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Modelling carrier decisions in an activity-based freight transportation framework

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List of symbols used in chapters 4 to 7

Logistic module

F_k = Fraction of actual realised links of commodity k

P_{kr} = Number of producers of commodity k in zone r

C_{ks} = Number of consumers of commodity k in zone s

N_k = Number of receivers per sender for commodity k

$G_{rskmnql}$ = Total Logistic Cost of commodity k transported between firm m in zone r to firm n in zone s, with a shipment size q using transport chain l

O_{kq} = Total ordering cost of commodity k for a shipment size q

T_{rskql} = Total transport cost between zone r and s for commodity k and a shipments size q using transport chain l

Y_{rskl} = Capital cost of the goods in transport between zone r and zone s for commodity k using transport chain l

I_{kq} = Inventory cost for commodity k and a shipment size q

K_{kq} = Capital cost of the goods in inventory for commodity k and shipment size q

o = Order cost of 55€

Q = Yearly demand (in ton)

q = Shipment size (in ton)

f = Frequency

D_{ph} = Distance pre haulage

D_{mh} = Distance main haulage

D_{eh} = Distance end haulage

TC_{hr} = Transport cost heavy road

TC_r = Transport cost rail

TC_{iww} = Transport cost inland waterway

Cap_r = Capacity rail

L_{hr} = Cost to (un)load heavy road

L_r = Cost to (un)load rail

TT = Total Transport time (in hours)

d = Interest rate (per year) of 4%

v = Value of the goods

w = Warehouse cost (per year) of 20%

Pickup and Delivery Selection Problem

N = Set of nodes (indices i, j

P = Set of n pickup locations (index i)

D = Set of delivery locations (index $i+n$)

O = Depot of the carrier

A = Set of undirected arcs

K = Set of vehicles (index k)

q_i = Quantity to be shipped from\to node i

Rev_i = Revenue for completing request i

$[e_i, l_i]$ = Time window of node i

d_{ij} = Distance between nodes i and j

t_{ij} = Travel time between node i to node j

ct = Travel cost per distance unit

Q_{max} = Maximum capacity of a vehicle

s_k = Start time of vehicle k

f_k = Finish time of vehicle k

ot_i = Operation time at node i

$$X_{ij}^k = \begin{cases} 1 & \text{if vehicle } k \text{ travels from } i \text{ to } j \\ 0 & \text{else} \end{cases}$$

$$Y_i^k = \begin{cases} 1 & \text{if vehicle } k \text{ performs request } i \\ 0 & \text{else} \end{cases}$$

T_i^k = Time of vehicle k after node i is served

L_i^k = Load of vehicle k after serving node i

Tabu-embedded simulated annealing algorithm

S_{best} = The best solution found yet

S'_{best} = Potential new best solution

S_{local} = The best local solution found yet

S'_{local} = Potential new best local solution

S = The current feasible solution

S' = A new feasible solution

$gNoImpr$ = The number of runs without an improvement in the General TSA algorithm

$NoImpr$ = The number of runs without an improvement in $TABU(S)$

K = Stopping condition of the general metaheuristic

$STOP$ = Stopping condition of $TABU(S)$

T = Global annealing temperature

T_0 = Initial global annealing temperature

δ = Factor for decreasing T

Problem variants of the pickup and delivery selection problem

C_{veh} = The fixed vehicle cost of one vehicle

$$Ylsp_i = \begin{cases} 1 & \text{if a LSP performs request } i \\ 0 & \text{else} \end{cases}$$

C_{lsp} = The cost of outsourcing one request to a LSP

i^{comp} = A compulsory request

L = Set of days in the planning horizon of a MPPDSP (indices l, m)

E_{il} = Indicates whether request i exists for day l

Abbreviations

$PDSP$ = Pickup and Delivery Selection Problem

$PDSPLSP$ = Pickup and Delivery Selection Problem with a Logistic Service Provider

$PDSPCR$ = Pickup and Delivery Selection Problem with Compulsory Requests

$MPPDSP$ = Multi-Period Pickup and Delivery Selection Problem

TSA = Tabu-embedded Simulated Annealing

LSP = Logistic Service Provider

Chapter 1

Introduction and problem statement

1.1 Freight transport

In modern society, a life without transport is unthinkable. Freight transport is indispensable. It is needed to ship products in their production chain and to bring them to their final consumer. Especially in a growing globalised context and consumption economy, its role is of crucial importance. Activities of firms are expanding, even across borders with the growing trend of globalisation. The rapid increase in global trade, alongside a range of economic practices (concentration of production to gain economies of scale, delocalisation and just-in-time deliveries), may explain the relatively fast growth of freight transport within the European Union (EU) (Eurostat, 2011). Due to these growing freight flows, a greater traffic intensity and a growing imbalance in the use of different transport modes is identified. Road transport is taking an increasing share of the modal split at the cost of more durable transport methods. Therefore, intermodal transport and the use of rail and inland waterways are promoted (Eurostat, 2011). This causes an increase in the logistic activities of firms as they become more dynamic. Public and private decision makers need to take these trends into consideration with regard to their decisions and a better projection of freight transport flows becomes necessary. Hence, there is a growing need for models that may predict future freight flows more accurately.

When it comes to modelling transport flows, most attention has been given to passenger traffic. Only recently modelling freight transport is receiving more attention due to the growing awareness that freight movements have an influence on general transport flows. It is hence crucial to integrate freight transport into the transportation planning process. Reasons for the gap between freight and passenger transport models are diverse, but in general it is stated that the movements of goods are more complicated to model than those of persons (Tatineni and Demetsky, 2005; Ortúzar and Willumsen, 2001). This is due to several characteristics of freight transport. An overview of the main characteristics of freight transport that have an influence on the modelling process is given.

First of all, freight transport is more **heterogeneous**, due to the great range in shipment sizes, value, weight and good categories (Tatineni and Demetsky, 2005; Ortúzar and Willumsen, 2001). A second category of characteristics are the **physical factors**. The characteristics and nature of raw materials and end products influences the way in which they may be transported, such as in bulk, packaged in light vans, in secure vehicles or in refrigerated containers. Therefore, a greater variety of vehicle types exists to match commodity classes than in the case of passenger transport. The **operational factors**, such as the size of the firm, its policy for distribution channels, its geographical dispersion and so on, strongly influence the possible use of different modes and shipping strategies. Futhermore, **dynamic factors** like seasonal variations in demand and changes in consumers' preferences play a significant role in changing goods' movement patterns (Ortúzar and Willumsen, 2001). Another important reason for freight modelling lagging behind is the lack of publicly available data. Most of the **scarce data** that is publicly available is aggregated to protect the identity of the individual actors (Tatineni and Demetsky, 2005). Also the **pricing mechanism** of freight transport services is different than in passenger transport. Within passenger transport prices are fixed and generally known to all users. Freight transport prices are usually negotiated as a long-term contract and are not uniform for all shippers (Tatineni and Demetsky, 2005). Most transport firms try to keep their rates confidential, to enforce their position on the market, when it comes to renegotiating prices. Several factors influence the price of a freight service, like the length of supply contracts, the extent of volume discounts, the importance of terminal facilities and the use of own-account operations (Ortúzar and Willumsen, 2001).

Several actors are involved in the decision making process of freight transport. It involves a complex relation between shipper, receiver and carrier of the goods. All of these different actors depend on each other. They may not have complete information, nor decision making power. This interaction between actors is hard to represent accurately in a transportation model and is the focus of recently developed models as discussed later on (chapter 2).

In conclusion it is very hard to create homogeneous groups within freight transport. This complicates the creation of a comprehensive freight transportation model that is able to predict freight flows for the future.

1.2 Freight transportation models

It is recognized at all levels of decision making that freight transport and economic development are linked. Models to predict future freight flows have to cope with changes in the logistics and freight industry. Freight transportation models are used to assess the impact of several policy measures, such as changes in national regulations, taxes or infrastructure investments in links, terminals and corridors (de Jong et al., 2013).

In the past, most transport models focused on modelling passenger flows. These models cannot be used as such for freight transport. One of the reasons for this, as mentioned earlier, is the fact that more actors are involved in the decision making process. A first group of actors are firms who are sending and receiving goods. Secondly, shippers are actors who are responsible for the organization of the consignment and modes. The last group consists of carriers who undertake the movement (Ortúzar and Willumsen, 2001). Next to this, several other firms are responsible for the transhipment, storage and custom facilities. The economic transactions between suppliers and consumers and the logistics operations that actually deliver the goods, are the two main drivers behind the rapidly evolving patterns of freight movements (Jin et al., 2005). To model the freight transportation process, the interaction between the different actors in the decision making process is important.

Wigan and Southworth (2006) stated that, at that time, freight planning models showed only a limited understanding of the agents involved and that limited attention was given to causes and dynamics underlying in freight demand and supply. Since, logistics behavior has been introduced into freight transportation models in order to increase policy-sensitivity and realism. The inclusion of logistics is one of the main developments in freight transportation models (de Jong et al., 2013). Logistics or logistics management is defined by the Council of Supply Chain Management Professionals (CSCMP, 2013) as “that part of supply chain management that plans, implements, and controls the efficient, effective forward and reverse flows and storage of goods, services and related information between the point of origin and the point of consumption in order to meet customers' requirements”.

Today, most of the state-of-the-practice models in freight transport are still four-step models, which focus on individual trips. These models have as main disadvantage that they are looking at the aggregated flows between zones and cannot model flows at a more detailed level. For that reason, they are missing out on the behavioural aspects behind transport and are having errors due to aggregation. The importance of incorporating logistic decisions and behavioural aspects in a freight transportation model is widely recognised (Tatineni and Demetsky (2005), Tavasszy et al. (1998), MOTOS (2006) and Liedtke (2009)). Some of the more recently developed four-step models are already incorporating logistic decisions. Still, these models are on an aggregated level and are not taking into account aspects of the different agents. A disadvantage is the transformation of commodity flows into truck flows which is done rudimentary. Four-step models fail to represent the attributes of individual shipments or the logistic process that determine the relationship between commodity flows and commercial vehicle flows.

Recent trends in freight modelling are moving to more activity-based models, which focus on each freight agent separately. They are better able to model individual operational decisions and interactions concerning logistics and transport. Furthermore, a disaggregated approach is applied, by looking at trips and decisions on a microscopic scale and no longer aggregating flows between different zones. This enables the understanding and representation of roles that each actor plays in the freight transportation system, interactions between actors and changes in actors and their interactions over time. Roorda et al. (2010) found that these elements are of fundamental importance in the development of more behavioural models for the freight system. Hensher and Figliozzi (2007) stated that four-step models are inadequate to deal with the "21^{st} century global customer-driven economy". In the beginning of this chapter several recent trends are mentioned it is hence required to have freight models that are able to account for supply chain relationships and logistic constraints. As found by Chow et al. (2010), freight demand models in practice rely on aggregate approaches that are insensitive to economic behaviour at the level of the firms who act as decision-makers.

In this thesis is opted to make a first step towards the development of an activity-based freight transportation framework to overcome some of the difficulties of recent models. Trip-based models fail to represent the economic behaviour to arrive at commodity flows from which the demand for transport is derived. Commodity-based models on the other hand struggle with a realistic representation for vehicle activities. Models at an aggregated level are not able to incorporate the decisions of the different actors involved in freight transport. The proposed conceptual framework of chapter 3 works on a microscopic level and take into account multiple transport modes. The representation of the different actors within a multimodal environment is not often done in research, as will be seen in chapter 2. Despite the advantages linked to the implementation of activity-based modelling, some drawbacks may be identified. First, a high need for low level data exists which is difficult to obtain. Secondly, the characteristics of different firms are hard to represent in one behaviour model. Furthermore, computational efforts when modelling large areas have to be kept in mind. From the literature study (chapter 2) it is clear that still much work needs to be done in the development of activity-based models. Barthélemy et al. (2010) found that the current disaggregated freight transportation models are lagging behind both on an operational and a conceptual level. Therefore, this thesis aims at making a first step in working out some logistical elements at a conceptual level. More specifically the focus goes to the decisions of the carrier (see section 1.3).

Being able to understand the drivers of freight transport makes it possible to forecast freight flows in the future and to calculate the impact of different policies on freight traffic. It will put policymakers in the position to get a better insight in the way the transport of goods comes about. To this end freight transportation models may be used.

1.3 Decisions of a carrier

One of the main actors involved in freight transport is the carrier. He has the responsibility to execute the actual transport on the different origin-destination (OD) legs within a transport chain. Therefore, he has to plan the different road transport requests he receives into vehicle tours. Within his planning he has to take into account time windows requested by his clients, the capacity of his vehicles and the order of pickup and delivery. The objective of the carrier is to achieve the highest possible profit. By accepting transport requests from clients he can increase his revenue. However, due to the limited amount of resources he is required to make a selection of the clients he wants to accept.

Within freight transportation models a detail representation of the decisions of a carrier is not often represented. When modelling at a microscopic level the incorporation of carrier decisions is an important aspect. The interaction between a firm and a carrier during contract negotiations are influenced by the optimisation process of the carrier. If the transport request of the firm may be matched with other transport requests received by the carrier, it is more likely that the request is accepted. Otherwise the request is declined and the firm has to find another carrier or adapted his demand. Also transport prices are determined by this interaction and the decisions of the carrier.

Also in the field of operational research the selection of paired pickup and delivery requests is not often studied. Two main bodies of routing literature are relevant for the pickup and delivery selection problem. On the one hand vehicle routing problems with profits and on the other hand literature concerning pickup and delivery problems. The pickup and delivery problems are more relevant to the problem at hand, however profit maximization has been more applied on vehicle routing problems. In chapters 5 to 7 of this thesis techniques are studied to solve this selection and planning problem.

1.4 Outline of the thesis

In this thesis, freight transportation models and their components are studied. The objective is to develop a new comprehensive freight transportation framework, in which logistic decisions are incorporated. Most attention is given to the decisions of the different actors involved in the decision making process. In a first part of this thesis components of the new framework for Flanders are described and detailed steps of the logistic decisions within the framework are given. The second part focuses on the carrier, one of the actors in the proposed framework. The actions of a carrier are defined and formulated on an operational decision level. This problem is solved with a heuristic. The outline of the thesis is presented in figure 1.1.

The main contributions of this thesis are situated on two domains. First, the proposed freight transportation framework is able to handle all the main actors involved and gives a detailed simulation of logistic decisions in a multimodal environment. Secondly, the formulation of carrier decisions as a pickup and delivery selection problem is a novel technique for modelling carriers in freight transportation models. Furthermore in the field of operations research this thesis makes a contribution as the traditional pickup and delivery problem is extended with the selection of transport requests.

Chapter 2 presents an overview of literature on existing freight transportation models. This chapter starts with a general history of freight transportation models. A selection of recent models is extensively reviewed based on several characteristics of these models. The main focus lies on the more recent activity-based transportation models. This chapter identifies gaps in scientific literature and highlights key components for a new framework.

Next in chapter 3 a new conceptual freight transportation framework is developed

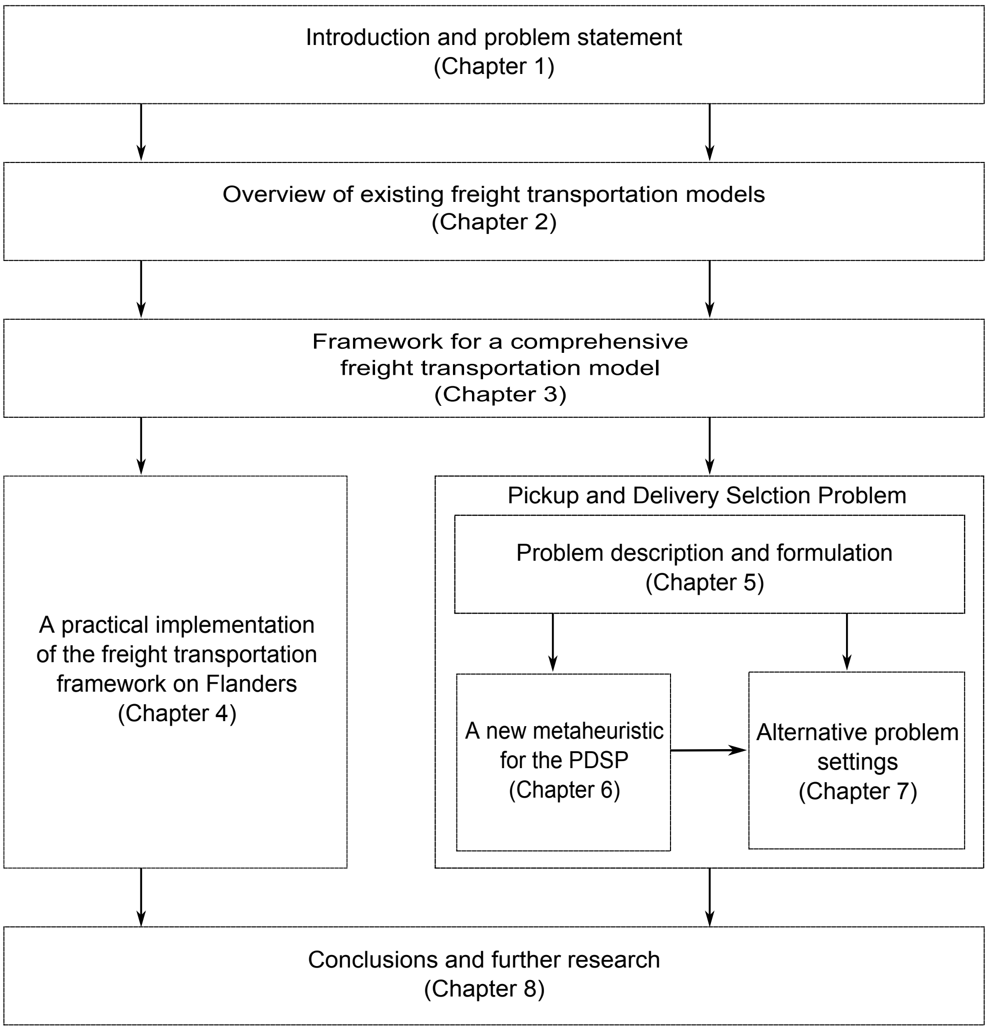

Figure 1.1: Outline of the thesis

to predict future freight flows and analyse the impact of policy decisions. This framework simulates actors at a microscopic level, which allows incorporating the impact of their logistic decisions. Within this framework, the main focus goes to the Logistic module and the interactions between the different actors. Other modules needs still be worked out further before it may be implemented. Also different elements within the Logistic module require further research, such as the behavioural aspects of the actors. Furthermore, the necessary data requirements to further develop the model are given. The Logistic module of the framework is tested on a small selection of communities in Flanders in chapter 4. The objective is to show how the different elements in the framework work and expose difficulties that could arise when extending the framework into a fully working model. A sensitivity analysis is conducted to show the influence of the different parameters on the model.

