheduled precisely on the earliest arrival time of the first store in a trip. Thirdly, the trip planner sometimes tolerates small violations of time windows if savings can be achieved. Besides, the trip planner is unaware of the exact travel durations and store visit durations when a plan is adjusted manually.
Problem analysis

It is important that the time windows of stores are adhered to, while this will become even more important in the future, as indicated in section 4.2. Nevertheless, management reports indicate that a considerable number of time windows are violated. An overview of the possible causes is given below:

- The calculated trip durations do not correspond to the real ones. Planners blame, among others, the following situations for plan deviations: (1) the extra time for backhaul is estimated from experience, (2) a road modelled in the road network file is not used, and (3) there is more return packing on Mondays due to the weekend sales peak;
- The interactive vehicle routing and scheduling system used for tactical trip planning does not provide a detailed insight into the trip execution process. Hence, it is impossible to quantify the effects of changes in the transportation process related to trip timing;
- The vehicle routing and scheduling system used for operational planning does not support the interactive specification of time schedules. The specification of time schedules meeting the time windows is consequently difficult.
4.4 Trip Planning in Retail Trade Organizations

Based on the background information provided in the chapters 2 and 3, and the description of trip planning at RetailCo in section 4.3, we now present a descriptive conceptual model which indicates the generic characteristics of trip planning in food retail trade organizations.

Layout of the Planning Support Environment

The layout of a Planning Support Environment (PSE) for vehicle routing and scheduling in the current situation is shown in figure 4-7. We will summarize the most important characteristics of the environment below. Numbers in brackets refer to the corresponding functions in the figure.

Figure 4-7 Layout of the PSE - current situation
Trip execution model
Vehicle routing and scheduling applications have a trip execution model for the calculation of trip durations. Travel and location visit durations are calculated separately. In the current planning systems, travel durations are based on a road network file or a travel duration matrix, while the store location durations are based on a linear function of the amount of goods to be handled.

Information exchange between planning and execution (4.5)
Before the trip, drivers receive trip instructions with the orders to be delivered, generally including a time schedule. The drivers note the plan deviations. After the trips, the trip data are used for the administrative settlement of trips, such as payments, and for the reports with management information. The trip data are generally not used for planning purposes.

Tactical trip planning (1)
Tactical trip planning deals with arranging the way trips are planned and executed. We only consider the issues related to the timing of trips; for example, the width of the time windows. Management reports provide information on the current trip execution process, while vehicle routing and scheduling systems are applied to evaluate changes in the transportation process. These systems, however, do not completely reveal the effects which changes have on the trip execution process.

Operational trip planning (2,3,4)
Operational trip planning comprises a planning task, but also the associated administrative tasks. The planning task, known as vehicle routing and scheduling, deals with the assignment of transportation orders to trucks, and the specification of a route and a time schedule for each trip. The task structures for planning trips in the figures 4–5 and 4–6 appear to be generally applicable. Several organizations use interactive planning systems for vehicle routing and scheduling. The purpose is to specify plans meeting the time windows. The current planning systems, however, are mainly oriented towards routing decisions, and provide little support for the interactive specification of time schedules.

Problem analysis
Meeting time constraints is important and will become even more important in the future. The following causes contribute to the regular violation of time constraints
in the current situation:

- The trip execution model for calculating trip durations shows one or more of the following deficiencies:
  - not all activities of the trip execution are modelled (e.g. the duration for picking up backhaul is estimated from memory);
  - cyclic or incidental effects are not modelled (e.g. more return packing on Mondays, or delays caused by structural traffic congestion);
  - the level of model detail is insufficient (e.g. no distinction is made between stores with and without unloading devices);
  - parameters or variables have incorrect values (e.g. travel durations in road network files differing significantly from the real durations);
- The planning support for handling time constraints is insufficient: at the tactical planning level, to quantify the effects of changes in the transportation process, and at the operational level, for the interactive specification of time schedules.
5

Trip Planning: Proposed Situation

5.1 Introduction

We presented a descriptive model of RetailCo in the previous chapter to clarify the perceived situation in trip planning, and outlined the associated abstraction. We also mentioned the problems related to trip timing.

We shall now introduce normative elements by describing a prescriptive conceptual model, in which we suggest solutions to the above-mentioned problems. The prescriptive conceptual model includes the answer to our first research question:

*What are the characteristics of a Planning Support Environment (PSE) for vehicle routing and scheduling if time constraints play a major role?*

The contents of this chapter are based on the descriptive models, proposals from literature, and a design theory.

The layout of the proposed PSE for vehicle routing and scheduling is described in section 5.2, while the components of this environment are discussed in
sections 5.3 to 5.6. Finally, the normative elements introduced in this chapter are summarized in section 5.7.

5.2 Layout of the Planning Support Environment

Our research is confined to an elaboration of the innovative components of a PSE for vehicle routing and scheduling, which are expected to solve the problems of time constraint violations. The components calling for improvement are the trip execution model for calculating trip durations, tactical planning support to quantify the effects of changes to the transportation process, and operational planning support for the interactive specification of time schedules.

Figure 5-1 shows the layout of a PSE for vehicle routing and scheduling in the proposed situation, based on the slightly extended layout of the current situation, as described in section 4.4. The extensions are discussed below. Numbers in brackets refer to the corresponding functions in the figure which are new or have been changed.

*Trip execution model*

A trip execution model for the calculation of trip durations is required for both tactical and operational trip planning (see below). In section 4.4, we concluded that a model for accurate trip duration calculation is often not available.

A model performing better than the current models is the backbone of the proposed PSE. As will be demonstrated in the next section, some uncertainty about the real trip durations is inevitable. In our opinion, the trip execution model should contain stochastic elements to make this uncertainty explicit.

*Construction of a trip execution model (6)*

The model parameters and variables of the trip execution model should have valid values in order to be able to specify punctual time schedules, also if changes in the transportation process occur.

We suggest the analysis of trip data for the construction (and maintenance) of a model corresponding well to the trip execution process. This type of information exchange between trip planning and trip execution is hardly elaborated in the current situation.
Tactical trip planning (1)
In order to solve the tactical planning problems in the timing of trips, it is necessary to familiarize with the details of the trip execution process. We indicated in section 4.4 that existing vehicle routing and scheduling systems cannot provide the required insight.

Several authors, see for example Sol (1982) and Hoover and Perry (1989), suggest simulation for supporting organizational decision making. Experiences with the simulation of trip executions can be found in the public transport literature: for instance, Gupta (1985) and Muller (1989) describe studies in which the influences of line frequencies and traffic light programmes are examined.

We think that the trip execution simulation with the above-mentioned trip execution model is appropriate for supporting tactical trip planning, as the uncertainty about the real trip durations is made explicit, and the effects of changes to the transportation process can be quantified.
Operational trip planning (3.7)

The specification of time schedules meeting the time constraints is vital in cases where time constraints play an important role. In section 4.4, however, we concluded that existing vehicle routing and scheduling systems provide little support to the interactive specification of time schedules; the signalling of time constraint violations is dominantly inadequate.

Several authors recommend simulation to test the feasibility of plans in manufacturing, see Novels and Wichmann (1989) and Larsen and Alting (1990). Verbraeck (1991) describes the simulation of a production process based on a provisional plan. The simulation outcomes determine whether constraints are violated, which may lead to an iteration in the planning process.

The trip execution simulation with the above-mentioned trip execution model and the associated graphics display of time constraint violations, in our view, can provide adequate support to the interactive specification of time schedules.

A new trip execution model is described in section 5.3, while its construction is discussed in section 5.4. The tasks and computerized support for tactical and operational trip planning are described in the sections 5.5 and 5.6.

5.3 Trip Execution Model

We will now describe a trip execution model which can be used for tactical and operational trip planning. We will first consider the modelling of the trip execution, and then introduce the structure of the model.

Modelling considerations

A trip execution model may have several deficiencies, as indicated in section 4.4. These cause uncertainty about the real trip durations, and should therefore be dissolved as far as possible. According to Monhemius (1987, pp. 168-169), an appropriate indicator expressing uncertainty is the mean square error. Let \( y_i \) be the real and \( \hat{y}_i \) the estimated trip duration of trip \( i \), then \( e_i = y_i - \hat{y}_i \) is the estimation error. If \( \sigma_e \) is the standard deviation of the estimation error, and \( \mu_e \) the expected value, then the mean square error \( mse \) is defined as follows:

\[
    mse = \sigma^2_e + \mu^2_e
\]

(5-1)
The value of the standard deviation can be kept small by applying a trip execution model with many influence factors. For low expected values of the estimation error, the model parameters and variables must have valid values. Hence, a trip execution model, which guarantees little uncertainty in the calculation of trip durations, requires the following:

- the trip execution should be modelled at a low aggregation level;
- all influence factors at the chosen aggregation level should be considered;
- the model parameters and variables should have valid values.

The above requirements will be discussed in detail in the remainder of this section.

**Aggregation level**
The trip execution is modelled in terms of trip components, defined as one or more activities which are part of the trip execution, and which are regarded as an uninterruptible unit. Examples are travelling between locations and visiting a location. A trip is a sequence of trip components, and the trip duration consequently equals the sum of the durations of the participating trip components.

Trip execution models at different aggregation levels can be obtained by decomposition. The trip components at a certain aggregation level can be divided into a number of components at a lower aggregation level. For instance, visiting a location can be split up into unloading the volume, loading the return packing, and filling in forms. See figure 5-2 for an illustrative trip decomposition.

**Influence factors**
For the trip components at the aggregation level selected, influence factors must be identified. We define an influence factor as a property of an object or a phenomenon in the problem domain affecting the duration of a trip component. Examples of influence factors are the volume to be unloaded, and the availability of unloading devices.

For the influence factors, model variables expressing the effect of the influence factor on the trip duration must be defined. These model variables can be used in the construction of a trip execution model. An example is the definition of the number of pallets as a model variable to express the effect of the volume to be unloaded on the location visit duration.
EXECUTE TRIP
- DEPART FROM INITIAL LOCATION
- TRAVEL BETWEEN LOCATIONS
  - DRIVE BETWEEN LOCATIONS
  - WAIT DUE TO TRAFFIC JAM
- VISIT LOCATION
  - UNLOAD VOLUME
  - LOAD RETURN PACKING
  - FILL IN FORMS

Figure 5-2 An example of a trip decomposition

The nature of the influence factors imposes demands on the types of the model variables. Quantitative influence factors, such as the distance between locations, can be straightforwardly mapped onto numeric variables with an interval or ratio value range. However, there are qualitative influence factors in addition to the quantitative ones. These influence factors can be modelled with class variables with a nominal or ordinal value range. An example of a qualitative influence factor is the type of unloading device: either a put-down container or a truck dock.

Another complicating element in modelling the trip execution is that influence factors may have interaction with their effect on trip durations. An example is a certain truck type and an unloading device, both affecting the location visit duration, for which the combined influence is unequal to the sum of the individual influences. Interaction of influence factors should be made explicit in a trip execution model.

Model parameters and variables
The values of the model parameters are estimated by the analysis of (historic) trip data. This parametrization of a trip execution model will be discussed in detail in section 5.4.

The definition of appropriate model variables is not always feasible, for several reasons. Firstly, it may be too difficult to assign a value to a variable adequately.
An example are the weather conditions: rain, fog and glazed frost definitely affect trip durations. However, their influence is location and time dependent, while only a general weather forecast is available.

Secondly, the value of a variable may not be known during planning. Variables which are suitable to account for trip durations can be unsuitable as forecasts because their value is only known after the trip executions. An example is the duration of incidental waiting.

It should be clear that a trip execution model whose model variables are defined for all influence factors, and whose model parameters and variables have a valid value during planning is Utopian. Hence, some uncertainty about the real trip durations is inevitable. If a deterministic model is used, the uncertainty becomes apparent when trip executions deviate from the plan. We prefer to make the uncertainty explicit in both tactical and operational trip plannings, and therefore propose that the trip execution model contains stochastic elements. It can then be used for the simulation of the trip execution.

Example of a trip execution model

Based on the above modelling considerations, we have designed a trip execution model, consisting of a structure (data void) applicable to several organizations. We will first discuss a hypothetical example to introduce the proposed structure, followed by a formal specification of the structure.

Assume that the duration of a store visit for retail products is fixed at 10 minutes, and a variable duration of 2.5 minutes per pallet if truck docks are available, but 4.5 minutes if not. The unloading of cooled products takes 1.5 minutes per pallet. Assume also that in 7.5% of the store visits, incidental waiting occurs with an - exponentially distributed - average duration of 15 minutes, and that the standard deviation of the random disturbances is 5 minutes.

The trip component VISIT LOCATION can be defined as follows, using 6 terms:

\[
\text{visit\_location} = 10 + \delta[\text{dock} \land \text{retail}] \cdot 2.5 \cdot \text{pallets} + \delta[\neg \text{dock} \land \text{retail}] \cdot 4.5 \cdot \text{pallets} + \\
\delta[\text{cooled}] \cdot 1.5 \cdot \text{pallets} + \text{B}(0.075) \cdot \text{E}(15) + \text{N}(0,5)
\]  
(5-2)

67
where:
  • \( \delta_{\text{proposition}} = 1 \) if proposition = true, and 0 otherwise;
  • pallets is the number of pallets;
  • \( B(p) \) is a Bernoulli distributed variable with mean \( p \);
  • \( E(a) \) is an exponentially distributed variable with mean \( a \);
  • \( N(a,b) \) is a normally distributed variable with mean \( a \) and variance \( b^2 \).

Defining the other trip components in a similar way completes the trip execution model.

Table 5-1 illustrates the way in which the above trip component can be defined according to the formal specification of the trip execution model (described below). Each row of the table defines one or more terms of the trip component. The general format of a term is: \( \alpha \cdot B(p) \cdot x \). The \( ct \)-column contains references to the class tables, as they are called, with values for \( \alpha \), of which an example is presented below. The \( B(p) \)-column indicates the probability of incidents to occur. The \( x \)-column consists of the model variables which are either read from the plan or random.

<table>
<thead>
<tr>
<th>term</th>
<th>( ct )</th>
<th>( B(p) )</th>
<th>( x )</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>( B(1) )</td>
<td>( C(10) )</td>
<td>fixed duration</td>
</tr>
<tr>
<td>2/3/4</td>
<td>( ct-1 )</td>
<td>( B(1) )</td>
<td>( pallets )</td>
<td>duration pallets</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>( B(0.075) )</td>
<td>( E(15) )</td>
<td>incidental waiting</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>( B(1) )</td>
<td>( N(0.5) )</td>
<td>random disturbances</td>
</tr>
</tbody>
</table>

Table 5-1 Example of a trip component for a store visit

The value \( C(10) \) in the \( x \)-column of table 5-1 indicates that the variable has a constant value.

A reference to the class table \( ct-1 \) is indicated in table 5-1, the class table being shown in table 5-2. Class tables model the effect of class variables on the trip duration. The values of class variables are used for the selection of one of the model variables in the \( \alpha \) column. Each row must contain an unique combination of values. Below, the variables unloading device and product type define the table entries.
Table 5-2 Example of a class table (table ct-1)

Structure of the trip execution model

After having discussed an example of a trip execution model, we will now specify the structure of such a model formally.

The calculation of trip durations is based on model variables, the value of which may or may not be known during planning. In the first case, the value is read from the plan. We will refer to these variables as \textit{plan-dependent} variables. In the latter case, the variables are modelled as random variables.

The plan-dependent variables are either numeric or class variables. We will indicate the set of $r$ numeric variables as $\mathbf{x}_n = (x_{n_1}, \ldots, x_{n_r})$, and the set of $s$ class variables as $\mathbf{x}_c = (x_{c_1}, \ldots, x_{c_s})$. The random variables are always numeric.

The model variables are used to define trip components. The trip execution model is organized around the following base set of trip components:

- DEPART FROM INITIAL LOCATION;
- TRAVEL BETWEEN LOCATIONS;
- VISIT LOCATION.

A \textit{trip component} consists of one or more terms. The duration of a trip component is the sum of the durations of the terms.
Definition 5-1
A trip component $tc$ is a vector $tc = (tm_1, \ldots, tm_n) \in TM \times \ldots \times TM$, and
- $\text{component\_duration} : TM \times \ldots \times TM \to T$ is a function,
where:
- $n$ is the number of terms;
- $TM$ is the set of possible terms;
- $T$ is the set of time instances;
- $tm_i \in TM$, $1 \leq i \leq n$, is a term;
- $\text{component\_duration}(tc) = \sum \text{term\_duration}(tm_i)$, $1 \leq i \leq n$.

A term of a trip component contains model variables. The duration of a term is obtained by reading the plan-dependent variables from the plan, and by sampling values for the random variables.

Definition 5-2
A term $tm$ is a 3-tuple $tm = (ct, B(p), x) \in TM$, and
- $\text{sample} : RV \to \mathbb{R}$, and
- $\text{term\_duration} : TM \to T$ are functions,
where:
- $RV$ is the set of random variables having a theoretical or an empirical probability distribution;
- $ct$ is a class table in which the values of class variables define entries to the model variables $\alpha \in RV \times \ldots \times RV$ (see below);
- $B(p) \in RV$ is a Bernoulli (1-binomial) distributed model variable with probability $p$ that $B(p) = 1$;
- $x \in RV$ is a random variable. The mean of $x$ can be specified as the value of a plan-dependent numeric variable $xn_i$, $1 \leq i \leq r$;
- $\text{sample}(rv)$ with $rv \in RV$ generates a random sample for $rv$;
- $\text{term\_duration}(tm) = \text{sample}($select\_entry$(ct, xc)) \cdot$
  $\text{sample}(B(p)) \cdot$
  $\text{sample}(x)$.