While chapters 3 and 4 are related to the general framework at a strategic level, chapters 5 to 7 are concerned with the operational decisions of a carrier. Chapter 5 introduces the daily selection problem carriers are confronted with. A carrier may receive more transport requests from his clients than he is able to handle with the limited resources at his disposal. This leads to a selection problem to determine which clients will be served and which will be declined. In the freight transportation framework of chapter 3 the assumption is made that an actor handles in order to maximize his profit. The operational planning problem of the carrier is modelled as a pickup and delivery selection problem (PDSP). The mathematical formulation of the PDSP is presented, in which the objective is to maximize the total profit gained.

A tabu-embedded simulated annealing metaheuristic is proposed in chapter 6 to solve the PDSP. Two new local search operators are created to handle the selection of profitable requests. Traditional local search operators are used to divide the selected requests between the available vehicles and constructed vehicle routes. Because the PDSP is not often investigated in literature, no ready to use benchmark data is available. An experimental design with two sets of benchmark data is set up to test the algorithm. One set of benchmark data is adapted from the data of Li and Lim (2001), the other set is generated specifically for the PDSP with the help of a full factorial design.

Chapter 7 studies alternative problem settings of the PDSP. First the PDSP with compulsory requests is studied. Due to long-term contracts it is no longer possible to refuse certain clients. These clients are set as compulsory requests and have to be accepted by the carrier. Other clients may still be refused and are only selected when profitable. A second alternative introduces a fixed vehicle cost to the PDSP. Vehicles are no longer at the disposal of the carrier for free, but a fixed cost has to be paid each time a vehicle is used. Next, a PDSP with the option to outsource requests to a logistic service provider (LSP) is presented. Here the carrier has three options: either to conduct the request with his proper fleet, to outsource the requests to an LSP or to decline the client. In a fourth problem setting an alternative revenue model for the carrier is proposed. Instead of setting a fixed price per kilometre and accepting requests with a profitable return, as many clients as possible are accepted and a price to cover the transport cost is asked. Finally, options for a multi-period PDSP are discussed and a small scale example is worked out.

To end, chapter 8 presents general conclusions and opportunities for future research.

Chapter 2

Overview of existing freight transportation models

2.1 Introduction

This chapter provides an overview of the literature concerning freight transportation models (Figure 2.1). The main focus lies on recent activity-based models, although also an overall picture of earlier freight transportation models is given.

In section 2.2 the development of freight transportation models from four-step models to activity-based models is presented. Special attention to models incorporating logistic decisions is given in section 2.3. In the remainder of the chapter, the different freight transportation models are analysed. Section 2.4 compares the models on six levels. First, the link with the economy is reviewed. A second level is the incorporation of logistic decisions. Further the scope of each model is highlighted, after which the transport modes used in the different models and the network assignment methods are given. The section ends with a detailed review of the different agents used in the agent-based models. Finally, conclusions are drawn in section 2.5.

2.2 Modelling history

The very first way of forecasting freight transport was done by **growth factor models** (Beagan et al., 2007). This is a straightforward method and may be applied to either historical traffic trends or forecasts of economic activity. The second approach recognises that the demand for freight transport is derived from economic activities.

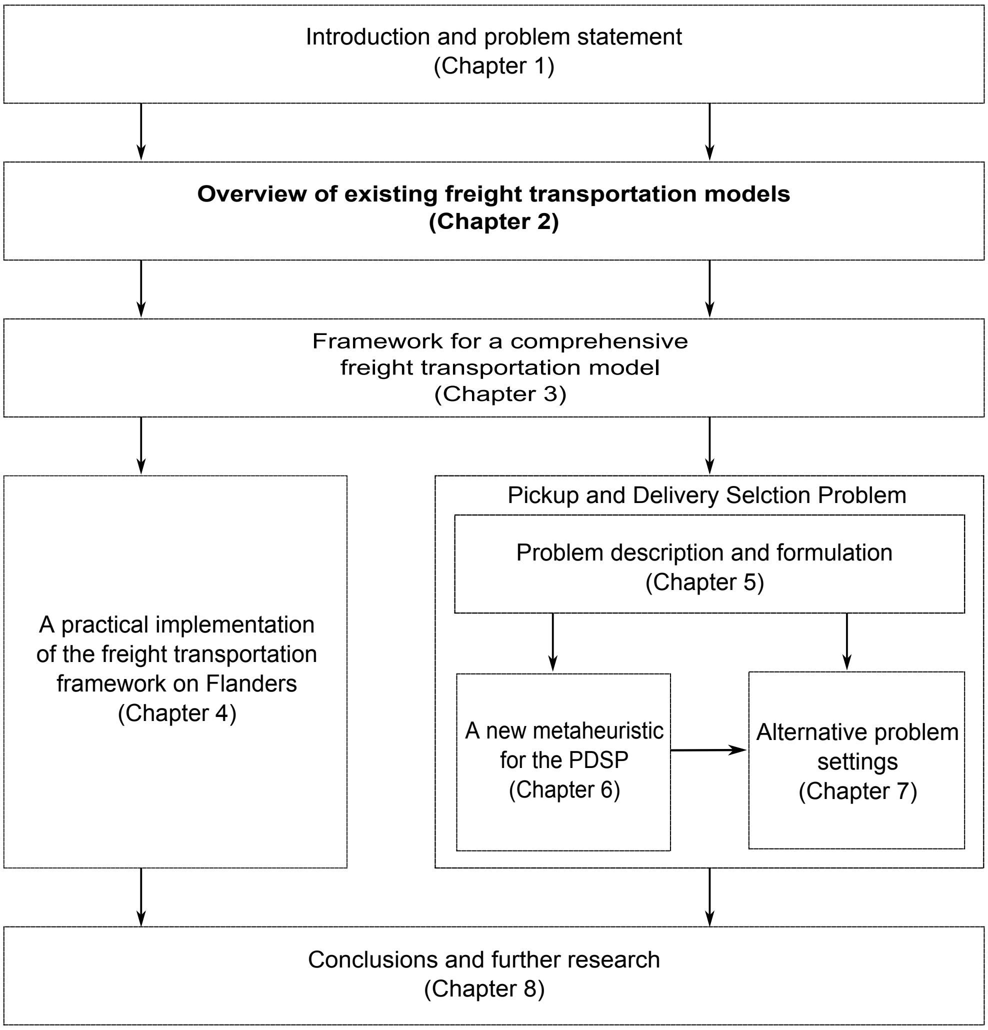

Figure 2.1: Outline of the thesis - Chapter 2

Growth factor models are a simple and inexpensive way to forecast freight transport, but this method assumes that relationships of the past will continue in the forecasting period.

Early freight transportation models followed the developments of passenger transport and were called **four-step models**. A four-step model uses individual vehicle trips as the unit of analysis and usually includes four sequential steps. These steps are: trip generation, trip distribution, mode choice and assignment (VDOT, 2009). In the first step, the number of daily trips that take place in a region is determined. The trip distribution step then links the trips "produced" and "attracted" geographically into complete trips. The next step, mode choice, establishes the type of transport mode each trip will use. The assignment step, finally determines the routes travellers chooses to reach their destination. A distinction may be made between three-step and four-step models, depending on whether a mode choice step is included or not. Each step has several models that may be used, for freight transport a good overview may be found in de Jong et al. (2004). One subcategory of these models are the **trip-based four-step models**. The input of trip-based models is mainly based on Origin-Destination (OD) matrices and indicators for trip generation, like the number of destinations, the floor space of a company or the number of employees (Boerkamps et al., 1999). One of the advantages, besides the low cost, is that these models can be easily integrated into a passenger transportation model.

Despite the fact that trip-based models are widely used, even today, they are also the object of a lot of criticism. Although the derived nature of transport is understood and accepted in trip-based models, this is not reflected in their structure (Jovicic, 2001). First of all, they ignore the fact that the demand for travel is derived from the demand for activity participation. They are not linked in a sensible way to the economic input/output which is the driver of commercial vehicle movements (Cavalcante and Roorda, 2010). The trip generation step is often done without incorporating data factors, like information on shipments, freight rates, amount of commodity generated by a firm and others. Secondly, their focus is on individual trips and ignores the spatial and temporal relationship between trips and activities.

Another subcategory of four-step models are the **commodity-based four-step models**. In these models the trip generation and trip distribution step is replaced by a commodity flow database. The mode choice and modal assignment step is maintained from the four-step models. These commodity-based models focus on the commodities that are transported between zones instead of truck trips. Consumption indicators are used as input for the generation of commodity flows (Boerkamps et al., 1999). In a last step, the commodity flows are transformed into vehicle trips via truck loading factors. Similar to trip-based models, commodity-based models are on an aggregated level, but make an explicit linkage between the economic supply and demand, which dictates the demand for goods and trade. A disadvantage of these models is the transformation of commodity flows into truck flows which is done rudimentary. Therefore it does not represent the attributes of individual shipments (size, value,...), or other logistic processes that determine the relationship between commodity flows and commercial vehicle flows (Cavalcante and Roorda, 2010).

In general it is possible to divide all models over these two subcategories. On one side there are the trip-based models, where the unit of analysis is based on vehicle trips. The other group consists of the commodity-based models, where the focus is on the goods that are transported (Boerkamps et al., 1999).

The previous discussed models are lacking the application of logistic choices and structures, as they follow closely the development of passenger transportation models. **Supply chain and logistics chain models** have been developed to overcome this problem (Chow et al., 2010). These models apply analytical methods to simulate logistics choices throughout the supply chain (Fischer et al., 2005). The structure of a four-step model is still applied, but adaptations have been made to incorporate logistic characteristics of freight transport. These models include the use of consolidation and/or distribution centres, so that routes between production and consumption may be modelled. Although this is a step in the direction of a more realistic and behaviour based model, it still has the disadvantage of being an aggregated model and is not able to represent the different actors involved in freight transport.

The latest state-of-the-art freight transportation models are based on the activity-based concept. **Activity-based modelling** has been practised since the beginning of the 1980's (Jovicic, 2001). Flows are modelled on a microscopic level and a clear link exists with the economic activity of firms. Activity-based models may provide a better forecast of reality, as they simulate behaviour and explicitly take into account logistic decisions. Liedtke and Schepperle (2004) define activity-based modelling as follows:

> "The activity-based modelling approach of freight transport explains how individual operational decisions concerning logistics and transports are undertaken, in order to give indications to a traffic planner how the whole transport system reacts on transnational and federal transport policy measures."

Although the theory of activity-based models is almost three to four decades old, research is still under development. As main subgroups tour-based models, hybrid models and agent-based models may be distinguished.

Tour-based models derive their methods form activity-based passenger models. The focus is on tour characteristics and not on the goods on board. Trip chaining has a significant importance in freight transport. This due to the fact that commercial vehicles make long tours with multiple stops, in contrast to passenger transportation where trip chains are not that common (Wang and Holguín-Veras, 2008). Until now only truck trips are modelled using tour-based models and there has not been an expansion to multimodal modelling yet (Fischer et al., 2005). The main example of a micro-simulation tour-based model has been developed by Hunt and Stefan (2007) for the region of Calgary.

Hybrid models combine the characteristics of commodity-based and tour-based models. First commodity flows between origin and destination are estimated, after which delivery routes for the transport of commodity flows are calculated. An example can be found in Wang and Holguín-Veras (2008).

Lately the group of **disaggregate agent-based models** is getting more attention. Disaggregate models use observations at the level of the business establishment or the shipment. These models have several advantages over aggregate models, which use groupings of those units as observations. Disaggregate models may be based on a foundation in behavioural theory, may include more detailed policy-relevant variables and do not suffer from the aggregation biases of aggregate models (Ben-Akiva and de Jong, 2008). Aggregation biases may occur when assuming that general trends in a nation will also hold for individual firms. Furthermore, an over- or underrepresentation of certain types of firms in the data may lead to false conclusions. To overcome these forms of biases the behaviour of each agent individually is simulated, which might lead to greater prediction realism. **?** claimed that by representing the decisions of individual agents, individual shipments can be modelled based on the characteristics of individual firms. Decisions about purchasing, sales and inventory may be represented in this way. Besides vehicle type choice, choices about the attributes of a shipment, like shipment size and frequency, are relevant in the disaggregated approach. While these models have made some progress, there is still work to be done, due to the lack of data and computational challenges. Also the behavioural representation of the agents needs to be further studied. The different model categories are summarised in table 2.1 on page 18.

2.3 Models incorporating logistic decisions

A good overview of early developments in freight transportation modelling may be found in de Jong et al. (2004) and Tavasszy (2008). In this section the main focus is on the more recently developed transportation models for freight traffic. First, this section starts with taking a look at some of the first models that try to incorporate logistic decision making. Next, disaggregated activity-based models are presented, in which a distinction is made between tour-based, hybrid and agent-based models. Although activity-based models also integrates the principles of the supply chain and logistics chain models it is opted to create two separate groups. The supply chain and logistics chain models are still on an aggregated level, where activity-based models are disaggregated and include more details. A classification of the models in the different categories is given, after which in section 2.4 an in depth analysis of the models is presented.

2.3.1 Supply chain and logistics chain models

In this category three different models may be identified. First, the SMILE model of the Netherlands was developed by the Transport Research Centre of the Ministry of Transport, NEI (Netherlands Econometric Institute) and TNO Inro. SMILE stands for Strategic Model for Integrated Logistics Evaluation. In 2003, TNO began with the actualisation of the SMILE model, which resulted in the SMILE+ model (Tavasszy et al., 1998).

The second aggregated model with a logistic module, was constructed in the SCENES project. SLAM (Spatial Logistics Appended Module) was developed for Europe and is a separated module in the SCENES project (SCENES Consortium, 2000).

The third model EUNET2.0 is an integrated regional economic and freight logistic model developed for the Trans-Pennine Corridor in the north of England (Jin et al., 2005).

2.3.2 Activity-based models

Within freight transport, an "activity" of shipments cannot be compared with e.g. a shopping activity within passenger transport, as stated by Liedtke and Schepperle (2004). However, this expression is already been used within the new generation of freight transportation models. Because of its microscopic scale and representative property, the activity-based approach may also be applied for the transport supply side. It may explain the effects of individual behaviour changes on the whole transport system, of which Liedtke and Schepperle (2004) claim that it improves the quality of forecasts for planners.

The Aggregate-Disaggregate-Aggregate model (ADA-model) presented by Ben-Akiva and de Jong (2008) is an activity-based model that forms an extension to the supply-chain and logistics chain models. The ADA-model has its main decision protocol at a disaggregated level instead of at an aggregated level as in the models in section 2.3.1. The previous national freight model system in Sweden (SAMGODS) was lacking logistic elements. In Sweden, as well as in Norway (NEMO model), a process to update and improve the existing national freight model system was started. An important part of this was the development of a logistics module. In both countries the ADA-model was introduced, to solve this problem. Another activity-based model is the nationwide micro-simulation freight framework from Samimi et al. (2009) called FAME: Freight Activity Micro-simulation Estimator.

A first sub-category of activity-based models are the tour-based models. In this thesis one model of this category is incorporated for comparison reasons, as the main focus will be on agent-based models. This model is the urban tour-based micro-simulation model for Calgary in Canada developed by Hunt and Stefan (2007).

Also a hybrid model is taken into account by way of example. This is the framework proposed in Fischer et al. (2005) for the Los Angeles County in California, which combines the features of logistic chain and tour-based models.

The main focus of this thesis goes to agent-based models. Six different models are presented. First the model of Oregon, United States, is a land use transport interaction model of the State of Oregon and includes elements of agent-based micro-simulation. The model is described in the work of Hunt et al. (2001) and Hunt (2003). A second model is developed at the Delft University of Technology and is called the GoodTrip model (Boerkamps et al., 1999). This model may be considered as an agent-based commodity model. The third model is the INTERLOG model created for the German region and is also situated within the subcategory of commodity transportation models. The model is represented in the work of Liedtke (2009). Wisetjindawat et al. (2007) proposes another micro-simulation model for urban freight movement in the Tokyo metropolitan area. Also Roorda et al. (2010) presented a conceptual framework for agent-based modelling of logistic services. Finally, the last model is included, the Transportation And Production Agent-based Simulator (TAPAS), which is a general tool for micro-level simulation of production and transportation of products (Davidsson et al., 2008). An overview of these model categories and related models can be found in table 2.1.

2.4 Comparison of existing models

This section describes the results of a comparative study between the different models presented in section 2.3. Comparing the models allows seeing the differences between the different model types. Furthermore, it may highlight certain shortcomings within the models. First in section 2.4.1, the link with the economy is investigated. It is studied how the different models take economic input factors into account. Second the logistic decisions that are incorporated are studied in section 2.4.2. Here the attention

Table 2.1: Model categories

<table>
<tr><th>Type of model</th><th>Trip-based</th><th>Commodity-based</th></tr>
<tr><td>Four-step</td><td>\</td><td>\</td></tr>
<tr><td>Supply chain and logistic chain</td><td></td><td>SMILE, SCENES, EUNET2.0</td></tr>
<tr><td>Activity-based</td><td></td><td>ADA, FAME</td></tr>
<tr><td>- Tour-based</td><td>Calgary</td><td></td></tr>
<tr><td>- Hybrid</td><td colspan="2">Fischer</td></tr>
<tr><td>- Agent-based</td><td></td><td>Oregon, GoodTrip, INTERLOG, Roorda, Wisetjindawat, TAPAS</td></tr>
</table>

is focused on how decisions on shipment size, mode choice and vehicle type are made and whether logistic chains are represented in the model. The next item is the scope of the models (section 2.4.3). It is studied how nationwide models are different than regional models with respect to the modelling scope. After which in section 2.4.4 the transport modes used are compared. The last step of most of the models is the network assignment, several options to handle this are discussed in section 2.4.5. Finally, more details on the agents in the agent-based models are presented in section 2.4.6. This shows that several options exist to represent the actors involved in freight transport.

2.4.1 Link with the economy

In the reviewed models, two main distinctions may be made when it comes to incorporating the economy in the model. The first category of models uses aggregated data of input-output (I/O) matrices. A second group of models works with more detailed individual data and are modelling the demand and supply of firms at a microscopic level. Next to these two groups a third group of tour-based models may be identified, which have a total different modelling approach. A separate group is created for these models, as they differentiate themselves from the aggregated and microscopic models. An overview of the models belonging to each group may be found in table 2.2.

Table 2.2: Link with the economy

Aggregated	**Microscopic**	**Tour-based**
SMILE	GoodTrip	Calgary
SCENES	INTERLOG	Fischer
EUNET2.0	TAPAS	
Oregon	Wisetjindawat	
ADA	Roorda	
	FAME	

First, the link with the economy within the aggregated models is discussed. In the SMILE model (Tavasszy et al., 1998), Make/Use (M/U) tables are applied instead of traditional I/O matrices. M/U tables provide a detailed insight into the production factors connected to the activity of each sector, including the commodities that are produced and consumed. One of the main reasons to use M/U tables instead of I/O tables is that they provide a clear separation between goods and services. Furthermore they create the opportunity to set up a production function for each sector and are very helpful in establishing the location pattern of both production and consumption. A second element at this level concerns the trade structure. This trade structure is described by connecting production and consumption together with import and export through trade channels. In addition, a regional breakdown is made using regional productivity per sector. After having determined the volume and nature of production and consumption at different locations, the spatial distribution of flows between locations is calculated (Tavasszy et al., 1998).

In the SCENES model (SCENES Consortium, 2000), EUROSTAT 1995 I/O tables for each EU15 country are used as base data. The tables were expanded from the 25-sector level to a 44-sector level and then disaggregated to the 205 internal zones. This was done based on Gross Value Added (GVA), population and other socio-economic data for each zone. The model uses a spatial adaptation of the Leontief input-output framework to produce OD matrices of tonnes by flow of transport. The I/O data on which the model was based does not provide any information about the pattern of intra-EU trade. For each country, information is only provided about imports from and exports to the rest of the EU as a whole. The pattern of trade between zones therefore had to be determined. The import and export totals for intra-EU trade, taken from each country, are therefore combined with observed trade data using a matrix expansion procedure. This allows the production of a zone to zone pattern of trades that is consistent with the overall totals for the fifteen EU countries (SCENES Consortium, 2000).

The core of EUNET2.0 is a set of iterations of the Spatial Input-Output (SIO) model that gives the zonal consumption and production by commodity type and represents the distribution chains. An OD matrix represents the output by freight type in units of the monetary value of goods transported. The main innovation in this study is that it connects the pattern of freight demand to the underlying spatial pattern of economic transactions, providing a transparent interrelationship between the growth of freight and the patterns of economic activity. This makes it possible to explore opportunities for decoupling freight growth from economic growth (Jin et al., 2005).

The model of Hunt (2003) for the region of Oregon, makes use of a general form of the spatially-disaggregated input-output model to identify patterns of spatial locations and interactions among the different economic sectors in an aggregate treatment. Trade flows between the model region and other regions are forecasted by allocating gross imports and exports by economic sector to the regions. Production functions based on the technical coefficients in the input-output 'make' tables are used to determine quantities of input commodities required, including goods, services, labour and space. Commodities flow from production zones to consumption zones, via 'exchange locations'. Exchange locations represent the places where exchange prices are determined and where commodities are transferred from the seller to the buyer, thereby allowing an allocation of transport costs. This is in contrast to the treatment in the standard spatially-disaggregated input-output approach, where it is the demand for additional production that is allocated, rather than the flows of commodities, and where the prices are always determined at the production location (Hunt, 2003; Hunt et al., 2001).

The ADA-model (Ben-Akiva and de Jong, 2008) also uses aggregated data. The model starts with the determination of flows of goods between production zones and consumption zones. This is commonly based on economic statistics that are only available at the aggregate level, like production and consumption statistics, input-output tables and trade statistics. Some models are proposed in the framework, but not further specified: a multi-regional I/O model, a regionalized national I/O model, or a spatial computable general equilibrium model. The ADA framework has been applied in Norway and Sweden. For Norway in the version 1 model, all firm-to-firm flows based on data of firms by number of employees and municipality are used. This means that no expansion is needed to determine the population of all goods flows in Norway as all the flows are taken as input. For Sweden a sample of firm-to-firm flows (for different size classes) is used, after which an expansion procedure needs to be applied to arrive at population totals.

Next, the second main group of microscopic models is presented. These models represent input data at an individual level and model the demand and supply at a microscopic level. In all these models a bottom-up approach may be identified.

Based on consumer demand, the GoodTrip model (Boerkamps et al., 1999) calculates the volume per goods type in cubic metres in every zone. The goods flows in the logistic chain are determined by the spatial distribution of activities, quality of accessibility and market shares of each activity type. This goods attraction constraint calculation starts with consumers and ends at the producers or at the city borders. Next, the goods flows of each goods type are combined by using groupage probabilities.

The INTERLOG model uses a sourcing module to address the choices of suppliers and the exchange of microscopic flows of goods between the actors of the transport demand side. Generation rates may be deduced directly from production statistics, but attraction rates must be constructed using information from monetary I/O matrices for the flows between industrial sectors and retail and the streams down to the consumers. Within supply chain management two options exist for the simulation system, either "pull" or "push". Within a push system product availability is based on forecasts. In contrast, a pull system controls the flow of products by adjusting inventory levels according to actual consumption. Hence, within a pull system the customer initiates the demand for goods (Harrison et al., 2003). Liedtke (2009) opted for simulations using the pull algorithm, because in production systems the recipients generally have more power. The set of suppliers for each company is determined using a guided Monte Carlo algorithm. For the appraisal of companies as potential suppliers a random choice function is used, which considers product availability (unused capacity), cost of transportation, communication and supply-chain vulnerability (sensitivity to distance) and the usefulness of the commodities (economic activity). These three parameters may be determined using the information of production statistics, input-output tables and truck surveys. After a company has chosen a set of suppliers, the necessary amount of production goods is distributed among the suppliers. The microscopic flows of goods are determined using a guided Monte Carlo search that automatically observes the production and attraction rate constraints.

Wisetjindawat et al. (2007) start with the generation of attributes of each firm, such as location, number of employees and floor area, using Monte-Carlo simulation from their distributions based on the aggregate data. Next, commodity production and consumption of each firm are estimated using regression techniques with the firm's attributes. The generated commodities are then linked from consumption points to production points according to the attractiveness of each production point. This results in commodity flows between consumption and production points. It is the demand at consumption points that determines the amount of commodity supplied at production points. Discrete choice models are selected to explain customer's behaviours on their purchasing choices, taking into account the following probabilities: distribution channel, shipper location and the probability of selecting each shipper. Commodities are then distributed from firms to firms over the entire area according to their relationships in supply chains.

In the TAPAS model the link with economy is not explicitly represented, but is included through the customer demand. Orders made by a customer depend on forecasts of consumption for the next time period. A customer may only access forecasts of future consumption but has no control over the actual consumption, which is assumed to follow a known probability distribution (Davidsson et al., 2008).

Roorda et al. (2010) integrate economic aspects in the process of commodity contract formation. The model starts by forecasting for each business establishment its commodity output (supply) and its associated commodity input (demand) for each commodity. This depends on the attributes of the business establishment, like its history of commodity inputs and outputs, its production capacity, end consumption and the price function. When the customer is a business establishment, the demand function would simply be a conversion of forecast commodity outputs into inputs using a matrix of technical coefficients. For an end consumer, the demand could be specified as a function of end consumer attributes, since they do not produce commodities. After demand and supply are established, a market interaction takes place which matches the commodity orders from customers to the output supply from vendors, using a random utility maximization model. For each commodity, each customer forms a choice-set of suitable suppliers whose advertised supply may fulfil the required order size and frequency. The market interaction also determines the length and the price associated with the commodity contract (Roorda et al., 2010).

The FAME framework of Samimi et al. (2009), starts with the generation of firms.

Individual firms with a similar geographic location, industry type and size are supposed to be homogenous and are grouped into one firm-type. Firm-types should be defined in this module with three mandatory characteristics (location, industry, size) in addition to the number of actual firms within each firm-type. A separate module exists for replicating the supply chains with their annual commodity flow. First an annual commodity OD flow in terms of dollar value and weight has to be obtained. This may be obtained from FAF (Freight Analysis Framework by the Federal Highway Administration) and is publicly available. In a next step the incoming and outgoing commodities for each industry are determined. If disaggregated data is not available for this step rough national estimates or local studies are used. Finally the module connects the firm-types and forms the supply chains.

To conclude this section, the models that use a tour-based modelling approach are discussed. First the link with economy in the tour-based model of Calgary (Hunt and Stefan, 2007) is reviewed. The generation of tours does not depend on economic data, but generates tours per zone and day for each industry. Also the framework proposed by Fischer et al. (2005) contains a tour-based component. Here tour construction is mainly used for transport of mixed commodities. The reason for this is that financial transactions and economic data related to mixed shipments are difficult to extract from existing economic data sources. Tour-based modelling has the advantage that it does not rely on data of financial transactions and economic data to generate truck trips. Data input for the tour-based components are derived from establishment surveys across a wide range of companies that operate truck fleets. Economic data are only used to generate control totals.

2.4.2 Logistic decisions

This section reviews the logistic decisions incorporated in the different models. The focus will be on how they handle the choice of shipment size, transport mode and vehicle type. Furthermore, the consideration of inventory cost, consolidation options, intermediate transhipment points and tour routing are examined. Table 2.3 gives an overview of the models that explicitly take into account shipment size, mode choice, vehicle type and the incorporation of logistic chains. If one of these items is not represented, it is denoted with '0', if it is not know from the literature a '?' is inserted. Although some elements are implemented in several models, the way these choices are modelled may differentiate considerably. This may be seen for the analysis of each model in this section.

Table 2.3: Logistic decisions

Model	**Shipment size**	**Mode choice**	**Vehicle type**	**Logistic chain**
SMILE	0	X	?	X
SCENES	?	X	X	X
EUNET2.0	?	X	X	X
ADA	X	X	X	X
FAME	X	X	?	X
Calgary	0	0	X	0
Fischer	X	X	?	X
Oregon	X	0	X	?
GoodTrip	X	X	X	X
INTERLOG	X	0	0	0
Wisetjindawat	X	0	X	?
TAPAS	X	X	X	?
Roorda	X	X	X	X

SMILE is one of the first models to represent logistic decisions. The chosen distribution chains are calculated by means of a simple logit model. The main function is to link trade relations to transport relations by considering warehousing services. Furthermore, several configuration options for distribution chains are investigated, which are characterised by the number and location of distribution centres. In the logit model that is used, total logistic costs are calculated that account for handling, inventory and transport costs for logistic families (homogeneous product categories). Logistic families are distinguished using the following product and market characteristics: value density, packaging density, perishability, delivery time, shipment size and demand frequency (Tavasszy et al., 1998).

The Spatial Logistics Appended Module (SLAM), within SCENES (SCENES Consortium, 2000), transfers trade flows into transport flows by taking into account the logistic costs and bundling possibilities of freight flows. The logistic module does not yet specify the mode choice in a chain, but identifies typical distribution structures for chains, based on the characteristics of the region, products, and the network. The appended module calculates the number and potential locations of distribution centres (DC) throughout Europe on a regional level by re-assigning tonnes per OD in relation to possible alternative chains. Regions that are attractive for the location of a DC will have a higher throughput in tonnes compared with the initial OD patterns. The outcome of the module is a revised OD table for transport in which some regions will benefit and attract more tonnes, compared with the OD table based on trade flows alone. The modal split in SCENES is performed using a multinominal nested logit model, with three levels of choice: between land modes and other modes, between different land modes and at the lowest level between heavy goods vehicles (HGV) and light goods vehicles (LGV).

In EUNET2.0, five types of logistic chains have been set up to represent the movements of goods into their individual distribution stages, depending upon the initial origin of the products (inside or outside the UK) and their destination (import or export). The complexities of these logistic chains differ from commodity to commodity, because the handling factor varies considerably between product groups. The distribution chain may include various distribution legs for consolidation at distribution centres or depots. Each type of distribution leg is assigned with a type of entity at its start and end point, the level of costs faced, and the mode/vehicle type mix used on that type of distribution leg. Combinations of distribution legs may generate a variety of distribution channels. Based on the handling factor of the product group more or less legs are used. The value matrix, created previous in the model (see section 2.4.1), is converted into tonnes. This is used to estimate empty returning lorries and is split by mode and lorry size. The matrix is converted into vehicles, who are assigned to the road and rail freight networks. When the network assignment is finished, the transport costs are fed back into the model. This ensures that the mode choice and the distribution pattern of goods movements are influenced by the actual door-to-door costs on the networks (Jin et al., 2005).

Ben-Akiva and de Jong (2008) propose a truly disaggregated logistic framework. It takes as input the Production-Consumption (PC) flows and produces OD flows for network assignment. The logistics model consists of three steps. First, a disaggregation step takes place to allocate the flows to individual firms at the production and consumption end. Next, the logistic decisions by the firms are modelled. Finally, the information per shipment is aggregated to OD flows for network assignment. The different logistic decisions included in the second step are the frequency/shipment size, the choice of loading unit and which mode to use for each leg of the transport chain. Also the use of distribution centres, freight terminals, ports and airports, and the related consolidation and distribution of shipments is included in the logistic decisions module. This leads to the number of legs in each transport chain. The basic mechanism in the model for decision-making on all these choices is the minimization of total logistics costs. A random cost discrete choice model can be obtained by using total annual logistics costs as the observed component and by adding random cost components that follow specific statistical distributions. These random components account for omitted variables, measurement errors and such. The total annual logistics costs are composed of order costs, transport, consolidation and distribution costs, cost of deterioration and damage during transit, capital costs of goods during transit, inventory costs, capital costs of inventory and stockout costs. In the ADA-model changes in logistics processes and in logistic costs have a direct impact on how PC flows are allocated to logistic chains, but only indirectly (through the feedback effect) impact the economic (trade) patterns (Ben-Akiva and de Jong, 2008).

In the FAME framework has five modules, two modules exist to determine logistic decisions. Individual shipment forecasting is carried out in the third module. Having the annual commodity flow between the firm-type pairs, every single shipment is generated. This leads to a shipping frequency and shipment size. Logistic decisions are simulated in the fourth module. Many detailed information about individual shipments are obtained from the past three modules including commodity type, weight and value of the shipment, origin and destination, and supply chain characteristics. This information should be utilized in this module to simulate the way that shipments will be delivered to final destinations. The core of this module is to develop a behavioral mode choice model. A prototype mode choice model has been developed based on an online establishment survey in the U.S.. Other logistic decisions could be modeled endogenously with the shipping mode or added to this module as a separate component (Samimi et al., 2009).

In the model of Calgary (Hunt and Stefan, 2007) the vehicle type and purpose for each tour are identified by micro-simulation, using Monte Carlo processes. For vehicle choice, three categories are considered: light, medium and heavy vehicles. This is followed by the specific tour start time, at which point the characteristics for the stops on the tour are identified, iterating stop-by-stop until the tour is finished. Tours are build incrementally by having a 'return-to-establishment' alternative. If the next stop purpose is not 'return-to-establishment', then the tour extends by one more stop. The choices are made based on the characteristics of the companies involved in the tour, each with different options, objectives, influences and choice structures.

Fischer et al. (2005) propose a framework in which a logistic chain model is combined with a tour-based model. The logistics layer describes the logistic decisions that are made to link producers and consumers, including the distribution channels that will be used, types of activities that will be conducted at intermediate handling points, locations of intermediate handling relative to producers and suppliers, and size and frequency of shipments. The decisions of logistic planners include the transportation mode between each point in the logistics chain and type of equipment used. The logistics chains are relatively simple with few choices of distribution channel options, and the goods remain homogeneous as they move through the logistics chain. The logistic chain model is only appropriate for certain types of commodities or industries. If shipments consist primarily of mixed goods and the movement of particular commodities becomes complex and intermingled with the logistics chains of other commodities, tour-based models will be used.