The class table of a term contains one or more rows, each containing values of class variables and a random model variable. One random model variable has to be selected during the plan simulation. The selection is based on the values of the plan-dependent class variables read from the plan.
Definition 5.3
A class table $ct$ is a $q \times (s+1)$ matrix $ct = ((c_{v_1} \alpha_1), \ldots, (c_{v_q} \alpha_q)) \in (CV^s \times RV) \times \ldots \times (CV^s \times RV)$, and

- $select_{entry}: ((CV^s \times RV) \times \ldots \times (CV^s \times RV)) \times CV^s \rightarrow RV$ is a function, where:
  - $q$ is the number of rows;
  - $CV$ is the set of possible values of class variables;
  - $c_{v_j} \in CV \times \ldots \times CV$, $1 \leq j \leq s$, is a column with elements $c_{v_i,j} \in CV$, $1 \leq i \leq q$, which are empty or contain a value in the domain of the plan-dependent class variable $xc_j$;
  - $\alpha_i \in RV$, $1 \leq i \leq q$, is a random variable;
  - $select_{entry}(ct, xc)$ returns $\alpha_i$ if $\forall j \in 1..s : c_{v_i,j} = \emptyset \lor c_{v_i,j} = xc_j$.

The trip components are used to model the trip execution process. The trip component for the departure from an initial location is meant to model deviations from the planned departure time. A trip execution consists of travelling between locations and visiting locations. Whether a truck has to wait at a location if it arrives before the begin of the time window is subject to specification. Eventually, the truck returns to the initial location. The code of (one replication of) the trip execution process is described below.

```
component_duration(depart_from_initial_location);
while return_to_initial_location do
  begin
    component_duration(travel_between_locations);
    if (arrival_at_location < begin_time_window) and waiting_required then wait;
    component_duration(visit_location);
  end;
component_duration(travel_between_locations).
```

A Bachman diagram of the above structure of the trip execution model is shown in figure 5-3. An instance of the entity type VRS ENTITY TYPE is an entity type which is part of the representation of a vehicle routing and scheduling problem; for example, any of the entity types shown in figure 3-2.

After explaining the trip execution model structure, we can now revisit two modelling considerations. Firstly, the proposed structure allows the description of the trip execution process at a low aggregation level. At the highest aggregation level, the departure from the initial location, travelling between locations, and
visiting a location are identified. The trip components at a lower aggregation level can be modelled as terms of the above trip components (see definition 5-1).

Secondly, the proposed structure offers several ways to express stochastic effects, ranging from a single term for the random disturbances, to a trip execution model in which, for example, both the duration to unload a pallet and the number of pallets are stochastic.

5.4 Construction of a Trip Execution Model

We will now describe the way in which (historic) trip data can be used to construct a trip execution model corresponding well to reality. We will first discuss the tasks for the construction of a trip execution model, and then describe the computerized support for these tasks.
Task structures

The task CONSTRUCT TRIP EXECUTION MODEL is an iterative process in which a model is conceptualized, (historic) trip data are collected, and the model is specified. In the conceptualization phase the make-up of a trip execution model is defined. The conceptualization phase can be left out if a model is already available, and only a model update is required. Trip data are mainly collected on the trucks, although other data sources may have to be consulted as well; for example, the road network file, or a file in which the availability of truck docks is indicated may have to be used. Model parameters are estimated in the specification phase. The task structure is shown in figure 5-4.

![Diagram](image)

**Figure 5-4** Task CONSTRUCT TRIP EXECUTION MODEL
The task CONCEPTUALIZE TRIP EXECUTION MODEL, shown in figure 5-5, is based on the modelling considerations indicated in section 5.3. After the trip decomposition, influence factors must be identified. Model parameters and variables must be defined for the influence factors. Iteration may be necessary if an adequate definition is infeasible. Interactions of influence factors and stochastic effects must then be identified, completing the information defining the make-up of a trip execution model.

Figure 5-5 Task CONCEPTUALIZE TRIP EXECUTION MODEL
Trip data must be analyzed in order to specify a trip execution model. According to Camp and DeHayes (1974, p. 340), the most direct approach is to gather the travel durations between locations for each location pair, as well as the durations of visiting a location for each location, both over a period of time. An alternative approach is a statistical analysis of influence factors with a limited set of trips, to specify a forecasting model.

The large data collection approach is likely to be the most accurate, but it needs an exhaustive data set which may be difficult to obtain. We regard both approaches as complementary. As an illustration, travel durations cannot be estimated precisely by influence factors, but require direct observations, as indicated in section 3.3. On the other hand, location visit durations may be expressed very well in terms of influence factors.

The statistical analysis of influence factors should be aimed at the specification of a trip execution model as described in section 5.3. Recall that the duration of a trip component is a linear function of numeric and class variables. The prediction of values of one criterion variable in a linear composition of predictor variables is suitable for the application of regression analysis (Green, 1978, p. 12). We think that regression analysis is an appropriate technique, although it cannot be used for all the terms of a trip component: incidental effects, such as incidental waiting at a store (see term 5 in table 5-1), must be estimated separately.

The estimates of the travel durations should be based on an analysis of the data gathered in the large data collection approach. These estimates can be used directly in a trip execution model, or can be applied to update a road network file or a travel duration matrix. The decision whether a travel duration has to be changed can easily be supported with a t-test.

The task SPECIFY TRIP EXECUTION MODEL is shown in figure 5-6. First, one or more terms of a trip component must be chosen. Then, trip data have to be selected, which includes the selection of observations of trips, the selection of variables, and possibly the transformation of variables into other variables. The analysis consists of (1) a regression analysis based on influence factors, or (2) a direct analysis of travel or location visit durations, for which at least the mean and the t-value are calculated. The analysis outcomes can be used to construct a trip execution model. The above procedure should be repeated until all terms have been specified.
Figure 5-6 Task SPECIFY TRIP EXECUTION MODEL

The task PERFORM REGRESSION ANALYSIS is shown in figure 5-7. Following phases are indicated: preliminary data analysis, define and estimate regression model, verify regression analysis assumptions, and interpret regression analysis outcomes. Iteration can take place after the first and the last two phases.

The purpose of the preliminary data analysis is to note and - if necessary - to remove peculiarities from the data. The analysis should provide a general "feel" for the data, which we regard, together with knowledge of the problem domain, essential to the analysis of real world data (Chatfield and Collins, 1980, p. 34). The preliminary data analysis can be supported by descriptive statistics and graphical plots of the criterion variable and the predictor variables. Two aspects deserve special attention. Firstly, regression analysis assumes independent predictor variables, which has to be verified. Secondly, the trip data should be
Figure 5-7 Task PERFORM REGRESSION ANALYSIS
checked for errors (Verbeek, 1991a). In particular, missing and extreme values have to be examined.

After the preliminary data analysis, a regression model must be defined. It is important that the model reflects a logical relationship between the criterion variable and the predictor variables. The regression model is used to calculate estimates of model parameters and the customary other statistics, such as residuals, the determination co-efficient $R^2$, and $t$-values for the parameters indicating whether a predictor variable adds information to the model.

The verification phase aims at checking the regression analysis assumptions. The residuals should have a zero mean, be mutually independent, and have a normal distribution. The variance of the residuals should also be constant across observations (Brook and Arnold, 1985, pp. 8-9). These assumptions must be verified by a residual analysis. Another aspect of the verification phase is the detection of outliers, which seriously affect the regression analysis outcomes; they are often caused by errors in the data or by incidental effects which should not contribute to the parameter estimation (see also section 7.2). Both the residual and the outlier analyses can be supported by descriptive statistics and graphical plots of the residuals. According to Du Toit et al. (1986, ch. 7), support for regression analysis can be provided by histogram plots of the residuals and scatterplots of the residuals against the estimated values of the criterion variable.

The interpretation of the regression analysis outcomes consists of two tasks. Firstly, the co-efficient of determination $R^2$ should be interpreted. Its value indicates the amount of variance of the criterion variable which is explained by the model, and determines the significance of the model as a whole. Secondly, the significance of each model parameter should be determined, which requires an interpretation of the calculated $t$-values.

A new regression analysis can be initiated after several tasks. In an iteration, either the regression model or the trip data are changed. Predictor variables may have to be added to or deleted from the model. Predictor variables may have to be transformed into other variables to obtain linearity, or to assure a constant variance of the residuals across observations. Furthermore, observations can be deleted from the data set, which may be convenient in the case of errors in the data.

Computerized support

Trip data can be gathered with forms, tachographs or digital trip data recorders. According to Lowe (1979, p. 5 and p. 11), tachographs record time, distances and
speeds on a chart, and are a compulsory fitment by law. Digital trip data recorders offer the same functionality as tachographs, but extensive driver and sensor inputs can be recorded as well. About 15 types of digital trip data recorders are commercially available in the Netherlands (NEA, 1990, p. 53). The digital trip data recorder will probably become a legally accepted replacement of the tachograph in the future (TVV, 1990, pp. 27-28).

Digital trip data recorders record data with a high accuracy, while a large amount of data can be gathered efficiently and processed automatically. However, we do not demand that this technology be used to collect trip data: the cheaper forms and tachographs may also prove satisfactory. The nature of the data to be recorded depends on the trip execution model, and will therefore vary from organization to organization.

We will now review the support components we propose for the specification of a trip execution model. The indicated functions should provide analysis support to the tasks mentioned above.

The function group TRIP DATA PREPARATOR is intended for the selection of trip data. It allows the free selection of observations and variables; for example, a data set with only the travel durations of a certain time period. Furthermore, variables can be transformed into other variables by specifying functions of variables.

```
function group TRIP DATA PREPARATOR
    [ functions
        select trip data          selects observations and variables
        transform variables       transforms variables into other variables
    ]
```

The function group TRIP DATA DIAGNOSER provides the functions for the support of the preliminary data, residual, and outlier analyses. Descriptive statistics of any variable (criterion variable, predictor variables, or residuals) can be printed. Plots of a single variable, or a variable against another variable can be displayed, as well as the data of a single trip.

```
function group TRIP DATA DIAGNOSER
    [ functions
        show descriptive statistics        shows a.o. the mean and the variance of a variable
        plot histogram                plots a histogram of a variable
        plot scatterplot            plots a scatterplot of two variables
        show trip                    shows the data of a single trip
    ]
```
The function group TRIP DATA ANALYZER aims at performing regression analyses and direct statistical analyses of travel or location visit durations. For a regression analysis, a regression model can be edited and estimated. Output are the estimates of model parameters, the residuals, the determination co-efficient \( R^2 \), and the \( t \)-values for the parameters. For a statistical analysis of travel or location visit durations, the mean and the \( t \)-value for testing against a specified value are calculated.

```plaintext
function group TRIP DATA ANALYZER
[
  functions
  edit regression model  creates, changes or deletes a regression model
  estimate regression model calculates the output for the defined regression model
  analyze durations calculates the mean and the \( t \)-value for travel or location
  visit durations
]
```

The above analysis support facilitates the construction and update of a trip execution model. Nevertheless, knowledge to use statistical methods is still required. The proposed analysis support is therefore intended for staff with ample knowledge of statistics.

A fully automated analysis of trip data, followed by an automatic update of the trip execution model is only feasible if the make-up of the trip execution model is fixed, and only new estimates of model parameters must be provided. This will probably be suitable in a limited set of problem domain changes, for which a moving average estimation can be used (Monhemius, 1987, pp. 170-175). Many changes, however, require a more comprehensive statistical analysis in which the appropriateness of the model make-up must also be considered. Because of the above and the expected low frequency of trip execution model updates, we will not pursue the automated analysis.

### 5.5 Tactical Trip Planning

We will now describe the way in which trip execution simulation can be used to support tactical trip planning, in order to be able to quantify the effects of changes to the transportation process. Task structures and computerized support will be discussed subsequently.
Task structures


The conceptualization and the model construction are mainly covered by the tasks CONCEPTUALIZE TRIP EXECUTION MODEL and SPECIFY TRIP EXECUTION MODEL, discussed in section 5.4. The formulation of a tactical planning problem acting as a starting point for the design of experiments must still be defined.

The task SOLVE TACTICAL PLANNING PROBLEM is shown in figure 5-8. The task is only meant for a limited set of problems: after problem formulation, we must check whether the timing aspects of the trip execution are involved. Solving a tactical planning problem is an iterative process in which several experiments can be conducted until satisfactory outcomes have been obtained. We will indicate the way experimentation and evaluation should be carried out in order to support tactical trip planning.

Experimentation

The experimentation consists of the following phases:

- verification and validation;
- performing a set of experiments.

According to Hoover and Perry (1989, p. 27), verification deals with the internal consistency of a simulation model, while validation is concerned with the correspondence between a simulation model and reality. A verification is required when the trip execution model described in section 5.3 is worked out in a tool for tactical trip planning support (see below). Amongst others, the following questions should be asked: (1) has the model structure been coded correctly?, (2) are the simulation control functions, such as generating random samples and initializing variables before each replication, correct?, and (3) have the output statistics been calculated correctly? This verification is discussed in chapter 6.

A validation is required to test whether the specification of a trip execution model as proposed in section 5.4 produces valid models. A confirmation renders the repeated validation during model construction or update superfluous. The specification of a model takes place by estimating model parameters term by term.
The validation concerns the ability of a specified model as a whole to calculate trip durations correctly, and is discussed in chapter 7.

Task structures are not defined because the above-mentioned verification and validation are non-recurring tasks.

Figure 5-8 Task SOLVE TACTICAL PLANNING PROBLEM

Experiments should be aimed at solving a tactical planning problem. An experiment consists of a number of replications with the same treatment. Following Ören and Zeigler (1979), a treatment comprises:

- the specification and the collection of input data;
- the specification of initialization and run control conditions;
- the specification of output data.
Trip execution models must be defined, and plan data must be generated while specifying and collecting input data. The trip execution model representing the current situation is the starting point for an experiment. An adjusted model can be used to evaluate changes in the trip execution process. For example, the term for incidental waiting at a store (see term 5 in table 5-1) can be removed to evaluate an improved co-ordination of the delivery and the receipt of goods. Planned trips are the second input data set. If the way of planning is not taken into consideration, actual plans can be used. Otherwise, a set of planned trips has to be generated in which the influences of the new way of planning are expressed. For example, trips can be generated without expected violations of time constraints to evaluate improved operational planning support.

The specification of initialization and run control conditions comprises usually the specification of the start up time, the run length, and the number of replications. In the case of a trip execution simulation, a start up time and a run length are not relevant as trips start and finish at given locations. The number of replications should be determined by the required confidence interval and confidence level of the experiment outcomes.

Concerning output data specification, performance indicators satisfying each planning problem cannot be defined. Nevertheless, the number of violations of time constraints, the size of these violations, and trip durations (mean and variance) are the most frequently required indicators.

The task PERFORM AN EXPERIMENT is shown in figure 5-9. First, a treatment should be specified, the trip executions are then simulated, and finally experiment outcomes are generated.

Evaluation
The results of the experiments are studied during the evaluation. Several solutions to the tactical planning problem can be proposed and worked out. The results can also give rise to further experiments. A single solution is selected by taking all the experimental outcomes into consideration.

Computerized support

We will give an overview of the support components proposed for the tactical trip planning below. The indicated functions should provide planning support for the tasks mentioned above.
Figure 5-9 Task PERFORM AN EXPERIMENT

The function group TRIP EXECUTION MODEL EDITOR is intended to define the trip execution models required to perform a set of experiments. Functions are available for editing the trip execution model and its elements.

```plaintext
function group TRIP EXECUTION MODEL EDITOR
{
    functions
    edit trip execution model  creates, changes or deletes a trip execution model
    edit trip component       creates, changes or deletes a trip component
    edit term                 creates, changes or deletes a term
    edit class table          creates, changes or deletes a class table
}
```

The function group EXPERIMENT MANAGER provides functions for the specification of experimental design treatments. A trip execution model and plan data can be selected. The plan data must be generated with a vehicle routing and scheduling system. The output data and the run control conditions can then be specified.
function group EXPERIMENT MANAGER
[
  functions
  select trip execution model
  select plan data
  specify output data
  specify run control conditions
]

The function group EXPERIMENT HANDLER mainly aims at the trip execution simulation, based on a specified treatment. A function is also available for generating output in terms of the specified performance indicators.

function group EXPERIMENT HANDLER
[
  functions
  simulate trip executions
  generate experiment outcomes
]

As is the case with the construction of a trip execution model, the above planning support is intended for use by staff, sufficiently experienced in performing simulation studies independently.

5.6 Operational Trip Planning

We will discuss planning support for the interactive specification of time schedules in this section. We will first describe the task structures, and then the computerized support for the tasks.