The commercial movements module in the model of Oregon (Hunt et al., 2001), determines the truck movements arising during a particular workday for each year. A fully disaggregate list of truck movements is synthesized. For a given commodity flow and aggregation of zone pairs, a shipment size of that commodity is randomly selected from the Commodity Flow Survey dataset and the flow is reduced by this amount. The vehicle type, starting time, and transshipment information for the shipment is synthesized taking into account similar shipments and vehicle movements being made nearby and this information is added to the list being generated by the model (Hunt, 2003).

In the GoodTrip model (Boerkamps et al., 1999) the goods flows between the activities are calculated by using distribution channel choice probabilities. Connecting goods flows with their logistic demands to the available transport modes and services, results in goods movement between locations per transport mode. The supply chains end at the consumer and not at the shops. This enables comparison of the effects of developments such as teleshopping, which is not possible with most existing freight transportation models (Boerkamps et al., 2000). The characteristics of goods movement in a linkage largely depend on the actor at the beginning and the end of a linkage: the shipper and the receiver. The receivers determine the delivery frequency, based on the demand pattern and the characteristics of the goods. Shippers are often responsible for transportation and therefore have to decide on mode choice, vehicle type, and vehicle size. They also decide on grouping of goods types with different logistic characteristics (Boerkamps et al., 2000).

In INTERLOG logistic decisions are subject of contract negotiations. First, shippers and recipients mutually agree on the regular delivery lot-size. If there is complete collaboration between them, the optimal lot-size may be determined using a total logistics cost function. While ordering and transhipment costs may be determined by analyzing the business processes, the transport rates may only be acquired in calls for bids. Therefore, shippers must make their decisions regarding lot-sizes using incomplete information. Next, shippers award bundles of similar shipment cases in the form of middle-term contracts to forwarding companies that carry out the transportation tasks on a daily basis in the constrained environment of the contract. Lot-size, frequency of delivery, time windows and weight of the shipment is already stipulated in the contract. The rate at which forwarders are willing to accept a contract, is based on either marginal cost of the extra shipment or on the basis of full cost. Mostly a combination of the two is made (Liedtke, 2009).

Wisetjindawat et al. (2007) convert the commodity flows to truck flows in three steps. The process starts with deciding the delivery lot-size and frequency for each commodity flow. This mainly depends on inventory and transportation costs. Inventory cost is proportional to the lot-size. On the contrary, transportation cost is proportional to delivery frequency and distance. Then, carrier and vehicle choice (small or large truck) are assigned to each lot-size. The characteristics of the shippers, customers, transported commodities, and firm spatial distribution strongly influence the decision on carrier and vehicle choices. Shippers are assumed to select the choice that minimizes the total delivery cost to customers, using a nested logit model. The type of carriers significantly impacts vehicle choice. Private and rental trucks will be used to serve only the customers of the shipper. On the other hand, shared truck or delivery service truck, will be used to serve customers of the shippers that are shared together. In the last step, the customers of each shipper, who have the same delivery frequency, carrier and vehicle type, will be grouped together to be delivered at the same time by a vehicle routing model. The vehicle routing model calculates the route travel time, which will be used as an input for the carrier and vehicle choice model to improve the results (Wisetjindawat et al., 2007).

The TAPAS model (Holmgren et al., 2007) uses an architecture with two levels, a physical simulator and a decision making simulator (see figure 2.2 on page 44). The entities in the physical simulator (like vehicles and products) are passive, while entities in the decision making simulator act independently. These two layers are connected by letting the decisions taken in the decision making simulator initiate the actions in the physical simulator. The shipment size is determined by the customer, based on the principles of the Economic Order Quantity (EOQ) model (Bergkvist et al., 2005). The calculation of the quantity to be shipped is based on fixed order cost and inventory holding cost. The presence of different vehicles, with different transport costs makes it difficult to estimate this quantity. Therefore, the order request contains a number of different quantities, based on the different vehicles. The same applies for lead time that may differ for the different transport modes and hence has an impact on the order point. Consequently, the customer uses estimated lead times and safety stock levels for the different products. Inventory levels are simulated in the physical simulator in a node, where a dynamic inventory level is kept. A node can be a connection point in the transport network and hence represent terminals and warehouses. Transport modes are connected to the links in the physical simulator. A vehicle may only travel links with the same transport mode. Also transport carriers are simulated as they perform transport along a link, with a certain volume capacity for each commodity type, maximum speed, transport cost, etc. (Bergkvist et al., 2005). The mode and vehicle choice depends on the links chosen to conduct the transport. For each precompiled transport route between origin and destination an offer for each link is made, after which the best offer is chosen. Transport modes are connected to the links, so depending on the route that is chosen the transport mode and vehicle choice are determined. Load consolidation is not currently included (Holmgren et al., 2007).

Also, the framework of Roorda et al. (2010) uses contracts to set the relations between actors and the logistic decisions. In the commodity contract, the order quantity is determined by the customer through an optimization of inventory levels. It is a function of the ordering cost, the carrying cost and demand. The order frequency is determined by the total demand and the shipment size. Either the vendor or the customer is responsible to make the logistic decisions for a possible list of shipments. When the business establishment has an internal logistics facility that is capable of delivering all shipments in a cost-effective way, no external logistics firm is required. Otherwise external logistics contracts are required. The establishment of logistics contracts starts with each logistics firm advertising its "supply" on the market. Logistics offers may be made for single shipments or for multiple shipments. Next, a business establishment forms a choice set of suitable logistics service providers and evaluates and selects a logistics service provider. A random utility maximization model is envisioned for this choice, similar to the one proposed in the ADA-model (Ben-Akiva and de Jong, 2008). Operational decisions about how to execute the movement of shipments are left to the logistics service provider. The process begins with transportation mode selection, based on the resources that the contracted logistics service facility has available. Consolidation decisions are the next step for the truck-only mode and are inherent in the process of intermodal transfer. In the non-consolidation branch, vehicle type choice depends on the attributes of the shipment, roadway regulations, etc. Consolidated shipments involve many of the same steps as are involved in the non-consolidation branch. However, these steps are repeated, for pickup, line-haul leg, and/or delivery legs of the journey. Furthermore, the shipment may require storage in between the process and the shipment is more likely to be coordinated as part of a tour at pickup and delivery.

2.4.3 Model scope

In this section the scope of the models is discussed. Two main groups may be defined: nationwide models and regional models. The models are grouped in the different categories, as may be found in table 2.4. A better insight is obtained in what the possibilities are for each model. Furthermore, if known, the zoning as well as the commodity categories are pointed out for each model. In Fischer et al. (2005) no details about the scope of the model is represented, therefore it is left out off the analysis.

Table 2.4: Model scope

Nationwide models	**Regional models**
SMILE	EUNET2.0
SCENES	Oregon
ADA	Calgary
INTERLOG	GoodTrip
TAPAS	Wisetjindawat
Roorda	
FAME	

2.4.3.1 Nationwide models

In SMILE (Tavasszy et al., 1998) the database contains data on structural elements, concerning topological, physical and logistical attributes. These attributes are measured for 542 types of products, sorted into 50 logistic families and for around 77 regions in the world, of which 40 in the Netherlands. To support policy analysis, the user may intervene at certain points in the model that reflect real world elements like infrastructure, regulations or services. This is done in the scenario and import/export modules that allow changes to be made in several variables related to prices, capacities, service performance levels or the users' preferences in the system.

The policy variables that may be adapted are: supply aggregates, structural changes in the economy, spatial aggregates, elasticities, cost factors, product characteristics and traffic and network characteristics. These variables may be changed per year and per commodity group (Tavasszy et al., 1998). Scenarios for simulations may be made by the user up to 25 years ahead. The model shows the impact of policy measures on freight flows and the environment. Reference scenarios were built to assist the user. These reference scenarios are derived from general economic scenario's as have been developed by the Dutch Central Planning Agency (CPB). They represent the economic environment in which the freight demand model is further specified. The user is assumed to define certain policy options or exogenous interventions in the system that creates specific changes in the cost structures and choice options available. These exogenous changes are checked upon internal consistency and then used to create a scenario (Tavasszy et al., 1998).

Within the SCENES (SCENES Consortium, 2002) project, forecasts for the development of GDP, population, employment and car ownership have been generated for 2020 and 2040 for Europe. The forecasts for 2020 were derived at the regional level (NUTS 2). A 'Specific scenario development' module exists, in which the behavioural trends of passengers and freight transport are simulated. There are two main groups of factors that may influence freight transport. A first group are the important exogenous factors, such as economy, competitive pressure, policy, culture, society and transport supply parameters. A second group of the endogenous trends refer to the behaviour of companies. The most important endogenous behavioural patterns are increase in a company's size, diversification into new areas of business, changes in the background, training and occupation of employees and production technology, distribution and procurement policy. The zoning system is based on a NUTS 2 level. There are 244 internal zones (205 in the EU area and 39 in the Central and Eastern European Country (CEEC) area) and 21 external zones. Furthermore, the model works with thirteen different groups of commodities called logistics families (SCENES Consortium, 2000).

The ADA-model (Ben-Akiva and de Jong, 2008) was specified in a project for Norway and Sweden. In 2006/2007 a version 1 model was constructed. Here the results for the version 1 model for Norway are presented, based on the assignment of more than 100.000 firms (senders) to almost 400.000 firms (receivers). There are more receivers than senders because senders may only be firms producing goods or wholesalers, whereas receivers include firms in all sectors. The number of firm-to-firm flows generated for Norway is five million. This number refers to annual flows, each of which may consist of several shipments. For each of those flows a sending firm, a receiving firm, a commodity type and an annual total flow is specified. The version 1 model for Norway distinguishes 32 commodity types, about 400 zones (municipalities in Norway, more aggregate zones abroad), transport chains of one, two, three and four legs, ten road vehicle types, 28 vessel types (including ferry), eight train types and two types of aircraft. The distinction between containerized/non-containerized is incorporated by defining container and non-container vehicles and vessel types. The runtime of this version 1 logistics model for Norway was up to two hours on a standard PC (Ben-Akiva and de Jong, 2008).

INTERLOG (Liedtke, 2009), developed for Germany, distinguishes explicitly between different actors in transport and logistics, their specific roles and decision-making rules. Furthermore, a continuous interaction between shippers and carriers is mapped at a micro-economic level. Reactions to policy measures may be manifold. All decisions relating to supplier choice, logistics network design, lot-size determination and mode choice can be reviewed by logistics actors to evade the effects of a policy measure. A multi-agent model offers the possibility of incorporating normative optimization engines into the descriptive actors' behaviour models to map manifold reactions on different time-horizons. From a scaling experiment it is concluded that around 10000 shippers/recipients should be simulated to achieve good results. There are approximately 240000 production and trade firms in Germany.

Inputs to the simulator of TAPAS are transport tasks, available transport resources and their characteristics, the available production resources and their characteristics, available infrastructure and the location of producers, customers, storages, etc. Given this task, the user of the simulator will be able to experiment with different control policies, by varying a number of parameters corresponding to different taxes, fees, regulations etc (Bergkvist et al., 2005).

The framework of Roorda et al. (2010) works with multiple representations of time. Fundamental business decisions are likely to be held not more than once per year. Supply chain management decisions, those decisions that act to change the resources available to a business establishment are mostly evaluated at monthly intervals. Market interaction decisions involving the formation contracts may vary widely, since a contract can be made for a single shipment or for a long-term alliance. Market interaction decisions are made on the basis of demand forecasts, which may be projected up to five years in the future, but updated annually or quite possibly quarterly for many business establishments. Logistic decisions are made daily. Of key interest is the time period over which price functions are updated. The framework may represent sensitivity to a variety of trends and policy scenarios. One of them is changes in costs. Costs are of key policy significance given fuel price volatility, proposals for carbon taxes, road pricing initiatives, and costs associated with delays due to increasing congestion. Because activities of each firm are traced through the simulation system, it would be possible to assess differential impacts of these trends/policies on business establishments from different industry sectors, sizes and locations. Also trends toward the outsourcing of logistics services to third party logistics firms may be represented. Furthermore, the impact of new supply channels can be modelled provided that logistics costs may be represented (Roorda et al., 2010).

The FAME model (Samimi et al., 2012) is developed for the entire U.S. A total of 45.206 firm-types, among more than 14.8 billion tons of domestic shipments are simulated. Four different categories of data are composed for the development of FAME: information on business establishments, aggregate freight movement, detailed information on a sample of individual shipments and supply chains and specifications of the transportation networks.

2.4.3.2 Regional models

The EUNET2.0 model (Jin et al., 2005) has made a projection of goods transport demand up to the year 2016 for the Trans-Pennine Corridor in the north of England. A number of assumptions are made regarding future developments of road and rail freight costs, warehousing location and logistic operations. Freight demand changes are predicted for ton-km and tonnes for 2016 based on 2001, under the assumption that logistics patterns and underlying handling factors for 2001 are unchanged up to 2016 and that the road speeds and vehicle operating costs are to remain constant. The model is capable of representing e.g. the continuing evolution of logistics operations such as those currently taking place with third party pallet logistic networks and the potentially further reduction of labour costs in the road haulage industry.

In Hunt (2003) the model of Oregon is presented, it covers the entire State of Oregon and the area about 50 miles just beyond the state boundaries to the north, east and south. This area is covered by 14.5 million grid cells, small enough that just one type of developed space (one category of building floor space) may be attributed to a given cell. The model steps through time in a series of one-year steps. The representation for the next year is influenced in part by the conditions determined for the previous year. This allows an explicit representation of various lagged effects and system inertia, like the migration of households, changes in transport supply and economic changes (Hunt, 2003). The ‘Regional economics and demographics’ module provides the model with regional control totals for production by economic sector, imports and exports by economic sector, employment by labour category, population in-migration, and payroll by sector for each year.

The City of Calgary in Canada has a regional travel model that covers the Calgary Region, an area centred on the City of Calgary and extending out approximately 80 km in all directions. It had a population of just over one million people in 2001. The model is based on data obtained in a set of surveys collecting information on the roughly 37.000 tours and 185.000 trips (within these tours) made in the Calgary Region by commercial vehicles on a typical weekday in 2001 (Hunt and Stefan, 2007). Its application in forecasting requires inputs regarding population, employment and transport supply conditions, along with specific information regarding truck route policy and vehicle-specific values of time and distance-based operating costs. For the analysis of policies impacting commercial movements, this representation will respond to changes regarding: road network capacities and connectivity, truck route policy, road tolls, fuel taxes, household travel (resulting in changes in roadway congestion) and population and employment level, composition and spatial distribution. The responses to such changes will occur in multiple elements of the micro-simulation. Tour generation, the allocation to start time period, tour purpose and vehicle type choice, next stop purpose and next stop location all respond to changes in travel conditions (Hunt and Stefan, 2007).

Boerkamps et al. (2000) present a first application of the GoodTrip model in the city of Groningen. The GoodTrip model is especially suitable to compare the effects of changes in the logistics of freight movement as for instance the implementation of new logistic concepts using new types of distribution centers or new infrastructure. The structure of GoodTrip makes it possible to investigate the effects of a large variation of developments in changes in consumption patterns, different supply chain organization, other delivery requirements, other distribution patterns and mode choice and environmental improvements.

Wisetjindawat et al. (2007) study the Tokyo Metropolitan Area (TMA). The area is divided into 56 zones according to the A-zone classification of the Tokyo Metropolitan Goods Movement Survey (TMGMS) comprising 52 zones within the study area and four zones nearby the study area for analysis of external trips. Commodities and industry types are categorized into respectively eight and thirteen groups. The impact of policies or economic trends is not discussed.

2.4.4 Transport mode

In table 2.5 an overview is given of the different modes and types of transport incorporated in each model. When a model includes a certain transport mode, this is denoted with an 'X', when there is a further division within a mode this is written in the box. For the ADA-framework (Ben-Akiva and de Jong, 2008) the table is filled in for the application in Norway, but it is possible to include other transport modes as ADA is described as a model framework with no details on transport modes included. Also the model of Fischer (Fischer et al., 2005) does not explicitly mention the modes that are used, as it is a proposed framework. For this reason question marks are inserted.

Transport with a ferry may have a further division between unaccompanied trucks (i.e., only trailers are dropped at ports), and accompanied trucks (i.e., when truck and driver are loaded onto the ferry) (SCENES Consortium, 2000). In SCENES, nine intra-zonal transport modes are defined. These represent trips of different length (five distance bands are distinguished) and by different means of transport (road, rail, IWW).

For modelling purposes some characteristics may be assigned to the different transport types. Examples found in the different models are: maximum speed, fuel type, fuel consumption when empty and when full, emissions per distance unit, loading capacity, transport cost per distance unit and time tables for certain transport modes.

Looking at the different transport modes used in the models, a major distinction that may be made is between the urban or more regional models and the national and international models. Urban or regional models focus more on road and rail transport, whereas the national models are defining more transport modes. Besides rail and road, national models mostly also include inland waterways and sea transport. In some cases even air transport is considered. An exception to this is the INTERLOG model which only considers road transport although it is a national wide freight transportation model.

2.4.5 Network assignment

The final step in the modelling process is the assignment of vehicle flows to the network. Three main groups of models may be recognised. The first group consists of models that use the shortest path method. The second group constructs tours after which they are assigned to the network. The last group of models takes congestion into account. At the end of this section some models are discussed that cannot be sorted into these three groups, also options to represent empty vehicle movements are presented. In the ADA-model, the model of Fischer and the FAME framework, the choice for network assignment is not specified in the model framework. For this reason these three models are not discussed in this section.

Table 2.5: Transport mode

Model	**Road**	**Rail**	**Sea**	**Inland waterways**	**Air**	**Pipelines**
SMILE	X	X	X	X	X	X
SCENES	HGV, LGV	bulk, container, shuttle	bulk, container, ferry	bulk, container, ferry	X	product
EUNET2.0	artics, rigid: > 25t, 7.5-25t, 3.5-7.5t, vans	X				
ADA	X	X	X	X	X	X
FAME	X	X	X	?	X	
Calgary	light, medium, heavy					
Fischer	X	X	?	?	X	?
Oregon	light single-unit, heavy single-unit, artics					
GoodTrip	X					X
INTERLOG	X					
Wisetjindawat	small truck large truck					
TAPAS	X	X	X			
Roorda	X	X	X			

A widely used method is the shortest (cheapest) path method. This method has been integrated in the model of Oregon, GoodTrip and TAPAS.

Table 2.6: Network assignment

Short path method	**Tour construction**	**Congestion**
Oregon	INTERLOG	EUNET2.0
GoodTrip	Calgary	Calgary
TAPAS	Roorda	Wisetjindawat

- The model of Oregon first starts with a Frank-Wolfe assignment at the aggregated level, where the vehicle trips are organized into an aggregate zone-to-zone trip table, which is used to find an equilibrium solution (set of link flows and travel times). Based on this equilibrium, the micro-assignment at the level of individual vehicles, is done link-to-link with shortest path assignment using randomly assigned utility function sensitivities to allow dispersion in travel choices. The result is a detailed all-or-nothing assignment of trips, based on equilibrium prevailing network conditions (Hunt, 2003; Hunt et al., 2001).

- In GoodTrip a shortest path algorithm is used whereby the tours per mode are assigned to their infrastructure networks, resulting in network loads, per mode on each network. The modelling process is sequential. There are no feedbacks to previous phases in the process. Congestion is not integrated into the model, although the option is provided by the framework (Boerkamps et al., 1999).

- Within the TAPAS model the shortest (cheapest) path problem, is extended with timetable and time window constraints. The network in the model is composed of directed links and nodes. For each link in the network, the average speed and length are determined as well as the mode allowed on the link. To calculate the cheapest path the transportation cost is composed of three elements: time based cost, distance based cost and link based cost. Also costs at the terminals are taken into account by simulating the loading and unloading times and the cost per time unit (Davidsson et al., 2008).

Another method for vehicle assignment is via tour construction. Forwarders often face a planning problem for en-route pickup and delivery. When a tour construction heuristic is integrated this problem is solved by first planning the pickup and delivery of orders and then assigning these tours to the network. The construction of tours is previous discussed in section 2.4.2.

- In the INTERLOG model a tour construction heuristic is used. It describes the sequential construction of a weekly tour, in which stops to be served in the future may be rearranged once new pickup and delivery stops are introduced. As a result of this tour-construction heuristic, individual truck tours are created and added to the network (Liedtke, 2009).

- In the framework proposed by Roorda et al. (2010) route choice depends on characteristics of the network, such as truck route restrictions and tolls. A firm will select the routes that minimize travel time and cost. Furthermore, the scheduling of vehicles has to be modelled together with route choice. For vehicles that are not shipping consolidated loads, this depends on driver availability, loading and unloading times, and the other stops or shipments that must be made by that vehicle. For vehicles that are shipping consolidated loads, scheduling is done together with tour construction and requires additional scheduling before the shipment is made. The reason for this is that intermediate storage, loading and unloading and shipment handling are involved.

Loading vehicles to the road network often results in congestion. When assigning vehicles to the network, it is essential to take these congestions into account as they may have a large impact on the chosen route. Several of the studied models integrate congestions into the modelling process.

- In the EUNET2.0 the road network has congested travel times that take account of the existence of passenger traffic on its links (Jin et al., 2005).

- In the model of Calgary the trip tables, resulting from the tour construction algorithm, are combined with those of the household travel model. These combined tables are loaded to the networks in the different time periods and network equilibrium is established taking account of the congestion on links. The resulting congested travel times from the network are fed back into the model, and the process is iterated until the travel times used by the model are consistent with those arising from the loading on the networks (Hunt and Stefan, 2007).

- In Wisetjindawat et al. (2007) the truck trip OD matrices by truck type are assigned to the network together with passenger trip OD matrices, resulting in link travel times. These travel times are again integrated into the model when determining delivery lot-size and frequency. An iterative process is started which recalculates the vehicle and carrier choices and vehicle routing, resulting in a reassignment to the network. Vehicle routing simulation provides a sequence to visit customers or a trip chain for each truck. The delivery route is chosen so that it minimizes route travel time, constrained by the maximum working hours of a truck driver and the limited carrying weight of a truck. The planning algorithm considers only the distribution of freight while pickup of load is not yet incorporated.

Finally the models SMILE and SCENES are discussed, as they cannot be categorised in one of the previous groups.

Within SMILE, a multi-modal network for six modes of transport is available. It is a strategic network which means that only the network structure is modelled. Not all alternative links between regions are visible to the user, but only a single link representing all alternatives. The optimal route in SMILE is sought for via the route choice disutility. This has a mode abstract, which is characterised by the values of several variables that affect the desirability of the mode's service to the public, like speed and frequency. More information on abstract modes may be found in Quandt and Baumol (1966). The weighted cost is calculated, where a combination is made of the physical distribution costs and time spent during transportation (Tavasszy et al., 1998).

The SCENES model gives a detailed representation of the transport network for all modes in the EU and the Central and Eastern European Countries (CEEC). These networks are specified to contain all of the most significant links between the NUTS2 zones. The links are given their real attributes by length, type and speed etc. The distribution of travel is based on theoretical expectations and knowledge of the general distribution of trips by distance. The assignment is a stochastic assignment, and there are 24 hour capacity-restraint functions in place on the road networks. Within the model a separated treatment for intra-zonal travel allows the characteristics of the shortest trips to be represented (SCENES Consortium, 2000).

Some of the presented models incorporate empty vehicle movements. In the models of Liedtke (2009) and Davidsson et al. (2008) empty runs are also simulated, but this is not further specified in the model.

In the ADA-model (Ben-Akiva and de Jong, 2008), empty vehicle flows are calculated as follows: the loaded trips are first calculated as described earlier. Next vehicle balances are used to let vehicles return from where they came, with specific shares for empty and loaded return trips. In this formulation, the probability that some of the empty capacity will also be used for transporting goods in the opposite direction is taken into account.

The tonnes of weight by origin and destination are used to estimate empty returning lorries in the reverse direction of the trade in the EUNET2.0 model (Jin et al., 2005). The number of empty return lorries is expressed as a proportion of the total loaded lorries for each origin-destination pair, based on average proportions of empty running for each category of product. An empty lorries origin-destination matrix is then created and empty lorries are assumed to travel in the reverse direction to the trade.

2.4.6 Agent-based models

This section elaborates on the role of agents or actors involved in the six agent-based models studied in this thesis. The main focus is on which actors are defined and what their responsibilities are in the decision making process. Interactions in the decision making process between the different actors are discussed.

The model of Oregon is a mix model for passenger and freight transport. Some modules are agent-based micro-simulations, others are aggregated representations. The actors defined in the model include: people, households, business establishments and developers. Only passenger transport is modelled using agent-based techniques. This is not yet applied to freight transport in the model (Hunt, 2003; Hunt et al., 2001). Therefore the model will not be further discussed in this section.

The groups of actors that are mostly used in agent-based freight models are shippers, receivers/customers, carriers and forwarders/transporters (Liedtke, 2009; Wisetjindawat et al., 2007; Boerkamps et al., 1999) and may be expanded to include politics as in the GoodTrip model. We will take a look at the different roles these actors play in the proposed models. To end this section models which define other options for agents are presented.

2.4.6.1 Receiver

The receiver initiates the demand and chooses a supplier to deliver the required goods. This may be done based on the attractiveness of the supplier and the relationship between firms in the supply chain of the commodity. In the model of Wisetjindawat et al. (2007) the attractiveness of suppliers is derived from the distance between supplier and customer and the amount of commodity produced by each supplier. In the GoodTrip model (Boerkamps et al., 1999) the receiver takes into account the product range and cost of the suppliers. Also the location of the different facilities and the available distribution centres play a role in choosing a shipper. After the shipper is chosen, the receiver decides on the delivery moment, shipment size and whether he conducts the transport himself or not. The delivery frequency depends on the characteristics of the good. Receivers of goods have the strongest influence on goods types and volumes (Boerkamps et al., 2000). In the INTERLOG model, shippers and recipients mutually agree on the regular delivery lot-size, frequency and time window. This is done through long-term cooperations between firms via the contract market (Liedtke, 2009).

2.4.6.2 Shippers

Shippers are firms which supply the goods to the receiver and are often responsible for the transport decisions. In Wisetjindawat et al. (2007) shippers play a major role in the selection of carrier and vehicle choice. This selection is strongly influenced by the characteristics of the shippers, customers, transported commodities and firm spatial distribution. The characteristics of shippers and customers may be represented by type of firms (retailer, wholesaler or manufacturer), number of employees, etc. Attributes of transported commodities include among others: commodity type, delivery lot-size and frequency. Boerkamps et al. (2000) state that shippers are often responsible for transportation and therefore have to decide on mode choice, vehicle type, and vehicle size. Furthermore, they decide on grouping of goods types, product range to offer, location of facilities, availability of distribution channels and whether or not to maintain own transport services. Liedtke (2009) lets the shipper divide the flow of goods into individual shipments. Shippers organize calls for bids for contracts, after which they award bundles of similar shipment cases in the form of middle-term contracts to forwarding companies. Each shipper may have several contract models in which the operational conditions for each transport relation are fixed.

2.4.6.3 Carriers or transporters

The actor responsible for the execution of the transport is defined as the carrier or transporter. Wisetjindawat et al. (2007) define four different types of carrier options: private truck, rental truck, share truck, and delivery service truck. The decision maker of private and rental trucks is still the shipper. On the other hand, share truck or delivery service truck is a kind of consolidation truck, which will be used to deliver customers that are shared together with other shippers. In the GoodTrip model (Boerkamps et al., 2000) the transporter has to know the logistic characteristics of the different types of goods, the travel times and the reliability of the traffic system to make an optimal decision on how to transport the goods. He determines the cost of transport modes and the vehicles he has available.

2.4.6.4 Forwarder

Forwarders differ from the carriers or transporters, as they have the extra responsibility to build and coordinate transport chains. They may be seen as a fourth party logistics service provider. The forwarding companies in the INTERLOG model (Liedtke, 2009) carry out the transportation tasks on a daily basis in the constrained environment of the contract. Contracts are made at two levels, a tactical and an operational level. The tactical decisions relate to temporally stable agreements and business relationships. At the operational level combinatorial problems related to day-to-day-planning, like the routing of trucks, are done. The number of interactions between shippers and forwarders in the calls for bids are limited. A certain shipper may have a preferred list of forwarders to conduct shipments. Other forwarders may become a potential business partner only by chance. The set of preferred forwarders of a shipper is updated in each simulation period (Liedtke, 2009).

Many companies act as both shipper and receiver. A single actor may fulfil all roles in the supply chain, that is, as receiver of goods deliveries, as shipper and/or as transporter of shipments. An actor may be active in different activity types, for example: consumer, supermarket, distribution centre, production factory, etc. (Boerkamps et al., 2000). At the same time, they may own a private fleet with which they deliver their own goods. Firms may use their private fleet to provide transportation services to other companies as well (Roorda et al., 2010).

2.4.6.5 Politics

Freight movements are also indirectly influenced by politics. The GoodTrip model (Boerkamps et al., 1999) defines this as a fourth agent, next to shippers, receivers and transporters. Politics have an influence on the market structure, as they are responsible for an optimal spatial-economic organization. On the transport market they may make a difference by regulating the accessibility and mobility of the transport. Furthermore politicians are responsible for the optimal availability and usage of infrastructure as well as the environmental burden traffic is causing.

2.4.6.6 Other options for agents

The framework of Roorda (Roorda et al., 2010) and the TAPAS model (Davidsson et al., 2008) differentiate themselves with regard to the choice of agents they have made. The models are working at an even more detailed level and are able to incorporate more of the interactions between, and the decisions of, the different agents. The remaining of this section elaborates on the agents defined in the TAPAS model and end with those of the framework of Roorda.

The TAPAS model (Davidsson et al., 2008) uses six different agents (see figure 2.2) which will be discussed next:

- Customer: is responsible for keeping inventories at reasonable levels by sending order requests to the transport chain coordinator (TCC) and choosing the best proposal from a cost perspective. An order request contains a delivery node, a product type, a single order quantity and a delivery time window.

- Transport Chain Coordinator (TCC): has a central role and is responsible for receiving order requests, sending product and transport requests and receiving the corresponding proposals.

- Product Buyer (PB): is the link between the TCC and the product planner (PP). When a product request is received he forwards it to all PP's and when the production proposals are returned, he sends them back to the TCC.

- Production Planner (PP): is responsible for creating a production proposal with a cost and the earliest time the products may be ready for pickup.

- Transport Buyer (TB): compiles transport solutions from producers to consumers. He sends the transport request to all transport planner (TP) agents. After the receipt of all requested link transport proposals, the TB combines them into a single transport proposal for each precompiled path between producer and customer. The best path is sent to the TCC

- Transport Planner (TP): controls a vehicle fleet which operates on a set of network nodes. He generates proposals for the requested product and quantity with departure and arrival times within the requested time window.

Many possible options are available for the location of the different decision making agents. The customer agent might be a retailer or a producer. The TCC might be a planner within a larger company or a third or fourth party logistics operator. The PB is often connected to the organization which hosts the TCC, but can be independent when the TCC is a third party logistics operator. The PP belongs to the producing company. The TB might belong to the same organization as the customer or as the TCC. The TP typically belongs to the organization owning and controlling the transport carriers (Bergkvist et al., 2005).

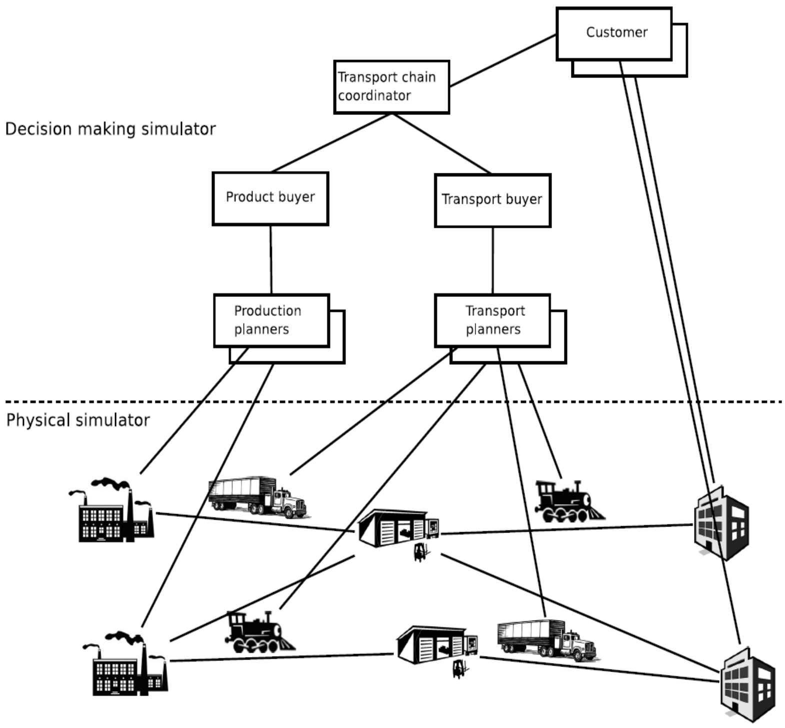

Figure 2.2: TAPAS model (Davidsson et al., 2008)

Roorda et al. (2010) establish a new set of agents in their framework. The main agents are business establishments, firms, facilities (commodity, business service and logistics service) and end consumers.

- A business establishment is an organization at a specific location which produces, processes, or stores commodities, or provides business or logistics services. A business establishment may include commodity production facilities, business services facilities and/or a logistics facility. This agent is responsible for the market interaction decisions and operational decisions. Market interaction decisions are defined as short to medium range decisions to offer or order commodities, services, or logistics on/from the market. Interactions with other establishments are regulated in contracts. Contracts specify the quantity, frequency and type of commodity, business service or logistics service to be provided and the price to be paid in return. Operational decisions are short term decisions on how efficiently or effectively to produce a product, or provide a service.

- A firm is an organization which owns or operates one or more business establishments. Within a logistics firm, business establishments at different locations may be integrated into a logistics network. Firms make fundamental business decisions and supply chain management decisions. Fundamental business decisions are long range decisions including the decision to start the firm or a business establishment. Supply chain management decisions are medium to long range decisions made in order to improve efficiency and effectiveness of the supply chain.

- A commodity production facility is one of the internal resources of a business establishment. The function of a commodity production facility is to produce or process commodity inputs. A commodity production facility has a production capacity and productivity. The only decisions for which a commodity production facility is responsible are operational decisions. Any decisions about vendors, customers and shipments would be made by the business establishment.

- Business service facilities provide services instead of commodities.

- A logistics service facility provides logistics services, including transportation and inventory. These services may be utilized internally as a private fleet, or sold to other business establishments as a third party logistics provider. Logistics service facilities may own resources, including vehicles of different types, transhipment centres, warehouses, intermodal terminals, and employees.