Task structures

The task PLAN TRIPS is shown in figure 5-10. After specifying a provisional plan and the time schedules, the trip executions are simulated. The simulation outcomes may indicate violations of time constraints. Examination of these violations may lead to an iteration in the planning process, or to a notification of stores/suppliers if the violations are not resolved.

The output of the task EXAMINE TIME CONSTRAINT VIOLATIONS is an evaluation of the punctuality performance indicating the seriousness of the violations, and a list of possible time schedule changes to resolve the violations; for example, shifts of
departure times and prescribing waiting in trips. Figure 5-11 shows the structure of the task.

Figure 5-10 Task PLAN TRIPS

Figure 5-11 Task EXAMINE TIME CONSTRAINT VIOLATIONS
Computerized support

The current vehicle routing and scheduling systems offer functions for generating and manipulating trips and time schedules (see section 3.4). Extra functions should be available for supporting the trip execution simulation, the generation of simulation outcomes, and the examination of time constraint violations. The functionality described below is a proposed extension to the functionality provided by existing vehicle routing and scheduling applications.

The trip execution simulation is based on the trip execution model described in section 5.3. Two remarks should be made about using this model for operational planning. Firstly, the plan-dependent variables of the trip execution model should be assigned a value in the plan, which may require that - concerning the normal plan data - extra data must be gathered. For instance, if delays caused by road works is an influence factor, a list of road works must be available.

Secondly, incidental effects (see term 5 in table 5-1) should be removed from the model. Incidental effects occur in a limited number of trips in reality, but have the characteristic to spread out in simulation runs. As a consequence, if the probability of a traffic jam occurring is 10%, and the average delay is 15 minutes, then the simulated average travel duration increases by 1.5 minute. A time schedule with an extra duration of 1.5 minute, however, does not guarantee time constraints to be met.

The simulation outcomes should indicate the likely violation of time constraints to the trip planner. The size of a violation is not a fixed value, but is based on a probability density function generated by the replications of a simulation run, of which an example is shown in figure 5-12.

Because a probability density function is difficult to interpret by the trip planner, an uncomplicated penalty indicator to express time constraint violations is preferable. Such an indicator $p_i$ can be calculated from any function $\phi$ of the probability of a violation occurring $p_v$, and the average violation size $s_v$:

$$p_v = \frac{\sum_{i=1}^{n} \delta_i}{n}$$  \hspace{1cm} (5-3)
departure time in reality

time window

real departure

08:00h - 10:00h
window width
violation size

departure time based on simulation outcomes

time window

probability density
departure

08:00h - 10:00h
window width

Figure 5-12 Probability density function of the departure time from a store

\[ sv = \frac{\sum_{i=1}^{n} sv_i}{\sum_{i=1}^{n} \delta_i} \]  \hspace{1cm} (5-4)

\[ pi = \varphi (pv, sv) \]  \hspace{1cm} (5-5)

where:
- \( n \) is the number of replications of the simulation run;
- \( \delta_i = 1 \) if a violation occurs in replication \( i \), and 0 otherwise;
- \( sv_i \) is the size of the violation in replication \( i \) (where \( sv_i > 0 \)).
Sec. 5.6 Operational Trip Planning

The type of $\phi$ function to be used depends on the weight of a violation. Elementary functions are $\phi(pv, sv) = pv$, $\phi(pv, sv) = sv$, and the expected size of a violation $\phi(pv, sv) = pv \cdot sv$.

In addition to penalty indicators for the time constraint violations, representing the time schedules and the time constraint violations graphically on a time bar informs the trip planner about the locations of likely violations, and the effect of changing time schedules on the resolution of violations.

The function group TIME SCHEDULE EVALUATOR is meant for providing the planning support discussed above. Except for a function to simulate the trip executions, there is a function to show the penalty indicators of time constraint violations for all the trips of a plan, and a function to display the time schedule and the violations of a certain trip graphically.

```plaintext
function group TIME SCHEDULE EVALUATOR

[ functions

    simulate trip executions
    show plan performance
    show trip performance

    simulates the trips of a plan
    shows the penalty indicators of all trips of a plan
    shows the time constraint violations in a trip graphically

]
```

The function group should be incorporated in a vehicle routing and scheduling application to enhance the interactive specification of time schedules.

5.7 Summary and Conclusions

The following components of a Planning Support Environment (PSE) for vehicle routing and scheduling are key if time constraints play a major role: (1) the trip execution model for calculating trip durations, (2) tactical planning support to quantify the effects of changes to the transportation process, and (3) operational planning support for the interactive specification of time schedules.

The structure of the proposed trip execution model is organized around trip components for the departure from an initial location, travelling between locations, and visiting a location. The duration of a trip component is a linear function of factors affecting trip durations. The linear functions allow the description of the trip execution process at a low aggregation level, and to model the stochastic effects.
We propose to analyze (historic) trip data in order to specify a trip execution model corresponding well to reality. An important role in the analysis is reserved for regression analysis. Computerized support should be available for the parameter estimation as well as for the associated tasks, such as selecting data and testing statistical assumptions.

Tactical and operational trip planning can be supported with the simulation of trip executions, for which the trip execution model can be used. Planning support for tactical trip planning should comprise computerized support for the specification of the treatments of an experimental design, the trip execution simulation, and the generation of experiment outcomes.

For the support of operational planning, computerized support providing information on violations of time constraints, both in terms of penalty indicators and graphically, should be available. This planning support is an extension to the planning support which is used in current vehicle routing and scheduling systems.
6

Prototype Implementations

6.1 Introduction

In chapter 5, we described the tasks and computerized support for the construction of a trip execution model, and for tactical and operational trip planning, to explain the characteristics of an adaptive trip planning support environment.

We will introduce two prototype systems customized for RetailCo in this chapter. The prototypes are implementations of the above-mentioned computerized support, and constitute our prescriptive empirical model.

Section 6.2 outlines a prototype system for the construction of a trip execution model. A prototype system for tactical and operational trip planning is described in section 6.3.

6.2 Trip Execution Modeller

We indicated the way (historic) trip data can be used in the construction of a trip execution model in section 5.4. We will now describe the prototype implementation
of the Trip Execution Modeller (TEM), a tool supporting the specification of such a model.

The TEM prototype was written in SAS, a data analysis software system, and runs on MS-DOS personal computers with an EGA/VGA graphics screen. The reasons for using SAS are its powerful functions for both data manipulation and statistical analysis. Furthermore, SAS is a RetailCo standard. The prototype applies the following SAS modules in addition to the basic one: the statistical analysis module (SAS/STAT, 1987), the graphics module (SAS/GRAPH, 1988), and the applications facility for menus and interactive applications (SAS/AF, 1988).

TEM is intended for use by staff familiar with SAS and statistics. The TEM prototype includes several functions to support the specification of trip execution models. However, standard SAS procedures can be called as well, which may be required for specific data analyses.

**Function hierarchy**

Figure 6-1 gives an indication of the TEM functions.

---

```
  TRIP DATA MANAGEMENT
    CONVERT FILES
    FILE MANAGEMENT
  ANALYZE DATA WITH REGRESSION ANALYSIS
    SELECT/TRANSFORM DATA
    PERFORM REGRESSION ANALYSIS
    SHOW GRAPHICAL PLOTS
  SHOW PUNCTUALITY PERFORMANCE
    SHOW SINGLE TRIP REPORT
    SHOW TRAVEL DURATION REPORT
    SHOW STORE VISIT DURATION REPORT
```

*Figure 6-1 Function hierarchy Trip Execution Modeller*
The functions can be called from a hierarchy of menus corresponding to the above structure.

**Functions**

Below, we discuss the functions of the TEM prototype for trip data management, regression analysis, and an indication of punctuality performance.

*Trip data management*

Trip data management includes functions for file conversion and file management.

Drivers fill in trip forms during the trip, as indicated in section 4.3. After the trips, the data on these forms are stored in SAS files. There are two files for each week: one with the general information items per trip, and one with the information items varying with each store visit.

The above-mentioned files cannot be used for the specification of trip components, for instance as no travel and store visit durations are registered. The TEM prototype therefore converts the data to a file containing the deviations from the planned trip departures and the travel durations, and a file containing the store visit durations. These target files also contain observations of the predictor variables for the trip components which are registered on the trip forms. In the remainder of this section, the target files will be designated as trip component files.

A report of source file errors is written to an error message file. We regard error detection as important because trip data are registered and entered manually, and errors may affect statistical analysis outcomes adversely. The error detection is based on a set of verification rules which must be obeyed. An example of such a rule is: \( \text{store\_arrival\_time} < \text{store\_departure\_time} \). The rules check the activity sequence within a trip, and check values of variables against their value range.

In the conversion function, a file with the planned travel durations and a file with information about the stores are merged with the trip component files. The variables in these files can be used as predictor variables in the analyses. The precedence structure of the conversion is shown in figure 6-2.
Figure 6-2 Precedence structure CONVERT FILES

File management

Command ==> Unlimited selections allowed.

<table>
<thead>
<tr>
<th>Libname</th>
<th>Name</th>
<th>Memtype</th>
</tr>
</thead>
<tbody>
<tr>
<td>TESDATA</td>
<td>TESSTR47</td>
<td>DATA</td>
</tr>
<tr>
<td>TESDATA</td>
<td>TESSTR48</td>
<td>DATA</td>
</tr>
<tr>
<td>TESDATA</td>
<td>TESERR47</td>
<td>DATA</td>
</tr>
<tr>
<td>TESDATA</td>
<td>TESERR48</td>
<td>DATA</td>
</tr>
<tr>
<td>TESDATA</td>
<td>TESANL-1</td>
<td>DATA</td>
</tr>
</tbody>
</table>

TES data files:

TESTRVII = Travel durations
TESERRII = Conversion errors
TESANL-1 = In- / output analysis

<ENTER> = Select files to delete
<END> = Stop making selections
<CANCEL> = Cancel selections

Figure 6-3 Function FILE MANAGEMENT
The implementation of the conversion function facilitates the simple modification of the calculation of values for new variables and the verification rules. These changes may be necessary each time a trip execution model is (re-)conceptualized, and new model variables are defined.

Trip component files, error message files, and analysis input and output files (see below) are TEM files. A screen of the file management function is shown in figure 6-3. An overview of the TEM files can be displayed, allowing the selection of files to be deleted.

*Analyze data with regression analysis*

Data selection and transformation functions, regression analysis, and plot facilities are available for a complete analysis.

In the TEM prototype, the required data are first identified by selecting the trip component files (either departure/travel or store visit files) for a period of one or more weeks, or the analysis output file (see below) in the case of iteration. This selection is followed by a data step in which values of new variables can be calculated and observations can be selected. The calculations and the selection criteria are specified in standard SAS statements. The screen of the corresponding function is shown in figure 6-4: the variables in the source file(s) can be listed, and statements can be entered. The statements which are indicated in the figure cause the calculation of the values of a new variable `pat_eqs` (pallet equivalents), and the selection of the observations with `pat_eqs > 20`. The selection/transformation function generates a single analysis input file to be used in the regression analysis of trip data.

After the selection/transformation of data, a regression model can be defined and evaluated. The SAS procedure GLM (General Linear Models) is used to calculate estimates of the model parameters and other statistics. The regression analysis outcomes are written to an output window in a standard format, from which they can be printed.
Some of the information resulting from the regression analysis is:

- the number of observations contributing to the estimates;
- the determination co-efficient $R^2$;
- the root mean square error of the model;
- model parameter estimates;
- $t$-values for $H_0$: model parameter estimate = 0;
- the significance probability of the $t$-value.

The regression analysis function also generates an analysis output file, which is a copy of the analysis input file to which the predicted value of the criterion variable and the residual value are added for each observation.

To support the analysis, the values of any variable in the analysis input or output file can be displayed graphically. Both histogram plots of a single variable and scatterplots of two variables can be specified and displayed on the screen. Together with a histogram plot, descriptive statistics can be written to an output window. Figure 6-5 shows an example of a histogram plot of residuals, and figure 6-6 shows a scatterplot of residuals against predicted store visit durations.
Figure 6-5 Example of a histogram plot of residuals

Figure 6-6 Example of a scatterplot of residuals against predicted values
Show punctuality performance
A screen displaying single trip data, and reports with travel and store visit durations are available to indicate punctuality performance.

On the screen, shown in figure 6-7, general trip information, and planned and real durations are displayed. Time window violations, and substantial differences between planned and real durations are highlighted (shaded grey in the figure). In addition to the display of trip punctuality performance, an examination of registration errors and the outlier analysis from the screen is possible.

The travel duration report is standard, and can be generated for the trips of a period of one or more weeks. The report is written to an output window, from which it can be printed. It contains the following information for each origin-destination pair of locations (called a section):

- origin-destination location pair;
- number of observations of the real travel duration;
- planned travel duration;
- average deviation from plan;
- \( t \)-value for \( H_0 \): average deviation from plan = 0.

The travel durations report is sorted in increasing order by the average deviations from plan, and provides information on the structural differences between planned and real travel durations on sections.

The store visit duration report is similar to the above one. Average deviations from the planned store visit duration are calculated for all stores.

Comparison with the design
The functions of the TEM prototype are an implementation of the computerized support indicated in section 5.4. However, there are a few minor differences:

- The menu structure of the TEM prototype does not correspond with the function classification in function groups. The menu structure is organized according to the flow relations of the task structures for the specification of a trip execution model;
The TEM prototype has a function for the conversion of trip data to a format suitable for the specification of trip components. This function defines the interface with the trip data registration.

<table>
<thead>
<tr>
<th>No</th>
<th>From</th>
<th>To</th>
<th>Time</th>
<th>Window</th>
<th>Travel</th>
<th>Store vis.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>do</td>
<td>002</td>
<td>8.03</td>
<td>8.32</td>
<td>8.00</td>
<td>8.30</td>
</tr>
<tr>
<td>2</td>
<td>002</td>
<td>123</td>
<td>8.56</td>
<td>9.45</td>
<td>8.30</td>
<td>10.00</td>
</tr>
<tr>
<td>3</td>
<td>123</td>
<td>093</td>
<td>10.44</td>
<td>11.30</td>
<td>10.30</td>
<td>11.30</td>
</tr>
<tr>
<td>4</td>
<td>093</td>
<td>234</td>
<td>12.02</td>
<td>12.42</td>
<td>12.00</td>
<td>12.30</td>
</tr>
<tr>
<td>5</td>
<td>234</td>
<td>do</td>
<td>12.34</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<END> or <CANCEL> = Return to menu  <PgUp>/<PgDn> = Previous/Next trip

Figure 6-7 Function SHOW SINGLE TRIP REPORT

6.3 Trip Execution Simulator

We indicated that trip execution simulation can be used to support trip planning, in sections 5.5 and 5.6. We will now describe the prototype implementation of the Trip Execution Simulator (TES), a simulation tool for the support of tactical and operational trip planning.

We will only discuss a single prototype for tactical and operational planning, as the structure of the trip execution model and the simulation functions are similar for both types of planning. Throughout the section, we will note the differences in the use for tactical and operational trip planning.

The TES prototype was written in Turbo Pascal (Turbo, 1989), extended with the Turbo Professional Toolbox (TurboProf, 1988), and runs on MS-DOS personal computers with an EGA/VGA graphics screen. Pascal was used rather than a
simulation language because it allows a straightforward implementation of the trip execution model as described in section 5.3, including the model edit functions.

**Function hierarchy**

Figure 6-8 gives an indication of the TES functions.

```
TRIP EXECUTION MODEL MANAGEMENT
   MODEL VARIABLES MANAGEMENT
   EDIT TRIP EXECUTION MODELS
   EDIT TRIP COMPONENTS
   EDIT TERMS
   EDIT CLASS TABLES

PERFORM EXPERIMENT
   DEFINE TREATMENT
   RUN EXPERIMENT

SHOW TIME WINDOW VIOLATIONS
   SHOW PLAN PENALTY REPORT
   SHOW TRIP PENALTY REPORT
```

**Figure 6-8 Function hierarchy Trip Execution Simulator**

The functions can be called from a set of menus corresponding to the above function hierarchy.

**Functions**

Below, we will give an overview of the functions of the TES prototype for trip execution model management, the performance of an experiment, and the identification of time window violations.

**Trip execution model management**

The TES prototype contains a straightforward implementation of the trip execution model described in section 5.3. Model construction starts by editing the terms and
class tables. A trip component consists of a selection of terms. A model is a
selection of trip components, with the indication whether waiting for early arrivals
is required. See figure 6-9 for an example of the screen for editing terms.

- Figure 6-9 Function EDIT TERMS

The TES prototype includes a function for editing a list with the plan-dependent
variables to be used for trip execution model definition. Variables must be declared
as numeric or class variables, and whether their values are plan, trip, or trip
component dependent.

The plan-dependent variable list also defines the variables required for the plan
file for the trip execution simulation. In the prototype implementation, plans are
converted to a TES format plan file by an easily adaptable SAS program.

Models for experiments at the tactical planning level can be set up with the
functions for trip execution model management. Only a single model representing
the current trip execution process is required for the support of operational trip
planning.
**Perform experiment**

To perform an experiment, a TES prototype function defines the treatment of an experiment, and one runs the experiment.

The definition of a treatment consists of the selection of a trip execution model, the selection of a plan file with planned trips, and the specification of the run control conditions. The specification of run control conditions indicates whether the simulation runs in *deterministic* or *stochastic* mode (see also section 5.3). In the deterministic mode, the mean values of the random variables are used, while in the stochastic mode random values are sampled. For the stochastic mode, a confidence level and confidence interval for the arrival and departure times of location visits should be specified, determining the basis for the calculation of the number of replications.

The simulated arrival and departure times in each replication of a trip are written to a simulation output file. This file can be used for the generation of experimental outcomes, for which simple SAS programs can be written in the prototype implementation. The nature of the experimental outcomes to be generated depends on the tactical planning problem to be solved.

Tactical trip planning can be supported by the functions for performing an experiment. For operational trip planning support, only a single treatment is required, in which the trip execution model representing the current trip execution process and the present trip plan must be selected. The simulation should run in the stochastic mode.

**Show time window violations**

The TES prototype has a report indicating the penalty indicators of the time window violations for all trips of a plan, and a report representing these violations within a trip graphically. Both reports are intended for operational trip planning support, and can be displayed on the screen.

Figure 6-10 shows an example of the screen with penalty indicators for all trips of a plan. High value indicators are highlighted (shaded grey in the figure). The rows of the table provide information on a single trip.
The following information is displayed in the columns. The names in brackets are Dutch abbreviations:

1 trip identifier (ritnr);
2 number of stores to be visited (fil#);
3 general penalty indicator based on the remaining indicators (straf);
4 expected number of times waiting on early arrival (wacht#);
5 expected overall duration of waiting on early arrival (duur);
6 expected number of time window violations (blok#);
7 expected overall duration of time window violations (duur).

The graphics report on time window violations can be called from the above mentioned screen by selecting a trip. Figure 6-11 shows an example of this report, consisting of bars with 5 bar lines. The first and last bars represent the departure from, and the arrival at the distribution centre, respectively, and the other two represent store visits.
Figure 6-11 Function SHOW TRIP PERFORMANCE

The 5 bar lines represent:

1. store visit duration based on plan;
2. time window violation based on plan;
3. time window of the store visit;
4. time window violation based on simulation (averaged);
5. store visit duration based on simulation (averaged).

The oblique lines between the bars indicate the travel durations.

Comparison with the design
The functions of the TES prototype are an implementation of the computerized support indicated in the sections 5.5 and 5.6. However, there are a few minor differences:

- The trip execution simulation can be run in a deterministic and a stochastic mode in the TES prototype. The mode toggle is implemented to enhance the evaluation of the simulation (see chapter 7);
To keep the implementation efforts restricted, no function is available in the TES prototype for the calculation of the output data of a treatment. The required format of the experiment outcomes must be generated by, for example, a SAS program; the functions for operational trip planning should be incorporated in a vehicle routing and scheduling system. The functions are now implemented in a stand-alone system, as the TES prototype is meant for illustration and evaluation purposes only.

Verification

After the implementation of the TES prototype, the internal consistency of the trip execution simulation was tested by verification. By exposing the prototype system to a number of special treatments, the correctness of the following aspects has been checked:

- the sampling of random values from probability distributions;
- the (re-)initialization of variables before each replication;
- the process flow of the trip execution;
- the calculation of the required number of replications;
- the calculation of the data for the simulation output file.

A structured walkthrough of the Pascal code handling the trip execution simulation was performed in addition.

No errors could be detected in the final version of the prototype. Details concerning the verification can be found in Marck (1991, pp. 35-40).
Using the Planning Support Environment

7.1 Introduction

The previous two chapters described the planning support for adaptive trip planning, consisting of a trip execution model adaptable to data on executed trips, and of facilities supporting tactical and operational trip planning. For RetailCo, a Trip Execution Modeller (TEM) and a Trip Execution Simulator (TES) prototype were set up.

We will devote this chapter to the planning support at RetailCo, the outcomes of which provide the answer to our second research question:

What are the effects of using the Planning Support Environment (PSE) for vehicle routing and scheduling?

This chapter discusses our and RetailCo staff’s application of the prototypes. It should be remembered that our engagement with RetailCo concerned a feasibility study, not the development of an operational information system.
In section 7.2, the construction of a new trip execution model for RetailCo is discussed. The validation of this model is described in section 7.3. A test whether the new trip execution model is an improvement on the current model is the subject of section 7.4. Section 7.5 gives an example of solving tactical trip planning problems. Section 7.6 describes the experiences with the planning support for operational trip planning. The effects of using the above-mentioned prototypes are summarized in section 7.7.

7.2 Construction of a Trip Execution Model

An adequate trip execution model is obviously essential to the specification of punctual time schedules. We will first report on the construction of a new model for RetailCo, and discuss the application of the conceptualization and the specification task described in section 5.4. We conclude by describing the resulting trip execution model.

Conceptualization of the trip execution model

The starting point for the construction of a trip execution model is the trip decomposition. RetailCo's trips are followed from the departure to the return to the distribution centre. Backhaul trips are not considered. The trip component for the departure from the initial location, i.e. the distribution centre, is not decomposed further. The trip component for travelling between locations consists of driving, parking and picking up the trailer if stores can be accessed by small trucks only, and delays, for example, caused by traffic congestion. The trip component for store visits consists of unloading the store volume, loading return packing, filling in forms, and incidental waiting.

Influence factors must be identified after the above trip decomposition, followed by model variable definition. We must determine whether values can be assigned to the model variables with acceptable effort, and whether these values are available during planning. No influence factors are identified for the departure from the distribution centre. The outcomes of the conceptualization for travelling between locations are listed in table 7-1, and for visiting a store in table 7-2.

Table 7-1 requires following comments. The main influence factors for the travel durations, i.e. the route, the length of the route links, and the average speed on each
link, are represented by the variable \textit{drive\_plan} containing the planned travel duration of the shortest path. The stores requiring trailer disconnection are identified by the variable \textit{trailer\_handling}. However, the parking location for the trailer is unknown during planning. The delays caused by structural congestion during peak hours depend on the origin-destination location pair, and time. Incidental (congestion) delays cannot be foreseen during planning, but they are recognized when real travel durations exceed the planned ones significantly. The driver’s experience, the driving style, and the weather conditions are influence factors for which model variable values can only be determined with difficulty.

<table>
<thead>
<tr>
<th>influence factor</th>
<th>ground for explanation</th>
<th>(v)?</th>
<th>(p)?</th>
</tr>
</thead>
<tbody>
<tr>
<td>route between locations</td>
<td></td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>length of link</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>average speed on link</td>
<td>{ \textit{drive_plan} }</td>
<td></td>
<td></td>
</tr>
<tr>
<td>parking trailer</td>
<td>\textit{trailer_handling}</td>
<td>+</td>
<td>+/-</td>
</tr>
<tr>
<td>picking up trailer</td>
<td>\textit{trailer_handling}</td>
<td>+</td>
<td>+/-</td>
</tr>
<tr>
<td>structural congestion</td>
<td>origin-destination location pair, time</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>incidental delay</td>
<td>deviation from plan is an outlier</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>experience of driver</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>driving style</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>weather conditions</td>
<td></td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

\(v\)? = can a value be assigned to a model variable with acceptable effort?  
\(p\)? = is the value of the model variable known during operational planning?

\textbf{Table 7-1 Influence factors and model variables for the travel durations}

Following comments apply to the contents of table 7-2. We distinguish between trips for retail products and for cooled products with the variable \textit{trip\_type}. Store visit durations largely depend on the store volume, represented by the variables \textit{pallets} and \textit{displays}. The duration of unloading a pallet may differ from the duration for a display, which makes the commodity type an influence factor. The variable \textit{return\_packing} indicates the amount of return packing. However, this amount is unknown during planning and is not registered accurately. For planning purposes, the amount is assumed to be proportional to the store volume. The variable \textit{unloading\_situation} describes the unloading situation at a store, such as the availability of unloading devices, and determines the duration to unload a pallet or display. Forms are filled in for each store visit. A truck may have to wait if it
arrives before a time window, and for several other reasons. Waiting is only registered on the trip form if it leads to an extra payment. Substantial deviations from plan are therefore used to detect waiting.

<table>
<thead>
<tr>
<th>influence factor</th>
<th>ground for explanation</th>
<th>v?</th>
<th>p?</th>
</tr>
</thead>
<tbody>
<tr>
<td>trip type (retail or cooled)</td>
<td>trip_type</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>store volume</td>
<td>pallets, displays</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>commodity type</td>
<td>pallets, displays</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>amount of return packing</td>
<td>return_packing</td>
<td>+/−</td>
<td>−</td>
</tr>
<tr>
<td>unloading situation</td>
<td>unloading_situation</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>filling in forms</td>
<td>always required</td>
<td></td>
<td></td>
</tr>
<tr>
<td>waiting on early arrival</td>
<td>arrival before time window</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td>incidental waiting</td>
<td>deviation from plan is an outlier</td>
<td>−</td>
<td></td>
</tr>
<tr>
<td>experience of driver</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

v? = can a value be assigned to a model variable with acceptable effort?  
p? = is the value of the model variable known during operational planning?

Table 7-2 Influence factors and model variables for the store visit durations

Note that model variables are not defined for all influence factors, or that model variable values are unknown during planning. Real trip durations are therefore slightly uncertain. The resulting stochastic effects in the trip execution process are modelled by adding a random disturbances term to the trip components for the departure from the distribution centre, for travelling between locations, and for store visits.

Specification of the trip execution model

Trip data must be collected for the specification; they are registered on trip forms and stored in SAS files as indicated in sections 4.3 and 6.2, after which road network and store information is added. Small changes in trip data recording were applied during the research, such as time measure in minutes rather than quarters of an hour.

As store visits only vary little from week to week, a data set covering a few weeks is a representative sample for the trip data analysis: 6 week trip forms were used, spanning about 2000 trips.
Sec. 7.2 Construction of a Trip Execution Model

The task structures of section 5.4 and the TEM prototype were applied in the specification phase. More than 40 regression and other analyses were carried out, before a complete trip execution model could be constructed.

We will only discuss the analyses contributing significantly to the model specification. The analyses for the departure from the distribution centre, the travel durations, and the store visit durations are described separately, after a few general remarks.

It was found that there were many outliers in the travel and store visit durations. Outliers are residuals which have a value significantly exceeding the inaccuracies due to the regression model applied, and which are caused by data errors or should be explained by influence factors currently not in the regression model.

An examination of the outliers indicated that they were mainly due to incidental effects such as incidental travel delays during the return to the distribution centre and incidental waiting at stores.

Two subsequent regression analyses were often required for an estimate of the model parameters of the trip execution model. The purpose of the first analysis was to identify outliers, which were then removed before the second analysis. The probability of incidental effects occurring, and their durations were then estimated by analyzing the removed outliers.

We will apply the following format for the definition of regression models in the remainder of this chapter:

\[ \text{criterion\_var} = \text{predictor\_var1\_predictor\_var2(predictor\_var3)} \]  

According to the above definition, the value of \text{criterion\_var} depends on a linear combination of \text{predictor\_var1} and \text{predictor\_var2}, in which terms for \text{predictor\_var2} exist for each value of class variable \text{predictor\_var3}.

\text{Analysis of the departure from the distribution centre}

Trip departure times are specified in quarters of an hour in operational trip planning. The variable \text{departure\_plan\_deviation} defines the difference between the real and planned departure times in minutes.

As no influence factors are identified for the departure from the distribution centre, only the stochastic effect of the plan deviations must be quantified. The outcomes
of the corresponding regression analysis for the retail product trips are shown in table 7-3. The analysis for the cooled product trips produces similar outcomes.

<table>
<thead>
<tr>
<th>Selected data</th>
<th>trips for retail products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observations</td>
<td>1756</td>
</tr>
<tr>
<td>Model</td>
<td>departure_plan_deviation = intercept</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.00</td>
</tr>
<tr>
<td>Root MSE</td>
<td>4.77</td>
</tr>
<tr>
<td>Parameter</td>
<td>Estimate</td>
</tr>
<tr>
<td>Intercept</td>
<td>– 0.33</td>
</tr>
</tbody>
</table>

Table 7-3 Analysis: deviations from the planned departure time

We conclude the following from the regression analysis outcomes in table 7-3. The value $R^2 = 0.00$ indicates that an intercept term does not contribute to the explanation of the variance of departure_plan_deviation. Apparently, the deviations from plan are randomly distributed around the planned departure time.

The value Root MSE = 4.77 indicates only a small variance in the plan deviations. Assuming a normal distribution, about 70% of the trips depart in the interval [departure_plan - 4.77, departure_plan + 4.77]. A plot of the residuals shows that the deviations are positively skewed normally distributed.

*Analysis of travel durations*

The travel duration is defined as the time elapsed between the departure from the origin and the arrival at the destination, and consists of driving, parking and picking up a trailer, and (congestion) delays.

The primary variable for the calculation of travel durations is the planned duration based on the road network file drive_plan. The difference between the real and the planned durations is defined by the variable drive_plan_deviation. We will attempt to explain the values of this variable by the linear combination of influence factors listed in table 7-1.
Sec. 7.2  Construction of a Trip Execution Model

The first regression analysis aims at the quantification of the effects of parking and picking up the trailer for stores with access limitations. Extra durations for trailer handling are required before and after such store visits. The analysis results are shown in table 7-4.

<table>
<thead>
<tr>
<th>Selected data</th>
<th>: all trips</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observations</td>
<td>: 5981</td>
</tr>
<tr>
<td>Model</td>
<td>: drive_plan_deviation = trailer_handling</td>
</tr>
<tr>
<td>R²</td>
<td>: 0.00</td>
</tr>
<tr>
<td>Root MSE</td>
<td>: 20.58</td>
</tr>
</tbody>
</table>

| Parameter    | Estimate | Pr > |t| | t for H₀: Estimate = 0 |
|--------------|----------|------|---|----------------------|
| no handling  | 5.10     | 0.0001 | 18.75 |
| parking      | 5.53     | 0.0034 | 2.93  |
| both         | 10.00    | 0.6270 | 0.49  |
| picking up   | 11.52    | 0.0001 | 6.79  |

Table 7-4 Analysis: effect of parking and picking up a trailer

We conclude the following from the regression analysis outcomes in table 7-4. The value $R^2 = 0.00$ indicates that the variable `trailer_handling` does not contribute to the explanation of the variance of `drive_plan_deviation`. Apparently, the plan deviations are mainly caused by other influence factors.

The parameter estimates show that the duration for no handling and for parking do not differ significantly. On the other hand, an extra duration is required for picking up. This duration is not necessarily caused by trailer handling.

The value Root MSE = 20.58 is high. This appears to be caused mainly by delays during the return to the distribution centre, which implies that such a return is an influence factor. One of the reasons for these delays is that drivers take a break after having visited all the stores of a trip.

The above analysis outcomes clarify the effect of parking and picking up a trailer. The observations including trailer handling have been removed from the data set in the following travel duration analyses.
The second regression analysis of travel durations aims at the quantification of the delays during the return to the distribution centre. Table 7-5 shows the outcomes of the analyses before and after the removal of the observations with a residual over 30 minutes.

<table>
<thead>
<tr>
<th>Selected data</th>
<th>return to the distribution centre, no trailer handling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observations</td>
<td>1640 / 1458</td>
</tr>
<tr>
<td>Model</td>
<td>drive_plan_deviation = Intercept</td>
</tr>
<tr>
<td>R²</td>
<td>0.12 / 0.14</td>
</tr>
<tr>
<td>Root MSE</td>
<td>34.89 / 11.38</td>
</tr>
<tr>
<td>Parameter</td>
<td>Estimate Pr &gt;</td>
</tr>
<tr>
<td>intercept</td>
<td>12.73 / 09.63 0.00 / 0.00 14.77 / 15.52</td>
</tr>
</tbody>
</table>

Table 7-5 Analysis: effect of delays during the return to the distribution centre

It is clear from the results in table 7-5 that the trips with residuals over 30 minutes have a significant impact on the variance of the travel durations to the distribution centre. About 10% of the observations have such a residual, and a plot shows that these are positively skewed normally distributed.

The third regression analysis of travel durations aims at the quantification of the effect of structural congestion. The delays caused by structural congestion depend on the location in the road network, and on the time of the day. In order to test whether congestion delays influence the trip execution at RetailCo, travel durations between the distribution centre and a store were analyzed. Only the first section (i.e. origin-destination location pair) of a trip is examined, because relatively few observations were available for travelling between stores, while for travelling to the distribution centre, too many plan deviations caused by other factors were found. Two predictor variables are used: firstly, the destination store zone (a zone contains about 10 stores), and secondly, the departure time from the distribution centre. The analysis results for one zone are shown in table 7-6.
Table 7-6 Analysis: effect of structural congestion (one zone)

We conclude the following from the regression analysis outcomes in table 7-6. The value $R^2 = 0.20$ indicates that the destination zone and the departure hour only explain a fraction of the variance of $\text{drive\_plan\_deviation}$. Nevertheless, there are clear differences in the parameter estimates.

The parameter estimates for the destination zone - departure hour combinations have been examined in detail. The parameter estimates of a single zone plotted against the departure hour are similar for the different zones. Firstly, the difference between the lowest and highest estimates is about 10 minutes. Secondly, no pattern indicating traffic peak hours can be recognized. A plot for two zones is shown in figure 7-1.