- End consumers initiate demand for commodities. Examples of consumers are households or the government. They are analogous to the final demand represented in an input/output model.

2.5 Conclusions

Barthélemy et al. (2010) notice that current freight transportation models at a disaggregated level are lagging behind, not only on an operational level but also on the conceptual level. There is a clear gap with passenger transport and extra research efforts are required. In chapter 3 a conceptual framework for Flanders will be constructed. For this freight flows need to be predicted within a multimodal network and for a small region. Furthermore, the current trends in economics and supply chain management as seen in chapter 1 have to be integrated. From the analysis of this chapter, the preference goes out to create an agent-based micro-simulated framework. Agent-based freight transportation models are suitable to incorporate new logistic trends and response to new government policies to predict future freight flows. They are able to better represent the link with the economy, interactions between different actors and the logistic elements inherent of freight movement. As micro-simulation allows to study the interactions between actors with traffic it is preferred for our model. Because the studied area, Flanders, is small micro-simulation may be applied. For large scale modelling this method becomes too expensive. Macro-simulation on the other hand works well for large networks, but does not include interactions between the actors (Barthélemy et al., 2010). Combining the representation of the different actors with the modelling of a multimodal network is seldom done in literature. From the literature review only two models take this into account (Roorda et al. (2010), Davidsson et al. (2008)), therefore this thesis tries to extend research efforts on a conceptual level with the new framework of chapter 3.

Within agent-based models a disaggregated approach is applied. Trips and decisions are considered on a microscopic scale as separate firm-to-firm flows and no longer as aggregate flows between different zones. This allows a detailed micro-economic background of the different commodity groups. Behaviour experiments performed by Liedtke (2009) showed that multi-actor micro-simulation may reproduce the effects of logistical reorganizations, such as changes in shipment sizes, transport service providers, truck types, tour construction and route choice. Furthermore, these models are ideally suited to represent the relationship with economy. Several reasons exist for implementing agent-based modelling. They have several advantages compared to the traditional four-step method and may address the different aspects of freight transport.

- *Characteristics of the different agents.* A diverse set of actors are involved in the production and distribution of goods, none of which may have full control or even knowledge of all decisions made throughout the supply chain (Roorda et al., 2010). Freight transportation is characterized by quite heterogeneous actors and objects: size of companies, flow of goods and shipments vary over several orders of magnitude. This may be addressed by using an agent-based approach. The approach distinguishes explicitly between different actors in transport and logistics, their specific roles and decision-making rules (Liedtke, 2009). The behaviour of each actor individually is simulated and this might lead to greater prediction realism. It gives the opportunity to include individual firm characteristics and detailed representation of commodity groups. When looking at single movements of goods, individual shipments may be modelled based on the characteristics of individual firms including more information of a shipment that would go lost in aggregated data. Therefore they are better able to model their individual behaviour in operational decisions. Decisions about purchasing, sales and inventory may be represented in this way. Agent-based modelling may explain the effects of individual behaviour changes on the whole transport system, therefore the quality of forecasts for public and private planners may be improved (Liedtke and Schepperle, 2004).

- *Interactions between logistic players.* The interactions between firms are diverse. Successful supply chains increasingly involve long-term alliances between suppliers, manufacturers, retailers, carriers and third party logistics firms. The prices and the level of service vary depending on the type of relationship that is maintained between these agents (Roorda et al., 2010). The interactions between logistics players impact freight demand characteristics in terms of the choice of modes, the shipment size, the ports to use, the time of day, frequency of shipments, etc., which are critical elements in the modelling of freight transportation demand (Beagan et al., 2007). With agent-based modelling it is possible to map a continuous interaction between shippers and carriers at a micro-economic level (Liedtke, 2009). By mapping the interactions of the different agents involved in the model, the opportunity exist to include pricing mechanisms and to take into account long- or short-term contracts between agents. This allows market interactions and pricing negotiations through the formation of contracts (Roorda et al., 2010).

- *Trends in supply chain management and logistics.* Business models are changing over time. The disaggregated approach of agent-based models, together with the representation of the different actors, enables better modelling possibilities for logistic decisions. Due to the dynamic nature of the freight logistics system, trends in industry supply chains need to be considered, especially in freight forecasting. For example, an increasing trend towards just-in-time logistics is having an impact on the modes used and size and frequency of shipments (Beagan et al., 2007). By explicitly simulating the different agents involved in the decision making process, the logistic decisions and chains may be represented.

Despite the many advantages in the use of agent-based models on a microscopic level, several drawbacks remain. A first difficulty is the data availability, a detailed model requires a lot of data. The gathering of disaggregate data leads to high costs and demands valuable time of firms. Most of the data that is available is at an aggregated level, which is not ideally suited for simulating separated agents. Also model accuracy has to be kept in mind. The literature review revealed that there are different ways of representing actors in the different models. Difficulties arise when trying to find a good representation of the different actors and model their complex interactions. The accuracy of the model depends on how good each agent may be defined and their interactions modelled. It is hard to incorporate all aspects of decision taking of a firm within a uniform model, due to individual firm characteristics and non-quantifiable elements that influences decisions. The rationality of agents has to be studied as choices made by firms might by subjective and irrational. A third drawback is the computability of the model. By simulating interactions between different agents the model expands if the number of agents increases. The computation time of a fully agent-based micro-simulated model has to be kept in mind.

In this thesis a new conceptual freight transportation framework for Flanders is proposed. Based on the review of the different existing models, chapter 3 presents the outline of the new framework. An analysis is made of the key components which need to be included in a freight transportation model. This serves as a base of the new proposed framework. Chapter 4 presents a worked example of the framework. A small scale example is used as the main purpose is to expose potential difficulties and points for attention when further implementing the framework. In a second part of this thesis the operational decisions of a carrier are investigated in chapters 5 to 7.

Chapter 3

Framework for a comprehensive freight transportation model

3.1 Introduction

To have a better insight in freight transport in Belgium and more specifically Flanders, the need exists for a model which may give a detailed representation of the freight flows. To achieve this, a first step is made in this chapter by building a conceptual framework for a new comprehensive activity-based freight transportation model. Within this framework our interest lays in the logistic module and the interactions between the different actors involved. This module will be our main focus.

As the conceptual framework is meant to be used for Flanders, this chapter starts by giving an overview of the existing freight transportation models in Belgium in section 3.2. Because these models are not part of the state-of-the-art models in literature it is opted to discuss them separately in this chapter instead of incorporating them in the literature review of chapter 2. Missing elements in these models are highlighted in section 3.3. Based on these missing elements and on the shortcomings of the different models in the previous chapter the key characteristics for a new framework are determined in section 3.4. This leads to the detailed description of the conceptual freight transportation framework in section 3.5. First, the different actors incorporated in our framework are highlighted, after which the Logistic module is further elaborated.

The section ends with some thoughts on the required data. At the end of the chapter, conclusions are formulated together with ideas for future research.

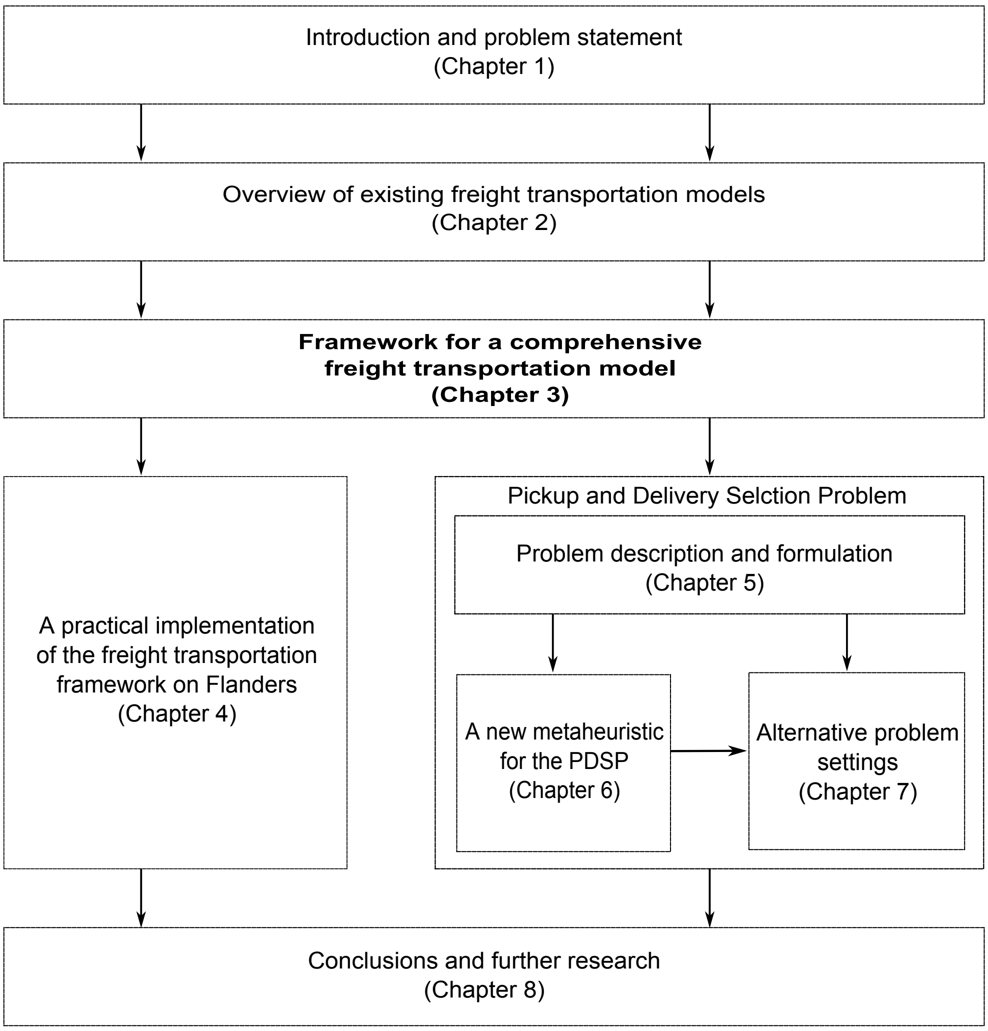

Figure 3.1: Outline of the thesis - Chapter 3

3.2 Existing freight transportation models in Belgium

In this section five different freight transportation models of Belgium are presented. To our knowledge, these are the only models documented in Belgium. The geographical area has been extended to Belgium, as only a single model is developed for Flanders (TRITEL). First the four-step models are presented in chronological order, to end with MOBILEC, a land-use interaction model with a main focus on economic\transport interactions. The models presented, include little or no logistic decision making and are all situated at the aggregated level. However, recently a first step towards a micro-simulation model is made with the DIDAM framework of Barthélemy et al. (2010).

The Walloon Freight Transportation Model (WFTM) is developed in the nineties by ADE, for the French speaking part of Belgium, Wallonia. It was used to develop a freight transportation plan for 2010. Expected changes in the infrastructure and OD matrixes were introduced at a very detailed level, from which a set of scenarios was built. Each scenario introduces new policies, new infrastructures or a combination of both. A separate scenario is created for each transportation mode: road, rail and inland waterways. An additional scenario takes into account the external costs of transport (Geerts and Jourquin, 2001). The model makes use of the NODUS software that automatically generates the virtual network. In this network each virtual link corresponds to a specific operation (moving, loading/unloading, transshipping and transiting) and all transportation modes and means are interlinked. This makes it easy to attach specific cost functions to each virtual link (Jourquin and Beuthe, 1996).

The next model is a four-step model for Flanders made by TRITEL (Verkeerscentrum Vlaanderen, 2006). The proposed model provides the possibility to integrate logistic centers into the road matrix in the form of Transport Logistic Nodes (TLN). Road relations are split into direct and indirect flows, where the indirect flows use the TLNs. This may allow a more precise representation of the flows in reality and better results in the assignment step (Verkeerscentrum Vlaanderen, 2006). Due to the representation of TLNs, the model makes a step towards integrating logistic aspects.

PLANET (Desmet et al., 2008) is developed by the Belgian Federal Planning Bureau. It models both passenger and freight transport in Belgium. PLANET is able to produce medium- and long-term projections of transport demand in Belgium, as also simulations of the effects and cost-benefit analyses of transport policy measures. The core of PLANET is a traditional commodity-based, four-step transportation model.

The four steps are transport generation, trip distribution, modal and time choice and vehicle stock. Furthermore three extra modules exist next to the four-step transport module. A policy module generates alternative scenarios to compare with the business-as-usual scenario and a macro module provides macro-economic projections for each zone. The last module is the welfare module which computes effects of transport policy measures on welfare.

A model that does not follow the traditional four-step structure is the MOBILEC (MOBILity\ECo nomy) model described in van de Vooren (2004). It was first used for the Netherlands after which it was adapted for Belgium and later on expanded for the entire Benelux. The model belongs to the category of land-use transportation interaction models. The model differs from other transportation models, where mostly either the economy influences transport or transport influences the economy. MOBILEC is a dynamic, interregional model that describes the interaction between transport and economy together with infrastructure and other regional features. Regional income determines the investments in infrastructure and wages have an influence on employment rates and purchases. This has an impact on traffic, which then again influences regional product and employment.

These four models use the 10 NST/R (standard goods classification for transport statistics - revised) commodity categories to divide their freight flows. The zoning for Belgium is done at a NUTS3 level (Eurostat, 2012), which corresponds to the 43 districts. Furthermore, they all focus on the three main transport modes: road, rail and inland waterways. The TRITEL model contains an option for combined transport and in PLANET the evolution of maritime, air and pipeline transport is imposed exogenously.

Finally, in the DIDAM framework of Barthélemy et al. (2010) the goal is to evolve towards a micro-simulated model that combines passenger and freight transport. The model allows the interaction of enterprises and transporters to be simulated. OD tables are generated using an agent-based simulation model. Between the agents the formation of transport contracts is simulated leading to a detailed OD table including empty trips. This model is still work in progress and only includes road transport.

3.3 Missing elements in existing regional models

When comparing the models for Belgium with the international trends in freight transportation modelling, it becomes clear that they are lagging behind.

A disadvantage of the freight transportation models discussed in the previous section is that they are lacking elements of logistic organization. A better link with the freight distribution industry is required to overcome this weakness. This would include the modeling of shipment size, use of distribution channels, consolidation options, tour planning, use of intermodal transport, etc. Furthermore, the choice of receiver or sender could also be modeled and represented in a contract market. This leads to the opportunity of simulating changes in the logistic chain and allows representing the influence of long-term contracts and negotiation power. In the model of Flanders (Verkeerscentrum Vlaanderen, 2006) a first attempt is made by including the TLN for truck transport. Also the NODUS software allows representations of logistics by including transshipping and transiting, as well as intermodal combinations.

An important element in freight transportation is the interaction between the different actors in the decision making process. It involves a complex relation between shipper, receiver and carrier of the goods. This interaction between actors is not presented in existing freight models for Flanders, as they all model freight flows at an aggregated level. This does not allow a detailed representation of the different actors involved. Due to the modeling at an aggregated level, no explicit link exists between the activity that induces transport and the transport flows themselves. The DIDAM framework of Barthélemy et al. (2010) is the first model in Belgium trying to incorporate enterprices and transporters. Still, this framework needs to be further studied and implemented.

Although the international models of chapter 2 are already showing more detail and a better representation of the way freight flows comes about, some shortcomings may still be noticed. Only a few of the presented models are capable of simulating interactions between actors in a multimodal framework. Most of the international models are nationwide models and are mainly situated in the United States of America. They are mostly only incorporating road traffic, such as the models of Oregon (Hunt et al., 2001), GoodTrip (Boerkamps et al., 1999), INTERLOG (Liedtke, 2009), Wisetjindawat et al. (2007). As Flanders is a small region with an import harbour and a frequent use of the rail transport, it is preferred to simulate a multimodal framework. Some of the international models include a multimodal network. This is the case for the ADA-model of Ben-Akiva and de Jong (2008). However, this model does not represent the different actors of freight transport. The model of Roorda et al. (2010) allows the representation of different actors and the simulation of a multimodal network. This model is still in a conceptual phase and has not been implemented yet. Furthermore, they represent the different actors in a very specific way. In the framework presented in section 3.5 a different representation is proposed. Besides, more options to integrate consolidation will be studied (section 3.5.3) and the decisions of carriers are modelled in detail (chapters 5 to 7). These extensions are aimed at the development of an improved framework for Flanders. They allow an extension of the international research with some new insides and a novel way of representing carrier decisions.

3.4 Key elements for an innovative freight transportation model

In light of the missing elements in the models for Belgium and the study of the international models in chapter 2, key elements for a new framework may be defined. The aim is to represent the different actors and their interactions in a multimodal framework. The decision making process of actors in a multimodal environment is seldom studied in literature. The objective is to develop an activity-based microsimulated model for Flanders. Liedtke and Schepperle (2004) concluded from their study that having a model for the transport of goods at a microscopic level, would be a significant improvement for transport forecasts and the assessment of policy measures at any point in process, due to its ability to map individual reactions. Because Flanders is a small region it is ideally suited to be modelled at a microscopic level.

First of all, the characteristics of freight transport have to be taken into account. The main characteristics are heterogeneity, physical factors, operational factors and dynamic factors (see chapter 1). When modeling at a micro-level, it is possible to look at individual instead of aggregated flows. This gives the opportunity to include individual firm characteristics and a detailed representation of commodity groups. When looking at single movements of goods, more information of a shipment may be represented that would go lost in aggregated data. Furthermore, production rates of firms may be included to incorporate changes in the demand pattern of customers, like in the TAPAS model (Davidsson et al., 2008).