A breakdown of parameter estimates demonstrates that each estimate is based on a few destination stores, and that the average deviation from the planned travel duration varies significantly across these stores. Furthermore, there are only few, if any, observations around 8:00 a.m.
We conclude that no structural congestion effects can be recognized. Apart from the occasional congestion in the north-eastern part of the Netherlands, the following reasons prohibit a quantification of these effects. Firstly, the destination zone is not a dependable predictor variable: the average deviation from the planned travel duration differs too much across the stores in a single zone. Neither can the destination store be used as a predictor variable because a store is usually visited at the same time instance for a period of time. Secondly, the deviations caused by congestions are approximately equal to the measuring and rounding errors in the planned travel durations.

The deviations from plan are not explained adequately by the a priori determined influence factors with the above travel duration analyses. However, it appeared that the deviations depend on the origin-destination location pairs. We will therefore discuss an analysis in which the average deviation from the planned travel
duration is calculated for each location pair (called a section). The results of this analysis clarify the structural differences between the real and planned travel durations in sections.

Prerequisites for a feasible analysis at the aggregation level of single sections are the number of sections not being too high, and the availability of several real travel duration observations for each section. As the distribution centre supplies more than 150 stores, there are at least $150 \times 150$ sections. However, in the 6 week period for which the trip data were analyzed, only 550 sections were used, while about 400 sections were used 4 times or more.

The average deviation from the planned travel duration is calculated for each section used more than 3 times. The analysis results for a few sections are shown in table 7-7.

<table>
<thead>
<tr>
<th>section from → to</th>
<th>drive_plan</th>
<th>average deviation</th>
<th># observations</th>
<th>$t$ for $H_0$: avg dev = 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>161 → 136</td>
<td>84.0</td>
<td>-12.0</td>
<td>23</td>
<td>-12.58</td>
</tr>
<tr>
<td>064 → 330</td>
<td>36.0</td>
<td>-7.0</td>
<td>11</td>
<td>-5.12</td>
</tr>
<tr>
<td>559 → 737</td>
<td>108.0</td>
<td>-5.0</td>
<td>13</td>
<td>-3.42</td>
</tr>
<tr>
<td>465 → 341</td>
<td>35.0</td>
<td>2.0</td>
<td>17</td>
<td>1.85</td>
</tr>
<tr>
<td>739 → 761</td>
<td>11.0</td>
<td>3.0</td>
<td>8</td>
<td>2.06</td>
</tr>
<tr>
<td>714 → 231</td>
<td>10.0</td>
<td>4.0</td>
<td>7</td>
<td>4.00</td>
</tr>
<tr>
<td>221 → 419</td>
<td>14.0</td>
<td>5.0</td>
<td>6</td>
<td>3.80</td>
</tr>
<tr>
<td>406 → 952</td>
<td>98.0</td>
<td>5.0</td>
<td>16</td>
<td>2.41</td>
</tr>
<tr>
<td>954 → 527</td>
<td>10.0</td>
<td>6.0</td>
<td>6</td>
<td>5.00</td>
</tr>
<tr>
<td>954 → 792</td>
<td>58.0</td>
<td>8.0</td>
<td>6</td>
<td>4.06</td>
</tr>
<tr>
<td>532 → 259</td>
<td>42.0</td>
<td>11.0</td>
<td>12</td>
<td>6.91</td>
</tr>
</tbody>
</table>

Table 7-7 Analysis: deviations from planned travel durations (partial)

The average deviations for all sections lie in the interval [-15, +15] minutes. The decision whether the average deviation from plan of a section differs significantly from zero is supported by a $t$-test. At a tolerance level $\alpha = 0.10$, about 200 sections appear to have structural deviations. If the average deviations are used to update the planned travel durations of the road network file, then the remaining value for the unexplained variance in travel durations is Root MSE = 5.
Analysis of store visit durations
The store visit duration is defined as the time elapsed between the arrival and the departure, and consists of unloading the store volume, loading return packing, filling in forms, and incidental waiting.

The first regression analysis aims at the quantification of the effect of the store volume and the unloading situation. The duration of a store visit depends on the number of pallets, the number of displays, and the unloading situation. In the analysis, only the store visits for retail products without waiting are considered. The outcomes of the regression analysis are shown in table 7-8.

| Parameter          | Estimate | Pr > |t|  | t for H₀: Estimate = 0 |
|--------------------|----------|------|---|-----------------------|
| intercept          | 24.17    | 0.0001 | 29.65 |
| pallets            |          |       |   |
| public road        | 2.69     | 0.0001 | 19.86 |
| parking place      | 2.71     | 0.0001 | 28.34 |
| truck dock         | 2.48     | 0.0001 | 34.83 |
| displays           |          |       |   |
| public road        | 0.95     | 0.0338 | 2.12  |
| parking place      | 1.36     | 0.0001 | 5.00  |
| truck dock         | 0.78     | 0.0005 | 3.51  |

Table 7-8 Analysis: effect of store volume and unloading situation

We conclude the following from table 7-8. The value $R^2 = 0.60$ indicates that the store volume and the unloading situation only partially explain the variance in store visit durations. The differences in the parameter estimates for unloading a pallet are
small, but there are clear differences between the parameter estimates for displays. Examination of the trip data reveals that this is caused by the unloading of generally only a few displays during store visits. From now on, the store volume will be expressed in pallet equivalents by the variable `pal_eqs`, where two displays are one pallet equivalent.

The above outcomes indicate that real store visit durations are not explained adequately by the *a priori* determined influence factors. However, it appeared that the durations depend on the unloading situation of a store. We will therefore discuss an analysis in which the average deviation from the planned store visit duration is calculated for each store. This analysis produces a classification of the stores which can be used for a detailed analysis of store visit durations.

The average deviation from the planned store visit duration for retail products is calculated for each store, and is used to assign the store to a class which is an influence factor for store visit durations. The class values are:

\[
\begin{align*}
\text{average deviation from planned store visit duration in} \\
(-\infty, -15) & \rightarrow \text{class}_{--} \\
[-15, -05) & \rightarrow \text{class}_- \\
[-05, +05) & \rightarrow \text{class}_{--} \\
[+05, +15] & \rightarrow \text{class}_+ \\
[+15, +\infty) & \rightarrow \text{class}_{++}
\end{align*}
\]

About 40 stores (25% of the total) are assigned to a class other than class_{--}, and thus have a structural - though small - deviation from plan. Only a few stores are assigned to class_{--}, and none to class_{++}.

The second regression analysis of store visit durations quantifies the effect of the store volume and the above classification of stores. Only the store visits for retail products without waiting are considered. The analysis results are shown in table 7-9.

The following conclusions can be drawn from the regression analysis outcomes in table 7-9. The value $R^2 = 0.73$ indicates - as expected - that the store classification explains the variance of `visit_real` better than the variable for the unloading situation in the previous analysis. The differences between the parameter estimates for unloading a pallet are rather small, however. For a full truckload consisting
of 30 pallets, the store visit duration between a slow and a fast store varies by about 20 minutes.

<table>
<thead>
<tr>
<th>Selected data</th>
<th>trips for retail products, no waiting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observations</td>
<td>2433</td>
</tr>
<tr>
<td>Model</td>
<td>visit_real = intercept pal_eqs(store_class)</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.73</td>
</tr>
<tr>
<td>Root MSE</td>
<td>10.19</td>
</tr>
</tbody>
</table>

| Parameter     | Estimate | \( Pr > |t| \) | \( t \) for \( H_0: \) Estimate = 0 |
|---------------|----------|----------------|---------------------------------|
| intercept     | 25.33    | 0.0001         | 32.83                           |
| pal\_eqs      |          |                |                                 |
| class\_---     | 2.17     | 0.0001         | 22.58                           |
| class\_-       | 2.27     | 0.0001         | 44.10                           |
| class\_++      | 2.53     | 0.0000         | 54.77                           |
| class\_+       | 2.90     | 0.0001         | 42.59                           |

Table 7-9 Analysis: effect of store volume and store classification

The regression analysis outcomes for retail product trips were used to determine the effect of waiting at a store. It appears that incidental waiting occurs in about 8% of the store visits, with an average duration of 20 minutes. A plot shows that the waiting durations have a positively skewed normal distribution.

The last regression analysis and the estimation of the effect of incidental waiting have also been carried out for cooled product trips. The results are similar to the above, and have been included in the following trip execution model specification.

The resulting trip execution model

The results of the above and other analyses were used in the specification of a new trip execution model for RetailCo. The model consists of trip components for the departure from the distribution centre, for travelling between locations, and for visiting a store. These trip components are discussed below. Section 5.3 describes the specification of trip execution models.
Sec. 7.2 Construction of a Trip Execution Model

The terms of the trip component for the departure from the distribution centre are shown in table 7-10. There is no structural deviation from the planned departure time. The random disturbances are gamma distributed with a standard deviation upwards of 4.5 minutes.

<table>
<thead>
<tr>
<th>term</th>
<th>contents</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>- 7.5</td>
<td>random disturbances shift: mean = 0</td>
</tr>
<tr>
<td>2</td>
<td>$\Gamma(2.0,3.25)$</td>
<td>random disturbances</td>
</tr>
</tbody>
</table>

**Table 7-10** Trip component for the departure from the distribution centre

The terms of the trip component for travelling between locations are shown in table 7-11. The real travel duration is primarily based on the planned duration in the road network file, but may have a structural deviation. In case of parking or picking up the trailer, an extra duration is required. For sections without the distribution centre (dc) as their destination, the fixed duration is 1 minute, and the random disturbances are normally distributed with a standard deviation of 5 minutes. At the return to the distribution centre, the fixed duration is 5 minutes and the standard deviation of the random disturbances is 10 minutes, while incidental delays occur in 10% of the trips. These delays are gamma distributed with an average duration of 30 minutes.

<table>
<thead>
<tr>
<th>term</th>
<th>contents</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><em>drive_plan</em></td>
<td>planned duration road network</td>
</tr>
<tr>
<td>2</td>
<td><em>mean_drive_plan_deviation</em></td>
<td>structural deviation</td>
</tr>
<tr>
<td>3</td>
<td>$\delta$[parking trailer] $\cdot$ 1.0</td>
<td>parking trailer</td>
</tr>
<tr>
<td>4</td>
<td>$\delta$[picking up trailer] $\cdot$ 6.0</td>
<td>picking up trailer</td>
</tr>
<tr>
<td>5</td>
<td>$\delta$[to dc] $\cdot$ $N(1.0,5.0)$</td>
<td>fixed duration/random disturbances</td>
</tr>
<tr>
<td>6</td>
<td>$\delta$[to dc] $\cdot$ $N(5.0,10.0)$</td>
<td>fixed duration/random disturbances</td>
</tr>
<tr>
<td>7</td>
<td>$\delta$[to dc] $\cdot$ $B(0.10) \cdot \Gamma(2.0,15.0)$</td>
<td>incidental delay</td>
</tr>
</tbody>
</table>

**Table 7-11** Trip component for travelling between locations

The terms of the trip component for visiting a store are shown in table 7-12. The store visit durations are modelled separately for retail and cooled product trips. Following terms are available for retail product trips: store visit durations consist of a fixed period of 25 minutes, and a period depending on the number of pallet
equivalents, ranging from 2.1 to 2.9 per pallet equivalent for the various store classes. The random disturbances of store visits are normally distributed with a standard deviation of 10 minutes. Incidental waiting occurs in 8% of the visits, with a - gamma distributed - average duration of 20 minutes.

Following terms are used for cooled product trips: store visit durations consist of a fixed period of 12 minutes, and a period of 1 minute per pallet equivalent. The random disturbances of store visits are normally distributed with a standard deviation of 4.5 minutes. Incidental waiting occurs in 4% of the store visits, with a - gamma distributed - average duration of 15 minutes.

<table>
<thead>
<tr>
<th>term</th>
<th>contents</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>retail</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$N(25.0,10.0)$</td>
<td>fixed duration/random disturbances</td>
</tr>
<tr>
<td>2</td>
<td>$\delta_{\text{class,---}} \cdot 2.1 \cdot \text{pal_eqs}$</td>
<td>unloading duration per pallet eq.</td>
</tr>
<tr>
<td>3</td>
<td>$\delta_{\text{class,--}} \cdot 2.3 \cdot \text{pal_eqs}$</td>
<td>unloading duration per pallet eq.</td>
</tr>
<tr>
<td>4</td>
<td>$\delta_{\text{class,--+}} \cdot 2.5 \cdot \text{pal_eqs}$</td>
<td>unloading duration per pallet eq.</td>
</tr>
<tr>
<td>5</td>
<td>$\delta_{\text{class,+-}} \cdot 2.9 \cdot \text{pal_eqs}$</td>
<td>unloading duration per pallet eq.</td>
</tr>
<tr>
<td>6</td>
<td>$B(0.08) \cdot \Gamma(2.0,10.0)$</td>
<td>incidental waiting</td>
</tr>
<tr>
<td>cooled</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$N(12.0,4.5)$</td>
<td>fixed duration/random disturbances</td>
</tr>
<tr>
<td>2</td>
<td>$1.0 \cdot \text{pal_eqs}$</td>
<td>unloading duration per pallet eq.</td>
</tr>
<tr>
<td>3</td>
<td>$B(0.04) \cdot \Gamma(2.0,7.5)$</td>
<td>incidental waiting</td>
</tr>
</tbody>
</table>

**Table 7-12** Trip component for visiting a store

We have described the construction of a new trip execution model for RetailCo. Comparing the new model to the current one (see section 4.3), a few remarks can be made. Firstly, the new model does not contain more *a priori* identified influence factors than the current model. However, structural deviations from plan - although modest in size - could be recognized for individual sections and stores. These structural deviations are corrected in the new trip execution model: directly for the travel durations, and by means of the store classification for the store visit durations. Secondly, the variance in the real trip durations is mainly caused by incidental delays during the return to the distribution centre, and by incidental waiting at the stores. These effects have been included in the new model - not implying that delay and waiting durations are calculated more precisely, but that the uncertainty of these durations has been made explicit.
7.3 Validation of the Trip Execution Model

The specification of a trip execution model takes place term by term. The new model as a whole should be validated for the correctness of its trip duration calculation. The performed validation will be described in this section. It includes the confirmation that the calculated and real trip durations are generally equal, and that the stochastic character of the trip execution process has been modelled correctly.

The validation was based on trip data of a 2 week period. These data were not used in the specification of the trip execution model.

Validation of the trip durations

The new trip execution model is expected to calculate the real trip durations for all possible trips, which implies that real and calculated trip durations should be virtually equal. The departure time from the last store of a trip is used as a yardstick for the validation because the random disturbances are large and incidental delays occur during the return to the distribution centre, while the return time is irrelevant to meeting time windows at stores.

Let $tr$ be the real and $tc$ the corresponding calculated departure time from the last store of a trip, then their difference $d = tr - tc$ should equal zero on the average. For the validation we attempt to confirm that the real and the calculated departure times differ significantly. The null and the alternative hypothesis are defined as follows:

$$H_0 : \bar{d} = 0 \quad \text{and} \quad H_1 : \bar{d} \neq 0 \quad (7-2)$$

In order to test the above hypotheses, a set of $n$ real departure times from the last store of a trip is used (i.e. $n$ trips), in which the departure time of trip $i$ is $tr_i$. For each real departure time, also a departure time $tc_i$ is calculated with the trip execution model. The calculation is based on the full model in the stochastic mode with one replication per trip (see also section 6.3).
The test statistic $t$ is defined as follows:

$$ t = \frac{\sum_{i=1}^{n} (tr_i - tc_i)}{s_d \sqrt{n}} $$

(7-3)

where $s_d$ is the sample standard deviation of the differences.

The test statistic $t$ has a Student distribution with $n-1$ degrees of freedom. The hypotheses will be tested with a tolerance level $\alpha = 0.10$:

reject $H_0$ if $t \begin{cases} \leq - t_{0.05}(n-1) \\ \geq t_{0.05}(n-1) \end{cases}$

(7-4)

The above validation was performed separately for retail and cooled product trips. The outcomes are listed in table 7-13.

<table>
<thead>
<tr>
<th></th>
<th>retail</th>
<th>cooled</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>282</td>
<td>77</td>
</tr>
<tr>
<td>$s_d$</td>
<td>24.9</td>
<td>28.8</td>
</tr>
<tr>
<td>$t$</td>
<td>- 0.03</td>
<td>- 0.38</td>
</tr>
<tr>
<td>$t_{0.05}(n-1)$</td>
<td>1.645</td>
<td>1.668</td>
</tr>
</tbody>
</table>

Table 7-13 Validation of the trip durations

The results indicate that the $H_0$ hypothesis should not be rejected for retail or cooled product trips. We therefore regard the new trip execution model valid for the (calculation of the) trip durations.

Validation of the probability distribution of the trip durations

The trip execution model is expected to calculate trip durations, but also to model the stochastic character of the trip execution process. The probability distribution of the deviations between real trip durations and trip durations
calculated in the deterministic mode should be equal to the probability distribution of the deviations between trip durations calculated in the stochastic and the deterministic mode (see also section 6.3). We will call the deterministically calculated durations *planned* and the stochastically calculated ones *simulated* from now on. We will use the departure time from the last store of a trip as a yardstick for the validation.

Let \( tr \) be the real and \( tp \) the corresponding planned departure time from the last store of a trip, then their difference \( dp \) is the real deviation. In a similar way, if \( ts \) is the simulated and \( tp \) the corresponding planned departure time, then their difference \( ds \) is the simulated deviation. The probability distribution \( Pr \) of the real deviations should be equal to the probability distribution \( Ps \) of the simulated deviations. For the validation we attempt to demonstrate that the above probability distributions do not differ significantly. The null and the alternative hypothesis are defined as follows:

\[
H_0 : Ps = Pr \quad \text{and} \quad H_1 : Ps \neq Pr
\]  

(7-5)

In order to test the above hypotheses, a set of \( n \) real departure times from the last store of a trip is used (i.e. \( n \) trips), in which the real departure time of trip \( i \) is called \( tr_i \). For each real departure time, a planned departure time \( tp_i \) is calculated with the new trip execution model. This calculation is based on the trip execution model without the terms for incidental effects in the deterministic mode. The value \( dr_i = tr_i - tp_i \) is the real deviation from plan for trip \( i \). Also, for each real departure time, a simulated departure time \( ts_i \) is calculated. This calculation is based on the full trip execution model in the stochastic mode with one replication per trip. The value \( ds_i = ts_i - tp_i \) is the simulated deviation from plan for trip \( i \).

To obtain a test statistic, the range of \( dr_i \), and \( ds_i \) is divided into \( k \) approximately equal intervals. The number of observations of \( dr_i \) in interval \( j \) is called \( fr_j \), while the number of observations of \( ds_i \) in interval \( j \) is called \( fs_j \). The following test statistic can then be used:

\[
\chi^2 = \sum_{j=1}^{k} \frac{(fs_j - fr_j)^2}{fr_j}
\]  

(7-6)
The test statistic $\chi^2$ has a $\chi^2$-distribution with $k-1$ degrees of freedom. The hypotheses will be tested with a tolerance level $\alpha = 0.10$:

$$\text{reject } H_0 \text{ if } \chi^2 \geq \chi^2_{0.10}(k-1)$$

(7-7)

The above validation was performed separately for retail and cooled product trips. The outcomes are listed in table 7-14.

<table>
<thead>
<tr>
<th>interval</th>
<th>$r_j$</th>
<th>$s_j$</th>
<th>$(s_j - r_j)^2 / r_j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>retail</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&lt; -30$</td>
<td>6</td>
<td>4</td>
<td>0.67</td>
</tr>
<tr>
<td>$-30 \ldots -20$</td>
<td>14</td>
<td>16</td>
<td>0.29</td>
</tr>
<tr>
<td>$-20 \ldots -10$</td>
<td>44</td>
<td>36</td>
<td>1.45</td>
</tr>
<tr>
<td>$-10 \ldots +00$</td>
<td>72</td>
<td>72</td>
<td>0.00</td>
</tr>
<tr>
<td>$+00 \ldots +10$</td>
<td>60</td>
<td>72</td>
<td>2.40</td>
</tr>
<tr>
<td>$+10 \ldots +20$</td>
<td>44</td>
<td>44</td>
<td>0.00</td>
</tr>
<tr>
<td>$+20 \ldots +30$</td>
<td>17</td>
<td>17</td>
<td>0.00</td>
</tr>
<tr>
<td>$+30 \ldots +40$</td>
<td>13</td>
<td>15</td>
<td>0.31</td>
</tr>
<tr>
<td>$+40 \ldots +50$</td>
<td>6</td>
<td>3</td>
<td>1.50</td>
</tr>
<tr>
<td>$&gt; +50$</td>
<td>6</td>
<td>3</td>
<td>1.50</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td></td>
<td></td>
<td>8.12</td>
</tr>
<tr>
<td>$\chi^2_{0.10}(k-1)$</td>
<td></td>
<td>14.7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>cooled</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; -20$</td>
<td>9</td>
<td>7</td>
<td>0.44</td>
</tr>
<tr>
<td>$-20 \ldots -10$</td>
<td>9</td>
<td>9</td>
<td>0.00</td>
</tr>
<tr>
<td>$-10 \ldots +00$</td>
<td>17</td>
<td>10</td>
<td>2.88</td>
</tr>
<tr>
<td>$+00 \ldots +10$</td>
<td>13</td>
<td>17</td>
<td>1.23</td>
</tr>
<tr>
<td>$+10 \ldots +20$</td>
<td>10</td>
<td>16</td>
<td>3.60</td>
</tr>
<tr>
<td>$+20 \ldots +30$</td>
<td>9</td>
<td>11</td>
<td>0.44</td>
</tr>
<tr>
<td>$&gt; +30$</td>
<td>10</td>
<td>7</td>
<td>0.90</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td></td>
<td></td>
<td>9.49</td>
</tr>
<tr>
<td>$\chi^2_{0.10}(k-1)$</td>
<td></td>
<td>10.6</td>
<td></td>
</tr>
</tbody>
</table>

Table 7-14 Validation of the probability distribution of the trip durations

These results indicate that the $H_0$ hypothesis should not be rejected for retail or cooled product trips. We therefore regard the new trip execution model as valid for the probability distribution of the trip durations.
The real and the simulated deviations from the planned departure time from the last store of a trip for trips for retail products are shown in figure 7-2. These results also indicate the deviations from plan to be expected if the new trip execution model is used for operational planning.

**Figure 7-2** Deviations from planned departures from the last store of a trip

We have described the validation of the new trip execution model for RetailCo so far. The outcomes support the statement that the model is a valid representation of the trip execution. Note that this does not imply that trip durations are calculated precisely, but that durations are calculated correctly on the average, and that the stochastic character of the trip execution process has been modelled adequately.
7.4 Comparison of Trip Execution Models

The new RetailCo trip execution model is expected to perform better than the current model (see section 4.3) concerning the specification of time schedules. We compare the new and the current model in this section. The comparison consists of two tests: the confirmation that the new model generally calculates trip durations more precisely, and that the new model improves the meeting of time constraints.

The comparison was based on trip data of a 2 week period. These data were not used in the specification of the new trip execution model.

Comparison based on the trip duration calculation

The new RetailCo trip execution model is generally expected to calculate trip durations more precisely than the current model. The departure time from the last store of a trip is used as a yardstick for the comparison because the random disturbances are large and incidental delays occur during the return to the distribution centre, while the return time is irrelevant to meeting time windows at stores.

Let $tr$ be the real and $tc$ the corresponding calculated departure time from the last store of a trip, then the absolute deviation $d = |tr - tsp|$ indicates whether the departure time has been calculated precisely. Let $do$ be the absolute deviation based on the current trip execution model, and $dn$ the absolute deviation based on the new trip execution model, then $dn$ should be smaller than $do$ on the average. For the comparison we seek evidence that the absolute deviations of the new model are significantly smaller than the absolute deviations of the current model. The null and the alternative hypothesis are defined as follows:

$$H_0 : \overline{dn} = \overline{do} \text{ and } H_1 : \overline{dn} < \overline{do} \quad (7-8)$$

In order to test the above hypotheses, a set of $n$ real departure times from the last store of a trip is used (i.e. $n$ trips), in which the departure time of trip $i$ is $tr_i$. For each real departure time, departure times are calculated with the current and the new model, $to_i$ and $tn_i$, respectively. The calculation of $tn_i$ is based on the trip execution model in the deterministic mode without the terms for incidental effects. The value $do_i = |tr_i - to_i|$ is the absolute deviation from plan for trip $i$ based
on the current model, while $dn_i = |tr_i - tn_i|$ is based on the new model. The test statistic $t$ is defined as follows:

$$t = \frac{(\bar{dn} - \bar{do})}{s_p\sqrt{2/n}}$$  \hspace{1cm} (7-9)

where $s_p$ is the pooled sample standard deviation.

The test statistic $t$ has a Student distribution with $2n-2$ degrees of freedom. The hypotheses will be tested with a tolerance level $\alpha = 0.10$:

reject $H_0$ if $t \leq -t_{0.10}(2n-2)$  \hspace{1cm} (7-10)

The above comparison has been performed separately for retail and cooled product trips. The results are listed in table 7-15.

<table>
<thead>
<tr>
<th></th>
<th>retail</th>
<th>cooled</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>282</td>
<td>77</td>
</tr>
<tr>
<td>mean($do$)</td>
<td>12.9</td>
<td>22.5</td>
</tr>
<tr>
<td>mean($dn$)</td>
<td>13.5</td>
<td>18.4</td>
</tr>
<tr>
<td>$s_p$</td>
<td>11.5</td>
<td>18.6</td>
</tr>
<tr>
<td>$t$</td>
<td>0.62</td>
<td>-1.36</td>
</tr>
<tr>
<td>$-t_{0.10}(2n-2)$</td>
<td>-1.282</td>
<td>-1.282</td>
</tr>
</tbody>
</table>

Table 7-15 Comparison based on the trip duration calculation

The results indicate that the $H_0$ hypothesis for retail product trips should not be rejected. The test therefore fails to demonstrate that the new trip execution model calculates trip durations more precisely. On the other hand, the $H_0$ hypothesis for cooled trips should be rejected. An improvement of the trip duration calculation has been demonstrated by the test.

A statistically significant improvement of the trip duration calculation does not necessarily imply that the punctuality performance of the trip execution will improve substantially. Note, for example, that the average absolute plan deviation for cooled trips only decreases from 22.5 to 18.4 minutes for the new trip execution model as compared to the current one.
Comparison based on the detection of time window violations

The trip execution model is used to identify likely violations of time windows during operational trip planning. Valid identifications allow plan changes such that fewer real violations occur as well. The valid identification of likely violations is an appropriate indicator of the contribution of a trip execution model to the real number of time windows adhered to.

A model in itself does not determine how often time windows are obeyed. Other planning aspects affecting the number of violations are the store orders to be scheduled, the position and width of the time windows, and the planning rules, such as scheduling trip departures as early as possible. These planning aspects have to be considered in the comparison of trip execution models.

Let $co$ be the percentage time window adherences or violations which are correctly identified by the current model, i.e. for which plan and reality correspond, and let $cn$ be the percentage based on the new model. For the comparison we are seeking evidence that $cn$ is larger than $co$. We define the null and the alternative hypothesis as follows:

$$H_0 : cn = co \quad \text{and} \quad H_1 : cn > co$$  \hspace{1cm} (7-11)

In order to test the above hypotheses, a data set with the trips of a 2 week period is used. For each trip, the arrival and departure times of store visits are calculated with the current and new trip execution model, based on the trip departure times specified by the trip planner. The new model is used in two modes: the deterministic mode without terms for incidental effects, and the full model in the stochastic mode with a large number of replications per trip.

In the stochastic mode, a violation is indicated if the probability is higher than 0.3. Based on the above, we can assign the store visits to the following categories, or their negations:

- $ar = \text{time window is adhered to in reality}$;
- $ac = \text{time window is adhered to according to calculation}$.

The values for $ac$ and $\neg ac$ are determined for the current model, the new model in the deterministic mode, and the new model in the stochastic mode.
Retail and cooled product trips have been compared separately. The outcomes are listed in table 7-16.

<table>
<thead>
<tr>
<th>category</th>
<th>current model</th>
<th>new model (deterministic)</th>
<th>new model (stochastic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>retail</td>
<td>ar ∧ ac</td>
<td>80.9%</td>
<td>83.3%</td>
</tr>
<tr>
<td></td>
<td>ar ∧ ¬ ac</td>
<td>7.8%</td>
<td>5.4%</td>
</tr>
<tr>
<td></td>
<td>¬ ar ∧ ac</td>
<td>3.6%</td>
<td>3.6%</td>
</tr>
<tr>
<td></td>
<td>¬ ar ∧ ¬ ac</td>
<td>7.8%</td>
<td>7.8%</td>
</tr>
<tr>
<td>cooled</td>
<td>ar ∧ ac</td>
<td>44.4%</td>
<td>57.6%</td>
</tr>
<tr>
<td></td>
<td>ar ∧ ¬ ac</td>
<td>23.1%</td>
<td>9.9%</td>
</tr>
<tr>
<td></td>
<td>¬ ar ∧ ac</td>
<td>13.9%</td>
<td>12.4%</td>
</tr>
<tr>
<td></td>
<td>¬ ar ∧ ¬ ac</td>
<td>18.6%</td>
<td>20.2%</td>
</tr>
</tbody>
</table>

Table 7-16 Comparison based on the detection of time window violations

We find high overall percentages of ¬ ac for the current model, both for retail and for cooled product trips. They indicate the store visits for which the trip planner could have identified a violation, but did not change the plan. A reason for the high percentages is that the trip departure times are rounded to quarters of an hour instead of minutes. Other reasons are indicated in section 7.6.

We will first discuss the comparison of the current model with the new model in the deterministic mode. The results in table 7-16 indicate that the new model is no improvement for retail trips. The number of correctly identified time window adherences (row: ar ∧ ac) only slightly increases from 80.9% to 83.3%, while the number of correctly identified violations (row: ¬ ar ∧ ¬ ac) does not change. On the other hand, the new model seems to be an improvement for the cooled product trips, as the percentage for identifying adherences increases from 44.4% to 57.6%, while the percentage for identifying violations also increases. The substantial increase for cooled product trips is mainly due to the combination of a more precise trip duration calculation and the narrow time windows.

In the stochastic mode, time window violations are indicated by probabilities in excess of 0.3. It is therefore logical that the number of correctly identified adherences decreases. Now, we are only interested in the detection of violations. The outcomes indicate that the number of correctly identified violations increases, both for retail and for cooled product trips (row: ¬ ar ∧ ¬ ac), which suggests that
the stochastic mode is effective. However, the increase in the store visits with an incorrect violation detection (row: \( ar \land \neg ac \)) is very large; larger than the increase in the correct identifications. This implies that during operational trip planning a large number of trips should be examined and changed superfluously, to achieve only a small increase in the adherences of time windows. We therefore conclude that the stochastic mode is not an improvement over the deterministic mode.

We have described the comparison of the new and current trip execution model above. The results demonstrate that the new model does not calculate trip durations for retail trips more precisely, and for cooled trips only a little more. It appears that simulation for operational trip planning is not profitable.

### 7.5 Evaluation of Tactical Trip Planning

The Trip Execution Simulator (TES) can be used to support tactical trip planning, especially if trip timing is involved. We will now discuss the outcomes of an evaluation of the TES prototype. The purpose is to assess the feasibility of simulation as an approach to support tactical trip planning; not to solve a specific planning problem at RetailCo. The evaluation is therefore based on a hypothetical - but realistic - planning problem. Details concerning the evaluation can be found in Marck (1991, pp. 75-96).

The stated tactical planning problem is the investigation of the nature of changes to the trip execution process and the width of time windows, having a favourable effect on the number of obeyed time windows. An example of a change to the trip execution process is the reduction of incidental waiting at stores, which can be realized by a better co-ordination of the delivery and the receipt of goods. Another example is prescribing waiting on arrivals before the time windows to increase the service level to the stores.

Experiments are performed with several trip execution model - time window width combinations (see below), based on planned trips in a 2 week period. The trips are simulated in the stochastic mode with one replication per trip. The required experiment outcomes are the percentages of time window violations.
The trip execution model described in section 7.2 representing the current trip execution is used as a starting point for the experiments. Treatments are specified at a varying time window width for the following models:

- current trip execution;
- current trip execution without incidental waiting at stores;
- current trip execution with compulsory waiting on early arrivals.

The width of the time windows starting at $tb$ and ending at $te$ varies in the experiments according to the following procedure:

1. set time windows $[tb, te]$ to the expected store visit durations;
2. set time window widening $d$ to 0 minutes;
3. set time windows $[tb, te]$ to $[tb-d, te+d]$;
4. simulate trip executions and determine experiment outcomes;
5. set time window widening $d$ to $d+5$ minutes;
6. repeat the steps 3 to 5 until no violations of time windows occur.

Experiments were performed for retail and cooled product trips. Two remarks should be made concerning the experiments. Firstly, no experiments were carried out for cooled product trips without incidental waiting at stores. Secondly, the left time window boundaries were not shifted left in case of compulsory waiting on early arrivals. The experimental outcomes are shown in figure 7-17.

The contents of table 7-17 lead to following conclusions. Firstly, time windows being equal to the expected store visit durations imply many violations. The table indicates the width required to guarantee a certain service level. For example, in the current trip execution for retail trips, if the number of $te$ adherences is required to be higher than 90%, the time window boundary should be at least 25 minutes right from the expected store visit departure. Note that this outcome is an average, not considering the sequence number of the store visit in the trip.

Secondly, the effects of a reduction of incidental waiting and prescribing waiting on arrivals before the time windows are quantified. It appears that a trip execution without incidental waiting has a positive effect on the number of obeyed time windows; to guarantee a 90% service level for $te$ now requires an average time window boundary 15 minutes right from the expected store visit departure. Prescribing waiting on early arrivals indicates an increase of the $te$ violations. This
implies that prescribing waiting - if introduced - should be combined with an adjustment of the time window definitions, to guarantee the required service level.