When developing an activity-based model, great care has to be paid to the choice of actors involved in the model. The actors most widely used in literature are shippers, receivers, carrier and forwarders or transporters (Liedtke (2009), Wisetjindawat et al. (2007) and Boerkamps et al. (1999)). Another more detailed representation exist in the model framework of Roorda et al. (2010), who differentiates between business establishments, firms and three types of facilities (commodity production, business service and logistics service). The way these actors interact with each other and how they are involved in the decision making process is of key importance in developing a micro-simulated activity-based model. This allows to include pricing mechanisms and to take into account long- or short-term contracts between actors. An opportunity exists to simulate market interactions and pricing negotiations. Furthermore, more attention has to be paid to logistic decision making. What are the responsibilities of each actor and on what may he have an influence? Dullaert et al. (2009) developed an agent-based communication support platform for multimodal transport. Which focus on the interactions between agents on an operational level. Their aim was to increase cost efficiency, service and safety for different transport-related actors. This platform should be able to facilitate the interaction between the different actors involved in multimodal transport by allowing real-time decision support and communication options. Although this platform is not used for the prediction of freight flows it shows an interesting inside in the interaction of the actors involved.

Two other main interactions that have to be taken into account are the link with economy and the logistic decisions made by the different actors. In the remainder of this section these two interactions are discussed. A close follow up of all these interactions is requested to have a more realistic image of freight transport flows.

3.4.1 Link with economy

As a starting point the relationship with the economy has to be included. Disaggregate models start from a detailed micro-economic background of the different commodity groups. Modeling the behavior of shippers and carriers helps to determine how much and in what way commodities will be moved. It allows the analysis of the relation between an economic activity and the resulting transport movement. Transport may be considered as a part of the logistics process and a production factor. Companies consider their output as the arrival of finished goods at their destination. For this not only labor and capital is necessary, but also transport becomes important as production factor (Meersman and Van de Voorde, 2008).

For companies the goal is to have goods on the right moment in the right quantity on the right place for production and to be able to distribute their finished goods and services to their clients. For that it is necessary to have people and goods at site and this implies transport. So there is a clear relationship between the economic activity of a company and transport. In most industrialised countries, 12% of total consumption expenditures are related to transport (Meersman and Van de Voorde, 2008). Freight transport in tonne-kilometres follows closely the evolution of the gross domestic product during the last decades. Still, the relationship has changed over time and the elasticity between freight transport demand and economic activity differences among countries and commodities (Meersman and Van de Voorde, 2008).

Understanding this relationship more clearly will put us in a position to better forecast transport and especially freight flows. This may be done by looking at the location and the needs of companies, so that traffic may be linked to transactions between companies and it becomes clear where and when vehicles will be on the road. This relationship also stands in the other direction. Changes in traffic flow may be translated into changes in economic activity, like employment and turnover.

Due to the trend toward globalization, the upcoming importance of supply chain management, and the development of ICT, the world's trading patterns are changing and as a result the physical trade flows. Such restructuring is leading to economic growth, better allocation of resources, and above all greater freedom of choice for consumers. The increase in international trade is, amongst other factors, caused by the fact that in the past few decades many trade barriers have fallen. Furthermore, trends in consumption, mass-individualisation and an economy that is running 24 hours a day, are influencing freight transport.

Through the developments in telecommunications and information technology, companies are able to better manage the physical movement of products over long distances. Many carriers have invested heavily in "track and trace" systems to be able to determine the location of any consignment at any time, improving the visibility of the global supply chain to shippers and their customers (Tavasszy et al., 2003) As a consequence of this booming international economy, more freight is on the move and this mainly by road. There is a growing need to disconnect this economic growth from traffic flows and to stimulate alternative transport modes, because we will not be able to keep expanding our roads. Freight transportation models may help to map the effects of political decisions on modal split.

The economic structure is important for freight demand. In Beagan et al. (2007), this is subdivided into three categories:

- **Types of industries:** This may be broadly classified into goods-related industries and service industries, with each of them having a unique impact on freight flows. Service-related trucking is unique in terms of the types of equipment and time-of-day activity.

- **Personal consumption:** The demand of households for goods and services is driven by economic growth. This demand increases the retail activity, which leads to more generation of local truck trips.

- **Trade:** Is composed of international, domestic and local trade, each of them having their own characteristics in terms of OD patterns of shipments, mode used, commodities handled, logistics chains and time dependencies.

For the modelling of freight flows the relationship between the economic activity of a company and transport has to be included. Economic growth leads to more economic activity, higher incomes, more consumption and eventually more demand for transport. Transport also has his influence on the economy. Congestion, damages to the infrastructure and employment each impact the economic activity (Meersman, 2011). In order to develop good freight transport forecasts, it is necessary to incorporate the relation between economic activity and freight transport demand into freight transportation models. If this relation is not represented in an appropriate way, it will weaken other parts of the model and the forecast. The relation between freight transport demand and economic activity is the starting point of most transportation models.

3.4.2 Logistic elements

The transportation of goods may follow a network of shippers, carriers, forwarders, terminals, distribution centres and others to arrive at its destination. These logistics chains are typical for the movement of freight and need to be taken into account when it comes to modelling freight flows. By explicitly simulating the different actors involved in the decision making process, the logistic decisions and chains may be represented. When it comes to logistic processes main items have to be included, like modeling shipment size and an appropriate mode and vehicle type choice. It gives the opportunity to incorporate inventory management at the customer and vendor site, to include warehouse management at distribution centers and to simulate terminal operations. To optimize distribution chain flows the location of distribution centers may be included in the modeling process.

A disadvantage of many of the freight transportation models is that they are completely lacking elements of logistic organization (Ben-Akiva and de Jong, 2008). The freight logistics system is very dynamic in nature and therefore trends in industry supply chains need to be considered. Trends like just-in-time logistics are having an impact on the modes used and size and frequency of shipments. Another important supply chain trend is the alliances between shipper and carrier, which have their impact on mode choice (Beagan et al., 2007). Two of the main trends that are stated in Hesse and Rodrigue (2004) are:

- **Demand-side orientation of activities.** While traditional delivery was primarily managed by the supply side, current supply chains are increasingly managed by demand.

- **Logistics services are becoming complex and time-sensitive.** This has led to the point that many firms are now subcontracting parts of their supply chain management to third party logistics service providers. These providers benefit from economies of scale and scope.

An important aspect of an activity-based freight model is to take logistics choices, such as the shipment size, into consideration. One of the problems which firms are confronted with is the choice of an appropriate inventory level and transport mode. To make this decision most authors are referring to the inventory-theoretic model, which uses the total logistic costs to determine which transport mode is most appropriate for the desired inventory level. This is done by taking into account all the costs in the supply chain, that are influenced by the mode choice. It is crucial to take these decisions into consideration while modelling freight transport to come to a more realistic image of freight movement today. An overview of the early developments in freight transportation choice models may be found in McGinnis (1989). Although the first inventory-theoretic models date from 1970 and were able to state the importance of integrated consideration of logistics and transportation in decision making, latter developed models are lacking this logistic insight (Liedtke, 2009). The more recent developed models are again taking the interaction of logistic decisions and transportation into their development. Still work has to be done to fully grasp the logistic impact on freight transport. This is a continuing challenge for future freight models.

A better link with the freight distribution industry is required to overcome this weakness and some models have made progress in this respect by modelling logistic processes such as the number and location of distribution centres, the choice of shipment size, carrier and travel mode (Rand Europe, 2002). Furthermore, the choice of receiver or sender could also be modelled using disaggregate random utility models. This leads to the opportunity of simulating changes in the logistic chain, for example: these days many goods are delivered from distribution centres to the retailers, rather than from manufacturers. The delivery patterns that are optimal for distribution centres are different from when they were shipped directly by the producer. Those movements are often made by truck fleets whose travel is organized into tours with many stops (Kuzmyak, 2008).

3.5 A new conceptual freight transportation framework for Flanders

As stated earlier, there is a need for a more comprehensive model that includes logistic elements. The objective is to develop an activity-based micro-simulated model, where the focus lies on the different actors. In this section, the different steps of our conceptual framework are discussed. The main focus is on the Logistic module of the framework. In figure 3.2 the different steps of the framework are shown. First, the Generation module generates the different actors with their attributes and locates them in the modeling area. Secondly, in the Market module different firms interact with each other and create shipper/receiver relationships. This results in Production/Consumption flows (PC flows). Next, the Logistic module takes place and models the freight flows and interactions between the different logistic players. Within this module also the 'Transport chain generation module' is included. Finally, the resulting freight flows are assigned to the network. In the remaining part of this section the different steps are elaborated in more detail. It has to be stated that the framework is in a conceptual state and not yet implemented.

As a basis for the new microscopic, activity-based freight transportation framework for Flanders, four building blocks are used. They represent the four main steps in the freight transportation model, i.e.: Generation module, Market module, Logistic module and the assignment to the network. The four building blocks used are related to the structure of the traditional four-step transportation model (de Jong et al., 2004). As opposed to the traditional four-step module we opted to include more detail and work on a microscopic level, by modeling every actor separately. The Logistic module of the framework makes a combination of some of the state-of-the-art models presented in chapter 2. The working of the 'Transport chain generation' module is inspired by the work of Ben-Akiva and de Jong (2008), as they make use of a multimodal transport network. The interactions between the different actors are based on the work of Liedtke (2009), although the INTERLOG model makes only use of road transport a good representation is given of the different actors involved in the process.

The key objective of the framework is to have a model that includes the simulation of logistic decision making. This framework needs to be able to give a more realistic representation of freight flows in Flanders than existing models. As Flanders is located next to the sea, with some important harbors and an expanded inland waterway system, we opted for a multimodal network. The main transport modes considered are road, rail and inland waterways. For road transport a differentiation is made between light road and heavy road. Because Flanders is geographically small, air transport is not included for inland transport. Also transport by sea is only feasible for import or export.

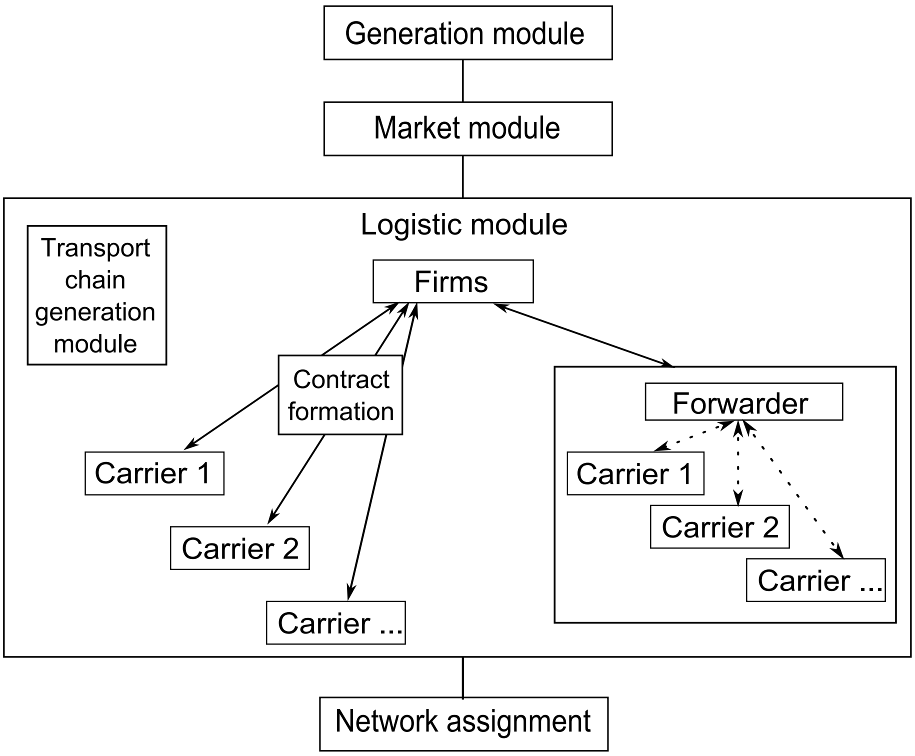

Figure 3.2: Conceptual framework

As stated by Holguin-Veras et al. (2011) it is important in freight transport to make a clear distinction between the generation of demand and the generation of traffic. The generation of freight demand is determined by the economics of production and consumption. Freight trips, on the other hand, are the output of logistic decisions. The greatest gap in many existing models is in the modeling of logistic decisions. Most frequently a rate is used to determine the link between freight demand and freight traffic flows. To improve this link, the focus of this research will be on the Logistic module. In our framework the generation of demand is included in the first two modules: Generation and Market module. The generation of traffic on the other hand is composed in the Logistic module. A general overview is given of each module, after which the focus in section 3.5.2 lays on the Logistic module. It has to be noticed that the following description of the framework gives an idea about how the different modules might be constructed and certain assumptions are made which have to be further investigated in a field study.

Generation module: In this step the level of detail has to be determined. Firms are generated, whereby location, economic activity, size and other attributes are assigned to a firm. Also the creation of multi-establishments firms may be considered in this step, to arrive at a better representation of reality. In these multi-establishments firms close interactions and co-operations between the establishments exist. This may be seen as well in the study of Roorda et al. (2010). Furthermore, firms' annual demand and supply are simulated. This step allows creating a clear link with the economy.

Market module: The supply and demand of the different firms are matched with each other. This involves the choice of a supplier for each firm, as well as the quantity to be purchased. Firms may interact with each other to form contracts and negotiate the price of the goods. This interaction is further explained in section 3.5.1.1 The result of this step is the annual commodity flow between pairs of firms and is represented by PC matrices.

Logistic module: In this step the order quantity, frequency and transport mode are chosen. Also whether or not to outsource the transport to carriers and forwarders is modeled and options for consolidation are considered. More details may be found in section 3.5.2.

Network assignment: The scheduling and routing of individual shipments onto the network is modeled. Terminals and consolidation centers might be included in the network to allow intermodal transport. This module might be extended with empty trips, which may be accounted for by tracking the different vehicles. This is often overlooked in freight transportation models. Also the impact of various constraints such as equipment and link capacities has to be looked into. Furthermore, different techniques to assign flows to the network may be considered. In chapters 5 and 6 the construction of routes are integrated in the decisions of the carrier. These routes may latter be assigned to the network.

For all these different modules, work has to be done in gathering data to be able to run the model. In section 3.5.4 options for data collection are discussed. The Generation and Market modules, together with the network assignment need to be further worked out in future research. At this moment they are based on the work of the state-of-the-art models presented in the previous chapter. The process may also be made sensitive to policy changes like pricing, weight restrictions, safety and travel time regulations.

In the remainder of the chapter the conceptual framework is elaborated in more detail. First, the different actors involved are presented in section 3.5.1. Next, in section 3.5.2 the logistic module is explained. Further research is required to model the other three modules within the framework, this however goes beyond the scope of this thesis. In section 3.5.3 the consolidation options of a forwarder are presented. Section 3.5.4 ends with some considerations concerning data collection.

3.5.1 Actors

As mentioned in the literature review, one of the main differences between modeling freight and passenger transport is that more actors in freight are involved in the decision making process. The economic transactions between suppliers and consumers, and the logistics operations that deliver the goods, are the two main drivers behind the rapidly evolving patterns of freight movements (Jin et al., 2005). Therefore, more attention has to be paid to the different actors. The way these actors interact with each other and how they are involved in the decision making process is of key importance in developing a micro-simulated activity-based model.

To see how different actors may influence freight flows, we first need to know the responsibility of each actor. Within our framework three main actors may be recognized. A first group of actors consists of firms who are sending and receiving the goods, respectively called sender and receiver. A next group of actors are the carriers who undertake the transport. Finally, forwarders are modeled, who may be responsible for the entire organization and execution of the transport, which may be in co-operation with carriers. Modeling individual actors at a microscopic level allows to include pricing mechanisms and to take into account long- or short-term contracts between actors. An opportunity exists to simulate market interactions and pricing negotiations. Different actors may have different objectives, which might be in conflict with one another. For example, a firm that receives goods wants to have a lowest possible inventory level and hence small shipment sizes, while a carrier wants to consolidate deliveries to have full truckloads, so that he has a lower cost. This section presents the different actors and their decisions to arrive at a freight flow. It describes how the role of the actors may be seen in the framework and which assumptions are taken. The interactions between the different actors in the framework are explained in more detail in the section 3.5.2.

3.5.1.1 Firms

A firm may be a sender or a receiver of goods, or both. First of all, the receiver initiates the freight flow by ordering goods. This may either be for consumption or for retail. The receiver looks at his needs and calculates the required demand. He determines the order quantity he wants to receive by keeping in mind the appropriate inventory level, the cost of the goods and the order and delivery cost. A smaller order quantity will imply a more frequent delivery and a lower inventory level. It will result in a higher transport cost but a lower inventory cost. Once the order quantity is known, the frequency may be deducted from the yearly demand and the order quantity.

The next step is to come to an agreement with a sender that may deliver the goods. The sender of the goods acts in response to a demand made by the receiver. To meet at this demand the sender first needs to establish its production capacity and the price at which he is willing to sell the goods. Furthermore he determines the fixed order cost for each order made by a customer. These decisions take place in the Market module.