<table>
<thead>
<tr>
<th></th>
<th>current trip execution</th>
<th>trip execution model</th>
<th>waiting on early arrival</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>violations</td>
<td>violations</td>
<td>violations</td>
</tr>
<tr>
<td></td>
<td>tb</td>
<td>te</td>
<td>tb</td>
</tr>
<tr>
<td>retail</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>00</td>
<td>55.5%</td>
<td>52.3%</td>
<td>50.8%</td>
</tr>
<tr>
<td>05</td>
<td>33.4%</td>
<td>38.5%</td>
<td>22.9%</td>
</tr>
<tr>
<td>10</td>
<td>12.9%</td>
<td>28.5%</td>
<td>6.2%</td>
</tr>
<tr>
<td>15</td>
<td>4.2%</td>
<td>20.7%</td>
<td>1.1%</td>
</tr>
<tr>
<td>20</td>
<td>1.3%</td>
<td>13.4%</td>
<td>0.4%</td>
</tr>
<tr>
<td>25</td>
<td>0.9%</td>
<td>8.9%</td>
<td>0.0%</td>
</tr>
<tr>
<td>30</td>
<td>0.2%</td>
<td>5.8%</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>0.2%</td>
<td>3.8%</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.0%</td>
<td>1.8%</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>1.3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>1.1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>0.0%</td>
<td></td>
<td>52.6%</td>
</tr>
<tr>
<td>cooled</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>00</td>
<td>47.0%</td>
<td>53.7%</td>
<td></td>
</tr>
<tr>
<td>05</td>
<td>31.6%</td>
<td>38.8%</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>19.7%</td>
<td>28.7%</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>10.9%</td>
<td>20.3%</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>5.3%</td>
<td>14.5%</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>3.0%</td>
<td>9.8%</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>1.4%</td>
<td>6.1%</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>1.0%</td>
<td>3.8%</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.4%</td>
<td>2.3%</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>0.2%</td>
<td>1.3%</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.0%</td>
<td>0.8%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>0.0%</td>
<td></td>
<td>28.1%</td>
</tr>
</tbody>
</table>

Table 7-17 Experiment outcomes tactical trip planning

The results of two series of experiments are shown in figures 7-3 and 7-4.
Figure 7-3 Experiment outcomes: retail trips - current trip execution process

Figure 7-4 Experiment outcomes: retail trips - no incidental waiting at stores
We have shown an example of solving a tactical planning problem in this section. The results support the statement that trip execution simulation with the trip execution model can be applied successfully to quantify the effects of changes in the transportation process.

7.6 Evaluation of Operational Trip Planning

The Trip Execution Simulator (TES), especially the (graphical) indication of time window violations, can be used to support operational trip planning. We will now discuss the evaluation of the TES prototype, carried out jointly with trip planners.

It was impossible to apply the TES prototype in the actual planning, for practical reasons. The prototype is a stand-alone system implemented to demonstrate planning support ideas. Furthermore, in the current situation at RetailCo, the punctuality demands are not yet as high as they will become in the future.

We decided to perform the evaluation in hypothetical planning sessions with the use of up-to-date actual plan data. The results below were obtained in two sessions with five planners. During a planning session, the trip planners could observe indications of time window violations, and suggest trip modifications to solve these. The real violations were checked for several trips, and compared with the indications. Questionnaires were completed by the planners at session ends. Three planners were interviewed to cover matters not included in the questionnaires.

Outcomes of the planning sessions

The TES prototype correctly indicated various time window violations, existing due to the following causes, during the planning sessions:

- The trips for cooled products have fixed time schedules with a few structural time window violations;
- Split deliveries (two trucks delivering to a single store) inevitably result in time window violations;
- Two stores with overlapping time windows were combined in a single trip, to reduce transport costs;
- A temporary change of a time window was mistakenly overlooked by the trip planner;
The departure time of a trip was specified incorrectly during the manual registration on the plan form.

We conclude that some time window violations are unavoidable and are accepted by the trip planner. Meeting all the time windows is therefore impossible. On the other hand, certain violations can be prevented by excluding trip planner mistakes, to which the TES can offer support, even when the trip execution model is not overly accurate.

Trip planners are extremely experienced in planning trips. During the hypothetical planning sessions, it was surprising that the planners recognized trips and stores on the basis of a graphical representation of the time schedule and the time windows. They could also identify the stores for ease or difficulty of unloading. However, this knowledge is qualitative (e.g. which stores are difficult?) and not quantitative (e.g. exactly how long does it take to unload?). Besides, trip planning knowledge differs within the group of planners.

We conclude that trip planner experience, although effective for the construction of plans, is unsuitable for the specification of time schedules, and that a trip execution model for the calculation of trip durations is definitely required.

Outcomes of the questionnaire and the interviews

The questionnaire contained the following questions:

1 Do the (graphical) reports indicating the time window violations identify the trips to be changed (called problem trips below)?
2 Is it clear how problem trips should be changed in order to resolve time window violations?
3 Is it possible to identify and to change problem trips within the timespan available for operational trip planning?
4 Is it possible to specify arrival and departure times of store visits with the information on the (graphical) reports?
5 Does the use of the Trip Execution Simulator (TES) contribute to the reduction of the actual number of time window violations?
6 Is the plan performance report a useful TES component (figure 6-10)?
7 Is the trip performance report a useful TES component (figure 6-11)?
The answer frequencies to the above questions are listed in table 7-18. A five-point scale ranging from a highly negative to a highly positive opinion is applied to all questions.

<table>
<thead>
<tr>
<th>question</th>
<th>--</th>
<th>-</th>
<th>□</th>
<th>+</th>
<th>++</th>
<th>missing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>1</td>
<td></td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td></td>
<td></td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Table 7-18 Answers to the questionnaire

The questionnaire also contained the following question: what are the most positive and the most negative points of the Trip Execution Simulator? The combined answers to all questions and the interviews suggest the following.

Firstly, the TES should be (functionally) integrated with a trip planning system, so that the reports can be inspected directly during planning. This is also necessary because the timespan for operational planning is restricted. The prototype being a stand-alone system was mentioned as the reason for the strongly negative opinion for question 3.

Secondly, the added value of the TES is mainly inspired by the graphical representation of time schedules and time window violations. However, the screens should also show the information available on the current planning forms. The unavailability of this information in the prototype caused the strongly negative opinion for question 7.

7.7 Summary and Conclusions

We have constructed a new trip execution model for RetailCo. The model does not contain more a priori identified influence factors than the current model. However, structural deviations from plan - although modest in size - could be recognized for individual sections and for individual stores. These structural deviations were
corrected in the new model.

The variance in trip durations is largely caused by incidental delays during the return to the distribution centre and by incidental waiting at the stores. These effects have been included in the new model. This does not imply that the durations of delays and waiting are calculated more precisely, but that the uncertainty about these durations is made explicit.

The validation results support the statement that the new model is a valid representation of the trip execution. This does not imply that all the trip durations are calculated exactly, but that the durations are calculated correctly on the average, and that the stochastic character of the trip execution process is modelled adequately.

A comparison of the new and the current model demonstrates that the new one does not calculate trip durations for retail trips more precisely, and for cooled trips only a little more. Furthermore, it appears that simulation for operational trip planning is not advantageous.

We note that inaccuracy of data due to manual registration is not the main reason for improper trip duration prediction. Firstly, the new model was specified term by term, and is valid as a whole, which supports that times are registered fairly accurate. Secondly, inaccuracy would have caused negative correlation between plan deviations of successive trip components, but such correlation is absent.

The results of solving a tactical planning problem support the statement that trip execution simulation with the new trip execution model can be applied successfully to quantify the effects of changes in the transportation process.

The evaluation of the TES prototype for use in operational trip planning suggests that a graphical representation of time schedules and time window violations is useful. A prerequisite is that the TES is integrated with the vehicle routing and scheduling system.
Epilogue

8.1 Introduction

We described the design and prototypical implementation of an adaptive trip planning support environment in this thesis. The study yielded answers to the research questions:

1. *What are the characteristics of a Planning Support Environment (PSE) for vehicle routing and scheduling if time constraints play a major role?*

2. *What are the effects of using such a PSE for vehicle routing and scheduling?*

Our research centered around the innovative components of a PSE, which were expected to solve the timing problems of trips in food retail trade organizations.

We stressed the importance of meeting time constraints in food retail trade organizations. Deviations from plan of even a quarter of an hour may induce costly idle times for drivers and store personnel. Other effects are the violation of
government imposed time windows, long waiting times due to other trucks occupying the store docks, and the inconvenience of goods being worked up directly in the sales floor area of stores.

8.2 Conclusions Related to Adaptive Trip Planning

The discussion of our conclusions will be based on the experience gained in using the PSE for adaptive trip planning at RetailCo.

Construction of a trip execution model

The newly constructed trip execution model differs from the current one: parameters have slightly different values, and structural deviations from planned durations for individual origin-destination location pairs (called sections) and individual stores are corrected. However, the new model does not calculate trip durations much more precisely than the current model. The corrections of plan deviations for sections and for stores reduce wrong parameter values, but are modest in quantity and/or size, and have no substantial impact on the overall accuracy of trip duration calculations.

There are several reasons for our inability to designate more influence factors as applicable or significant - contributing to an accurate trip duration calculation. First of all, certain influence factors cannot be assigned model variable values, or the values are unknown during planning, especially for incidental effects such as incidental waiting at stores (see also tables 7-1 and 7-2). In addition, the following characteristics of the data set with historic trip data prohibit the improved prediction of trip durations:

- The deviations from planned durations attributed to influence factors are sometimes similar to the measuring errors inherently present in the values of (criterion/predictor) variables;
- Planned time schedules and real trip durations are - slightly - correlated, implying that time schedules with time slack may result in a slower trip execution;
· Observations are unavailable in some situations when the significance of influence factors must be determined. For instance, most stores are visited at regular times, which excludes the detection of delays caused by structural traffic congestion;
· Some data are only recorded for the administrative settlement of trips and not for trip execution analysis. For instance, waiting at stores is only registered if it leads to extra payment;
· Part of the trip data is not registered accurately because it is done manually. For example, where arrival times at stores almost equal the time window boundary, the boundary is registered.

Most of the above-mentioned characteristics of the data set in our study can only be changed partially, if at all.

Based on the above, we conclude:

*The availability of (historic) trip data does not necessarily facilitate the construction of a trip execution model calculating trip durations accurately. There is a certain level of uncertainty in trip durations - too high to meet the time constraints satisfactorily in our case - which cannot be reduced by means of collecting and analyzing trip data.*

The collection and analysis of trip data can be applied successfully for the following purposes. Firstly, to correct wrong parameter values, based on structural deviations from plan for travel and store visit durations (see e.g. table 7-7). This is especially useful for low quality trip execution models. Secondly, to construct a simulation model of the trip execution for tactical trip planning (see below). The trip data recorded for the administrative settlement and for management reports also fulfil the above two purposes; the collection of extra data for this type of adaptive trip planning is superfluous.

**Tactical trip planning**

The above-mentioned use of (historic) trip data is a solution alternative to the problems concerning trip timing, which is based on an increase of the information processing capacity. Galbraith’s (1973) information processing model indicates that this is not the only solution possible: alternative organizational structures with
lower information processing requirements might be more effective. Changes in the structure can be based on other coordinating mechanisms (e.g. decision rules) or a reduction of the information processing need (e.g. slack resources).

In our case, the uncertainty in trip durations can be reduced by modifying the trip execution process. The analysis of trip data showed that the variance in trip durations is mainly caused by incidental waiting at stores and by delays during the return to the distribution centre (see also tables 7-10 to 7-12). This observation suggests that both the stores and the drivers are parties which can help to increase the punctuality. Potential measures applicable to stores are: (1) make the stores responsible for waiting, for instance by passing on the costs, and (2) ensure that time windows for distribution channels do not overlap. Driver related measures are: (3) increase the drivers’ awareness of the distribution process, and (4) provide the drivers with public-transport-type time tables, promoting the synchronization of trip execution and plan.

In spite of changes in the transportation process, trip durations will remain somewhat unpredictable. Trip planners will have to accept the uncertainty, while the organization of the physical distribution system should allow incompletely defined durations. Possible measures are: (5) specify time schedules including time slack, and declare waiting on arrivals before time windows compulsory, (6) restrict the number of store visits per arrival before visit windows compulsory, and (7) relax the time windows or punctuality standards, ensuring that disturbances in the trip execution do not necessarily lead to serious time window violations.

Tactical trip planning deals with the above-mentioned changes in the transportation process, the related costs, and the remaining trip duration uncertainty. The simulation experiments described in section 7.5 demonstrated the effects of some realistic changes and the remaining uncertainty, which provided an assessment of the effectiveness of solutions to the frequent time window violations.

Based on the above, we conclude:

*Changes in the transportation process can improve the adherence to time windows of stores. Trip execution simulation has been demonstrated to be a viable approach to quantifying the effects of such changes in which the dynamic aspects of the trip execution are involved.*
Operational trip planning

As some uncertainty in trip durations is inevitable, we proposed the trip simulation to test plans during operational trip planning. Simulation experiments, however, indicated that the detection of likely time window violations is not effective: there are too many incorrect detections, while incidental effects cannot be foreseen during planning.

Planning rules, such as "15 minutes slack between store visit durations and time windows ensures less than 20% violations" are useful, and can be determined by means of trip simulation at the tactical planning level. Such simple rules, combined with screens plotting time schedules and time window violations, and the planning support keeping planners from making slips, can reduce time window violations, in our opinion.

Based on the above, we conclude:

*Trip execution simulation has no added value at the operational planning level. Planning support consisting of a set of planning rules and a graphical representation of time schedules and time window violations, combined with facilities preventing planners from making slips, is effective for time schedule specifications.*

8.3 Conclusions Related to Planning Support Environments

Our research experiences can be helpful in establishing robust design principles for information systems to support decision processes, such as PSEs. In our view, attention should be paid to the following issues.

The application of computerized decision support is often based on the assumption that an increase in the quantity and/or quality of the data automatically results in better control information. This is not necessarily true, as demonstrated by our and other research, see for example Sol (1982) and Reuji1 (1982). The cautious conclusion may be drawn that decision support should not rely too much on the availability of adequate data. Whether high data requirements are a restraint is situation dependent, and should be considered in the design stage. In our view, decision support with minor data requirements should be regarded with increased
interest in designing decision support systems.

Typically, the way an information system controls the real system should be reconsidered before an (renewed) information system is realized. We have shown that trip execution simulation is a practical approach for evaluating changes in the transportation process (i.e. both trip execution and trip planning). This observation advocates the integration of tactical and operational decision support in organizations confronted with turbulent environments, as described in chapter 1. Especially, a simulation model of the problem situation could be specified and kept valid continuously, in order to be able to provide decision support at the tactical planning level when required.

The value of the operational planning support is mainly determined by the graphical representation of time schedules and time windows, and by its capability of preventing trip planners from making slips. The integration with a vehicle routing and scheduling system is also required. These two observations add proof to the validity of design principles reported earlier by others. Firstly, according to Sprague and Carlson (1982, ch. 4), a decision support system should provide a representation which resembles the way a problem is conceptualized. Secondly, such a system must offer integrated support for all the decision maker’s tasks: both the problem solving and the administrative ones, as described in chapter 1 (see also Van Weelberen, 1991).

8.4 Future Research

The research was confined to a study of components of an adaptive PSE for vehicle routing and scheduling in food retail trade organizations. Based on this restriction and the research outcomes, we consider the following potential research areas.

Physical distribution in food retail trade organizations is characterized by a fixed set of delivery locations (i.e. stores), high punctuality requirements, and a well organized physical distribution system. It would be worthwhile to investigate the applicability of adaptive trip planning support in other sub-markets of the road transportation industry; for instance, the international full truckload services in which trip timing is quite different.
We mentioned the traffic congestion increase on the roads in the Netherlands being a trend demonstrating the importance of time schedule specification. In our study at RetailCo, we only paid little attention to the effects of traffic congestion. First of all, it would be valuable to quantify the effects of increasing traffic congestion on the trip duration uncertainty. The trip execution simulation described in this thesis can then be applied to determine traffic congestion influences on the functioning of a physical distribution system. As our research indicated, incidental congestion delays are difficult to anticipate during planning. This observation, combined with the perceived problems concerning trip duration prediction, prompts the question: how can up-to-date traffic information be used in order to restrict congestion delays of trucks during travelling, for instance by means of rerouting?

Numerous research efforts were related to decision support in the last few decades. Nevertheless, continuing research is required, as the information systems discipline is in search of a broader base of theories and experiences. It would be interesting to realize the concept of a PSE described in section 1.2 in empirical studies. Attention should be paid to the effectiveness of large data sets describing dynamic phenomena, as their feasibility is as yet poorly understood. Furthermore, special attention should be paid to the uncertainty inherent to the dynamics of a problem domain as well as the application of simulation at the tactical planning level to assess the effectiveness of solutions handling this uncertainty, which has proven to be a viable approach in our study.
References


149
References


References

Golden, A.A. Assad (eds.), *Vehicle Routing: Methods and Studies*, Elsevier
Wesley, Reading, Massachusetts, 1989.
W.A. Gale (ed.), *Artificial Intelligence and Statistics*, Addison-Wesley, Reading,
Massachusetts, 1986.
Huitink, B., "Het Waarom en Hoe van Geautomatiseerde Routeplanning",
Vervoerslogistieke Werkdagen 1988*, Faculty of Civil Engineering, Delft
In 't Veld, J., *Analyse van Organisatieproblemen*, Elsevier, Amsterdam, The
Netherlands, 1983.
Jol, K., "Dit is uw Planner! Bliep!", *BeroepsVervoer*, Vol. 47 ,No. 38, 1987,
pp. 8-21.
Hamerslag, A.J.H. Weenink (eds.), *Proceedings Vervoerslogistieke Werkdagen
1988*, Faculty of Civil Engineering, Delft University of Technology, Delft, The
Hamerslag, A.J.H. Weenink (eds.), *Proceedings Vervoerslogistieke Werkdagen
1988*, Faculty of Civil Engineering, Delft University of Technology, Delft, The
Kamphuis, P.F., "Automatisering in het beroepsgoederenvervoer over de weg",
Kleindorfer, G.B., G.A. Kochenberger, E.T. Reutzel, "Computing Inter-Site
Distances for Routing and Scheduling Problems", *Operations Research Letters*,
References


153
References


Robroeks, J.A.N., Automatisering van de Routeplanning van een Vrachtautoloot ten behoeve van de Distributie van Goederen, MSc Thesis, Faculty of Civil Engineering, Delft University of Technology, Delft, The Netherlands, 1985.


References

Tigchelaar, J., "Waarom distributiefijnplanning wel kan en ... moet", Tijdschrift voor Inkoop en Logistiek, Vol. 6, No. 1-2, 1990, p. 3.
Index

adaptation 7
adaptive feedback see feedback
aggregation level 65, 71
algorithm 2, 30, 41
Anthony, R.N. 6
a priori 116, 119, 122
Assad, A.A. 35, 36, 40
Bachman diagram 36, 72
backhaul 33, 24, 108
Ballou, R.H. 2, 18, 19, 21
Belardo, S. 38
Benbasat, I. 11
Bodin, L. 2, 31, 32, 33, 41
Bots, P.W.G. 9, 10, 45
Brands, M.C.M. 21
Branston, D. 25
Brook, R.J. 78
Brussaard, B.K. 6
business logistics 3, 17
Camp, R.C. 75
Chatfield, C. 76
class table 68, 70
class variable see variable
control mechanism 42
costs 1, 19, 144
criterion variable see variable
customer service 19, 26
data void 67
Davis, G.B. 8
decision support 5, 8
De Jong, R. 24
Desrochers, M. 31
deterministic mode see mode
direct feedback see feedback
distance matrix 36, 38, 53
distribution centre 18, 20, 46
distribution channel 21, 26, 47
Duchessi, P. 41
Du Toit, S.H.C. 78
DVK 25
EDI 22
Elam, J. 11
entity type 31, 33, 71
euclidean distance 36
evaluation 14, 83, 132, 136
Evans, S.R. 38
EVO 2
feedback
  adaptive 8
direct 8
Fildes, R.A. 37
Filman, R.E. 41
Fleuren, H.A. 31
Frowein, J.C. 2
function group 40
function hierarchy 92, 100
graphical 40, 89, 102, 137, 145, 146
Green, P.E. 75
Gorry, G.A. 9
Gupta, A.K. 63
Index

Hamerslag, R. 25
Haven, J. 25
Hirshfeld, D.S. 6
Hooban, J.M. 39, 40
Hoover, S.V. 81
Huber, G.P. 7
Huitink, B. 39
ill-structured 8, 9, 45
incidental effect 68, 75, 87, 111, 122
influence factor 65, 109, 110
information paradigm 6
Jol, K. 39
Jongenotter, W.J. 24
Kaiser, H. 24
Kamphuis, P.F. 1, 23
Keen, P.W.G. 9
Kleindorfer, G.B. 36
KNV 1
Kok, G.Ph. 3, 19
Larsen, N.E. 64
level
  micro 9
  meso 9
  macro 9
logistic chain 18
Lowe, D. 78
macro level see level
Maltz, A.B. 33
Marck, D. 105, 132
Martens, P.H. 32
McKinsey 3
memory aids 42
meso level see level
micro level see level
mode
  deterministic 102
  stochastic 102
Monhemius, W. 64, 80
Muller, Th.H.J. 63
NEA 36, 79
Novels, M.D. 64
NP-hard 31
numeric variable see variable
objective function 32
open-loop planning see planning
operational planning see planning
operation 40
Ören, T.I. 82
organizational chart 49
outlier 78, 111
Panko, R.R. 11
Passino, A.M. 4
physical distribution
  operation 21, 47
  structure 19, 47
  trend 22, 52
plan-dependent variable see variable
planning
  definition 5
  level 6
  open-loop 4
  operational 6, 55, 59, 64, 85
  session 136
  support environment 5, 10, 58, 62
  tactical 6, 54, 59, 63, 80
predictor variable see variable
problem analysis 57, 59
problem domain 4, 6
product type
  cooled 47
  retail 47
punctuality 4
questionnaire 137
$R^2$ 78, 80, 96
Index

criterion 75, 78, 96, 111
numeric 66, 69
plan-dependent 69, 70, 101
predictor 75, 78, 79, 111
vehicle routing and scheduling
  problem 30, 31
  objective 30, 32, 39
  system 38
Verbeek, A. 78
Verbeek, P.J. 40
Verbraeck, A. 10, 64
verification 78, 81, 105
Waters, C.D.J. 38, 41
Weber, R. 31
Weenink, A.J.H. 39
Samenvatting

Inleiding

Bedrijven die beschikken over voertuigen willen deze zo goed mogelijk inzetten: vervoersopdrachten dienen aan een voertuig te worden toegewezen en voor iedere rit die een voertuig maakt, dienen een route langs de te bezoeken adressen en een tijdschema te worden opgesteld. Deze ritplanning is het onderwerp geweest van veel onderzoek. Eerst ging de aandacht uit naar algoritmen, terwijl later meer nadruk is gelegd op het ontwikkelen van interactieve planningsystemen.

Het opstellen van tijdschema's voor ritten is een belangrijke taak. Een tijdschema bepaalt op welke tijdstippen rijden, laden, lossen en overige activiteiten dienen te beginnen en eindigen, waarbij rekening moet worden gehouden met tijdsrestricties zoals beperkte bezoektijden van adressen. Het voldoen aan tijdsrestricties vereist dat tijdschema's en werkelijke rituduren goed corresponderen. Een planningsysteem dient hiertoe een ritmodel te bevatten dat rituduren correct berekent.

De volgende twee ontwikkelingen vragen om extra aandacht voor het opstellen van tijdschema's. Allereerst is er een trend in fysieke distributie waarbij in toenemende mate hoge eisen worden gesteld aan de stiptheid van afleveringen, met name in de levensmiddelendetailhandel. Daarnaast is er een sterke groei van het wegverkeer met als gevolg meer congesties en dus meer onverwachte vertragingen, die een negatieve uitwerking hebben op de nagestreefde stiptheid.

In het onderzoek wordt getracht de volgende vragen te beantwoorden:

1. Wat zijn de karakteristieken van een planningsondersteunende omgeving voor ritplanning als tijdsrestricties een belangrijke rol spelen?

2. Wat zijn de effecten van het gebruik van een dergelijke planningsondersteunende omgeving?
Samenvatting

Het onderzoek beperkt zich tot distributie in de levensmiddelendetailhandel en richt zich hoofdzakelijk op de onderdelen van een planningsondersteunende omgeving die als innovatief bestempeld kunnen worden.

De huidige situatie in de detailhandelorganisatie RetailCo vormt het vertrekpunt voor het onderzoek. Eerst worden een bedrijfsspecifiek model en een algemeen beschrijvend model opgesteld. Daarna wordt een algemeen voorschrijvend model opgesteld dat vervolgens binnen RetailCo wordt geïmplementeerd en gebruikt.

Fysieke distributie in detailhandelorganisaties

De fysieke distributie in detailhandelorganisaties, met name supermarkten, is veelal goed georganiseerd, wat garandeert dat een hoog servicienivo bereikt wordt tegen gelimiteerde operationele kosten. Het transport van de goederen van de leveranciers en de distributiecentra naar de winkels is een schakel in een geïntegreerde logistieke keten.

Ritplanning is een dagelijks terugkerende activiteit, waarbij het belangrijk is tijdschema’s op te stellen die voldoen aan de tijdsrestricties. Deze restricties bestaan om de volgende redenen:

- de verschillende distributiekanalen die bij een winkel samenkomen dienen op elkaar te worden afgestemd, zodat voertuigen van verschillende kanalen niet tegelijkertijd bij een winkel arriveren;
- het transport van goederen en de verwerking in de winkels moeten worden gecoördineerd, zodat verwerking direct na ontvangst kan plaatsvinden;
- de lokale overheden leggen tijdvensters op om de nachtrust te waarborgen en overdag vrachtauto’s in winkelgebieden te weren.

Het groeiend aantal artikelen dat door de winkels stroomt, in combinatie met de beperkte voorraadcapaciteit van winkels, vraagt om een hogere frequentie van de bevoorrading. Tijdsrestricties worden in de toekomst belangrijker.

Huidige situatie ritplanning

Op grond van de huidige situatie bij RetailCo, aangevuld met algemene kennis over ritplanning, kan het volgende worden gesteld.
Samenvatting

Ritplanningsystemen beschikken over een ritmodel voor de berekening van rtduren. Rijduren en laad-/losduren worden afzonderlijk berekend: rijduren met een wegenetwerkbestand of -matrix en laad-/losduren met een lineaire functie van de hoeveelheid goederen die moet worden verwerkt.

Voor een rit ontvangt de chauffeur een ritinstructie met de af te werken orders, waarbij veelal ook een tijdschema is aangegeven. Tijdens de rit noteert de chauffeur afwijkingen van het plan. Na de rit worden de ritgegevens gebruikt voor de administratieve afwikkeling, zoals het verrichten van betalingen. De ritgegevens worden meestal niet gebruikt voor planningsdoeleinden.

Taktische ritplanning houdt zich bezig met de wijze waarop ritten worden gepland en uitgevoerd, waarbij wij alleen datgene beschouwen wat gerelateerd is aan het tijdsaspect (bijvoorbeeld de breedte van tijdensters). Managementoverzichten geven inzicht in de bestaande rituitvoering, terwijl ritplanningsystemen worden gebruikt voor het evalueren van veranderingen in het transportproces. Deze systemen kunnen echter geen duidelijk inzicht geven in effekten van veranderingen op de uitvoering van ritten.

Operationele ritplanning bestaat niet alleen uit een planningstaak, maar ook uit bijbehorende administratieve taken zoals het registreren van orders. De planningsstaak bestaat uit het toewijzen van orders aan voertuigen en het specificeren van routes en tijdschema’s. Verschillende organisaties gebruiken interactieve planningsystemen. De huidige systemen zijn hoofdzakelijk gericht op het vaststellen van routes en in mindere mate op het opstellen van tijdschema’s.

Een analyse van de huidige situatie brengt de volgende problemen aan het licht:

- Het ritmodel voor het berekenen van rtduren vertoont veelal één of meer van de volgende tekortkomingen:
  - sommige activiteiten van de rituitvoering zijn niet gemodelleerd;
  - cyclische en incidentele effekten (congesties) zijn niet gemodelleerd;
  - het nivo van detaillering is onvoldoende;
  - parameters of variabelen hebben onjuiste waarden;
- De planningsondersteuning om met tijdsrestricties rekening te houden schiet tekort: op taktisch nivo om effekten van veranderingen in het transportproces te kwantificeren en op operationeel nivo voor de interactieve specificatie van tijdschema’s.
Ontwerp en implementatie van een planningsondersteunende omgeving

De basis van een planningsondersteunende omgeving voor ritplanning wordt gevormd door automatisering van de administratieve taken en de aanwezigheid van een interactief planningsysteem. In het onderzoek zijn als aanvulling hierop een ritmodel en extra ondersteuning voor de taktische en de operationele planning uitgewerkt.

Het ritmodel is opgebouwd uit ritcomponenten die het vertrek van een startlokatie, het rijden tussen lokaties en het bezoeken van een locatie beschrijven. De duur van een ritcomponent is een lineaire functie van faktoren die de ritduur beïnvloeden. Met de lineaire functies kan de rituitvoering gedetailleerd worden beschreven en kan (met kansvariabelen) het stochastische karakter van de uitvoering van ritten worden gemodelleerd.

Het specificeren van het ritmodel vindt plaats met behulp van een analyse van (historische) ritgegevens. Een belangrijke plaats wordt hierbij ingenomen door regressie-analyse. Gecomputeriseerde ondersteuning dient beschikbaar te zijn voor schatten van parameters en de hieraan gerelateerde taken, bijvoorbeeld het selekteren van ritgegevens en het testen van statistische veronderstellingen.

Taktische en operationele ritplanning kunnen worden ondersteund met simulatie van rituitvoeringen, waarvoor het beschreven ritmodel geschikt is. Gecomputeriseerde ondersteuning voor de taktische planning dient te omvatten: het opzetten van simulatie-experimenten, het simuleren van ritten en het genereren van uitvoer. Voor de operationele planning dient op grond van ritsimulaties inzicht gegeven te worden in de verwachte schendingen van tijdsrestricties, zowel in termen van prestatie-indikatoren als grafisch. Deze planningsondersteuning is een uitbreiding op de functionaliteit van bestaande ritplanningsystemen.

Voor RetailCo zijn prototypes gebouwd: een Ritgegevens Analyse Systeem (RAS) en een Rituitvoering Simulatie Systeem (RSS). Het RAS heeft onder meer functies voor het beheren van ritgegevens, het analyseren van ritgegevens met behulp van regressie-analyse en het tonen van afwijkingen tussen geplande en werkelijke tijdsduren voor het rijden tussen lokaties (trajecten) en het bezoeken van lokaties. Het RSS heeft functies voor het beheren van ritmodellen, het uitvoeren van simulatie-experimenten en het tonen van schendingen van tijdsrestricties.
Samenvatting

Gebruik van de planningsondersteunende omgeving

Voor RetailCo is met gebruikmaking van het RAS een nieuw ritmodel opgesteld. Dit ritmodel bevat niet meer invloedsfactoren dan in het bestaande model reeds aanwezig zijn. Het is echter wel mogelijk gebleken structurele afwijkingen van geplande tijdsduren te corrigeren voor afzonderlijke trajecten en winkels, alhoewel deze afwijkingen van bescheiden omvang zijn. Een vergelijking van het nieuwe ritmodel met het bestaande model laat zien dat het nieuwe model rituduren niet wezenlijk nauwkeuriger berekent.

De variantie in de afwijkingen van geplande rituduren wordt voor een groot deel veroorzaakt door wachten bij winkels en vertragingen gedurende de terugkeer naar het distributiecentrum. Deze vertragingen en het wachten zijn gemodelleerd, wat niet betekent dat hiermee rituduren meer nauwkeurig kunnen worden berekend, maar dat de onzekerheid ten aanzien van rituduren expliciet is gemaakt.

Met het RSS zijn veranderingen in het transportproces voor het verkleinen van het aantal schendingen van tijdsrestricties doorgerekend. De uitgevoerde experimenten tonen aan dat een belangrijke bijdrage mag worden verwacht van het verminderen van het incidenteel wachten bij winkels.

Het signaleren van schendingen van tijdsrestricties met behulp van simulaties van rituitvoeringen is getest. De uitkomsten tonen een sterke toename van het aantal onterechte signaleringen (schendingen die in werkelijkheid niet optreden), terwijl het aantal terechte signaleringen weinig toeneemt.

De evaluatie van het RSS binnen de operationele planning laat zien dat planners soms fouten maken en geeft aan dat de grafische weergave van tijdschema’s en schendingen van tijdsrestricties nuttig is. Voorwaarde is dat het RSS geïntegreerd wordt met het ritplanningsysteem dat een organisatie gebruikt.

Conclusies

Op grond van de ervaringen met het gebruik zijn de volgende conclusies getrokken:

*De beschikbaarheid van (historische) ritgegevens bevordert niet altijd de konstructie van een ritmodel dat rituduren nauwkeurig berekent. Er bestaat een onzekerheid ten aanzien van rituduren - in ons geval te hoog om bevredigend met tijdsrestricties om te gaan - die niet verlaagd kan worden door middel van het verzamelen en analyseren van ritgegevens.*

167
Samenvatting

Veranderingen in het rituitvoeringsproces kunnen een bijdrage leveren aan het voldoen aan tijdsrestricties. Door middel van het simuleren van ritten is het goed mogelijk de effekten te kwantificeren van veranderingen die te maken hebben met de dynamische aspecten van de rituitvoering.

Het simuleren van rituitvoeringen binnen de operationele planning levert geen voordeel op. Planningsondersteuning die bestaat uit een aantal planningsregels en een grafische weergave van tijdschema's en schendingen van tijdsrestricties, in combinatie met ondersteuning die het maken van fouten voorkomt, is daarentegen wel effektief voor het specificeren van tijdschema's.
Curriculum Vitae