When the sender and receiver have come to an agreement about the sale, they have to determine the means of transport. An agreement has to be found on the delivery moment (i.e. earliest/latest pickup and delivery times), the shipment size and whether they conduct the transport by themselves or not. Several possibilities exist: first of all they have to see if either of them has the own means, an own fleet, for delivering the goods and determine if this is the most appropriate way to deliver the goods. If none of both parties has an own fleet, they have to outsource the transport. For this they may choose to use a carrier or contact a forwarder to take responsibility of the entire transport. Firms are likely to plan their shipments such that total logistic costs are minimized. The main cost variables are transportation and inventory costs.

3.5.1.2 Carriers

Carriers are responsible for the movement of the shipments. The main task of the carrier is the scheduling and routing of vehicles. A carrier may receive his requests from either firms or forwarders. Each transport request that is accepted is planned into a vehicle route. However, a carrier may turn a contract down if it is not profitable.

A carrier may negotiate with firms or forwarders for transport contracts. In these transport contracts a shipment size is specified between the origin and destination and at specific pickup and delivery times. The decision to accept a transport request, as well as the vehicle routing and scheduling is made by the carrier. Furthermore, he may consolidate orders to achieve economies of scale. In our model all vehicle tours begin and end at the carriers' depot. The decision making process of a carrier is modelled in chapters 5 to 7.

3.5.1.3 Forwarders

Within the presented framework, forwarders have the responsibility to build and coordinate transport chains. They constitute the link between firms and carriers when transport decisions are outsourced by firms. A forwarder organizes the transport chain. His actions are related to the shipment rather than the vehicle. For each transport request, the forwarder determines the optimal transport chain. This includes decisions about the use of terminals or consolidation centers, and which transport mode to use for each transport leg. For each transport leg the forwarder may contract the service of a different carrier, according to the transport mode chosen and the capacities of the carrier. A forwarder has a list of preferred carriers with which he does business. Forwarders have to consider possibilities of multimodal transport for which terminals are used to transfer the goods and make contracts with several carriers, or they may opt for a single transport mode. Furthermore, he can make use of consolidation centers to manage and group the different transport requests he receives. In section 3.5.3 the consolidation options are further elaborated.

3.5.2 Logistic Module

In this section, the different steps of the logistic decisions module are explained. Within the Logistic module a separate module is included for the creation of transport chains. It is run separately, before the logistic decision making process. This preprocessing step is based on the ADA-model of Ben-Akiva and de Jong (2008).

The 'Transport chain generation' module computes a Total Logistic Cost (TLC) function for each of the transport chains. The TLC function exists of an ordering cost, inventory cost, capital cost of the goods in transport and in inventory and transport cost. The transport cost is carrier specific and is split into several components: a link-based cost composed of a distance and time-based cost, a transshipment cost depending on the modes used and a cost for loading and unloading a vehicle.

Transport chains are created with the different transport modes. In total 30 chains combinations are possible. These chains may be divided over ten categories, represented in appendix A. In the first category (road), heavy road consolidated is considered as a third transport mode option in addition to light road and heavy road (unconsolidated). For Flanders the category for air transport, as well as the categories including sea transport, are only used for import and export.

The 'Transport chain generation' module determines the optimal transfer points within each predefined transport chain (possible combinations with road, rail, inland waterways and sea). The optimal transfer point is determined based on the TLC function. The module tests the different possibilities of transfer points in each predefined transport chain and chooses the transfer point that has the minimum TLC. This procedure is executed for each combination of zones and commodity types. Afterwards these transport chains are used by the companies depending on the zone in which they are located, the commodity goods they are transporting and the availability of a transport mode. For the creation of the general transport chains between two zones and for each commodity category, an average transport rate is used as well as the most common vehicle/vessel type. Later in the module, when the transport chains are implemented the exact transport rate is used and the possible vehicle/vessel types are examined.

When forwarders have different cost functions than those experienced by firms, different transport chains may be created. A forwarder may receive better financial conditions from a terminal. For this it is useful to create a separate 'Transport chain generation' module for forwarders or use different parameter settings. Further research may look into the difference in use of transport chains between the different actors. A field study may examine the effect of economies of scale, which a forwarder may or may not receive.

In the following subsections the different possible steps in the Logistic module of the framework are described in further detail. Firms may either work together with a carrier (3.5.2.1) or a forwarder (3.5.2.2), before taking their final decision (3.5.2.3). Attention has to be drawn to the fact that the framework is still in a conceptual phase and may be subject to changes as future research may reveal different interactions between actors.

3.5.2.1 Relation between firms and carriers

The objective is to include negotiation processes between firms and carriers. PC flows at a firm-to-firm level represent shipments between senders and receivers. For each shipment, given as a yearly flow, firms have to decide whether the transport will be outsourced to a carrier, a forwarder or done by an own logistic department, if present. This decision is made by taken into account the possible ownership of a vehicle fleet. Interactions between firms and forwarders are discussed in subsection 3.5.2.2. When a carrier is contacted, it is up to the firm to decide which shipment size it will use and which transport chain to follow. Furthermore a time window is assigned to the shipments. Based on these decisions several preferred carriers may be contacted to receive an offer bid.

The optimal shipment size that will be used is calculated in two steps. An initial shipment size is determined, after which this is optimized depending on the interaction between the actor responsible for the transport and the carrier. Because the 'Transport chain generation' module generates transport chains for all the firms in a certain zone based on an average yearly demand and shipment size, this has to be adopted to fit the needs of the firm under consideration. The first step determines for each of the available transport chains created in the 'Transport chain generation' module an initial shipment size. This is done by implementing the yearly demand of the firm and minimizing the TLC function for each chain. As the exact transport cost is not yet known, the transport rate of the previous simulation period is used. Only the first simulation run incorporates an average transport rate, based on the input data. Afterwards the transport rate for each carrier is update after each simulation period. When the initial shipment sizes for each chain are known, a call for offer will be executed to obtain the exact transport rate. The call for offer will be sent to preferred carriers based on their suitability for transport on a leg of the transport chain. Each firm has a list of preferred carriers with which they are willing to do business. A separate list for each transport mode is used and may be updated every x^{th} simulation period. If the firm responsible for the transport has an own vehicle fleet, it may execute the transport or parts of the transport chain himself. A call for offer exists of a pick-up and delivery place, a shipment size, the frequency of delivery and a time window in which the order has to be executed. When receiving a call for order, the carrier will check whether it may fit into his operations. Finally, the carrier will return an offer bid to the firm. The offer bid exists of a transport rate and a time window. After receiving the offer bid of the carrier, the firm responsible for the transport will recalculate the optimal shipment size in a second step. The optimal shipment size will be recalculated for each transport chain that is still profitable. This is done based on the received transport rate of the carrier or the calculated transport rate of own transport. A new call for offer based on the new shipment size will be formulated and the carriers send back a new offer bid. This process will continue for a certain number of iterations or until an equilibrium is reached.

The decisions of a carrier may be formulated as a selective pickup and delivery problem (see chapter 5). The objective is to maximize the profit gained by selecting transport requests. A carrier faces the daily problem of optimally scheduling his transport orders. Each day a carrier receives transport requests from his clients, which have to be executed within a certain time period. To obtain a maximal profit the carrier has to group certain orders and create an optimal sequence of pickup and delivery of the different tasks. A carrier may refuse a transport order, when he believes the order is not profitable. If a request is accepted it will generate revenue when the transport is completely fulfilled. In our framework only current requests are taken into account and the possible loss of future requests is ignored. The operational decisions of a carrier are further explored in chapters 5 to 7. In chapter 6 a fixed transport price is used, on the other hand in chapter 7 a transport price based on actual costs is proposed, which will allow iterating the negotiation process.

3.5.2.2 Passing down transport decisions to a forwarder

Within the framework an option is inserted to rely on forwarders for the organization and execution of transport orders. This implies that a forwarder will be held responsible, not solely for carrying out the transport, but also for the choice of an appropriate transport chain and optimal shipment size. Based on a list of preferred forwarders of a firm, transport decisions may be passed down to a forwarder. This is done by sending out a call for offer, containing the yearly commodity flow between a sender and receiver, to their preferred forwarders.

First, the forwarder determines the transport chain and shipment size. This will be done similar as in subsection 3.5.2.1. It is possible that a forwarder uses transport chains with other transshipment point as they may have a stronger relationship with certain terminals. This will enable them to receive better transshipment rates. Furthermore, a forwarder may be specialized in a certain transport chain in which they may offer lower transport rates. Therefore, the forwarder makes use of a different parameter setting in the 'Transport chain generation' module than the firms (see section 3.5.2). This may influence the optimal shipment size calculated by the forwarder. Next, the forwarder decides which carrier he will use for each transport. Due to the position of a forwarder and his probably larger demand, it may be assumed that he will receive different transport rates from carriers than firms will.

The forwarder will negotiate transport rates with a carrier and make long-term fixed contracts. This allows the transport rates to be constant for a certain period of time. Furthermore, long-term contracts save computation time as the negotiation process does not have to be repeated in each simulation period. The list of preferred carriers of a forwarder may be different than that of a firm. The decisions made by the carrier will follow the same procedure as described in subsection 3.5.2.1, but a different discount policy may be handled for forwarders. Finally, the forwarder calculates the rate for the entire transport for each transport chain and responds to the call for offer. The transport solution that the forwarder considers as most profitable will be returned to the firm. This solution consists of an optimal shipment size/frequency of delivery, an optimal transport chain including transfer points and the transport rate.

3.5.2.3 Final decision made by the firm

The firm responsible for the transport will determine the optimal transport chain and respective shipment size, based on the offer bids of the carriers, forwarders and his own transport rate. After he has received all offer bids from the preferred forwarders and carriers and has made his own calculations, he has a list of possible transport solutions. Based on the minimum TLC of the transport chains he has calculated or the lowest transport rate he received from a carrier or forwarder, he will choose the optimal transport solution. Next, a contract is created with the carriers or forwarder involved and this contract may be fixed for a predefined number of simulation periods. The transport rates are kept fixed for a certain time span and allow the simulation of long-term contracts.

The Logistics module gives output on an OD level, containing the following information: shipment size and frequency, transport mode, which actor is responsible for the transport, total logistic cost of the transport and finally the tour in which the shipment is included and whether it is consolidated with other shipments. This information may be used for the final step of the freight transportation framework, to arrive to an assignment on the network.

3.5.3 Consolidation options of a forwarder

This section focuses on integrating consolidation options into the freight transportation framework. Consolidation is often overlooked in freight transportation models, although it may lead to several advantages. One of the main advantages is the possible reduction in distribution costs by consolidating several small shipments. This allows dividing the fixed costs between more shipments. Furthermore, social gains, including a reduction of air pollution, congestion and accidents, may be achieved from consolidation (Caris et al., 2010). If policy makers want to fully grasp freight flows, a detailed freight transportation model is essential. Consolidation plays an important role in intermodal transport and may have an effect on modal shifts. For these reasons consolidation is an important part of our freight transportation framework. Special attention is paid to the different consolidation options of a forwarder. This leads to a more realistic representation of transport cost and shows that direct transport is not always the most advantageous mode of transport. To the author's knowledge it is the first time that these different consolidation strategies are considered within a freight transportation framework.

Within the Logistic module of the framework an option is inserted to rely on forwarders for the organization and execution of transport orders. Forwarders have the responsibility to build and coordinate transport chains. They form the link between firms and carriers, when transport decisions are outsourced by firms. For each transport request, the forwarder determines the optimal transport chain. This includes decisions about the use of terminals or consolidation centres, which transport mode to use for each transport leg and determining an optimal shipment size. For each transport leg the forwarder may contract the service of a different carrier, according to the transport mode chosen and the capacities of the carrier. A forwarder is ideally positioned to consider consolidation options, because he works for several clients and is responsible for multiple shipments.

The different steps of the decisions that are modelled for a forwarder are as follows. First, the forwarder determines the transport chain and shipment size (see section 3.5.2.2). After that, he will consider possibilities to consolidate different shipments to generate a lower total logistic cost. Next, the forwarder decides which carrier he will use for each leg in the transport chain. The forwarder will negotiate transport rates with a carrier and make long-term fixed contracts. Finally, the forwarder calculates the rate for the entire transport for each transport chain and responds to the call for offer. The transport solution that the forwarder considers as most profitable will be returned to the firm. In the remainder of this section the consolidation options of a forwarder are explored.

Hall (1987) defines three different ways of consolidation. The simplest form is inventory consolidation, where items that are produced are stored and transported in the same load. A second form is vehicle consolidation where items are consolidated over space, this occurs in classical “milk-runs”. The last form considered by Hall (1987) is terminal consolidation. Items from different locations are gathered at a terminal, where they are sorted and reloaded onto new vehicles. From the terminal they may be shipped to different destinations. In our framework this last form is used and terminal consolidation is considered as an option for forwarders. Vehicle consolidation is applied in the decision making process of a carrier but will not be further explained in this chapter.

Woxenius (2007) gives six different transport options from an origin (O) to a destination (D), see figure 3.3. In these transport chains terminal consolidation, as defined by Hall (1987), may take place at each hub. As the purpose of our freight transportation framework is to simulate large networks with multiple shipments and multiple actors, only three options are considered. This limitation is necessary to keep calculation efforts within bounds. The first option is the direct link presented by Woxenius (2007), in which goods are transported direct from the sender to the receiver without terminal consolidation. Secondly, a corridor network is considered whereby shipments may be consolidated between two common terminals. The last option that is taken into account is a network of connected hubs, in which the main haulage of a shipment may be consolidated.

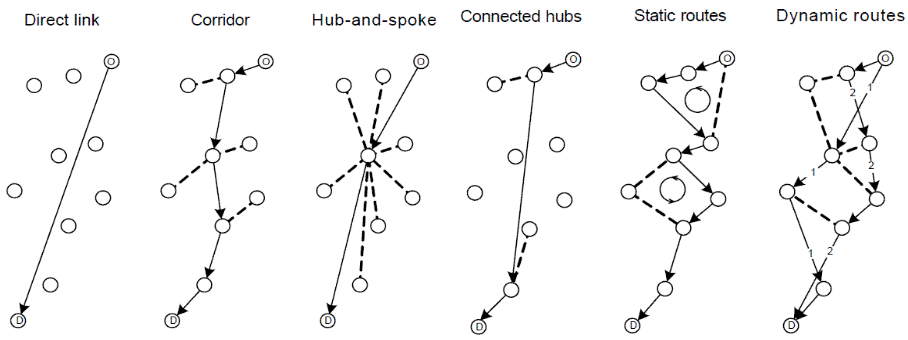

Figure 3.3: Consolidation options (Woxenius, 2007)

After a forwarder has determined which transport chains are the most profitable to operate a certain shipment, the previously discussed consolidation options are considered. As a forwarder has several clients and multiple shipments, he is ideally positioned to consolidate different shipments. To start the shipments are ranked based on their begin and end terminal. If more than one shipment share the same begin and end terminal, it is checked whether they may be consolidated. This is done according to the connected hubs system of Woxenius (2007). Another option is to build a corridor with several shipments heading in the same direction and which may have the same begin terminal or end terminal but not necessarily both. Shipments are consolidated along parts of the corridor which they share with other shipments, the remainder of the transport is unconsolidated.

Consolidation options are calculated for the three transport chains with the lowest total logistic cost without consolidation. Three transport chains are considered instead of only one, as difference between the TLC of the transport chains may be small and the chain with the lowest TLC might not be suitable for consolidation. By consolidating several shipments the transport price per shipment may go down and could stimulate a modal shift. Due to this the preference may go to another transport chain. Furthermore consolidation allows a more efficient use of transportation resources.

3.5.4 Data

Working on a micro-level implies a high need for data. Freight modeling lags behind due to a lack of publicly available data. Most of the scarce data that is publicly available is aggregated to protect the identity of individual actors (Tatineni and Demetsky, 2005). Most transport firms try to keep their rates confidential, to enforce their position in the market, when it comes to price negotiation.

Within this conceptual framework a need exists for a detailed data collection. Next to the data available from the government, an additional data collection will be necessary. A survey collected at different firms may be required to understand the underlying relationships and their decisions regarding transport. On the demand side, information on individual shipments like: location of senders and receivers, shipment size and frequency, use of terminals and price settings by carriers and forwarders may be gathered. Furthermore, data on transport duration, like port activity, average speed and driver rest hours allows the calculation of delivery times. Also data on transport costs needs to be collected, such as costs per distance traveled, road tolls, terminal charges, handling costs and storage costs.

With modern technology it may become easier to collect data for activity-based models. Most trucks are equipped with a tachograph, to register the speed and driving times. Also GPS-systems may help to track data of where and when trucks and goods are on the move.

3.6 Conclusions and further research

In this chapter, a new freight transportation framework for Flanders is proposed. The objective is to create a conceptual agent-based micro-simulated framework for Flanders, which is able to incorporate more logistical elements than current models in Belgium. It has to be noticed that the current models in Belgium are not at the same state-of-the-art level as the international models of chapter 2. Therefore, in a first step the models that already exist in Belgium are studied and weaknesses are listed. From the literature review of chapter 2 the key characteristics for a agent-based micro-simulated model may be identified. The interest lays on an improved representation of the different actors within a multimodal framework. From the literature study it has become clear that only a few models combine a detail representation of actors together with modelling multiple freight transportation modes. In this chapter, basic building blocks are established for the framework. First, the actors are presented, after which the framework with its different modules is given. The chapter ends with a step by step overview of the Logistic module and some thoughts on data collection. Chapter 4 demonstrates how the Logistic module of the proposed freight transportation framework functions, by means of a worked example. Special attention is given to different actors. A new technique for the representation of carriers decisions is studied in chapters 5 to 7.

Further research opportunities exist in the modelling of the other three modules (Generation module, Market module and Network assignment) within the framework. Currently, these modules are not modelled as our focus is on logistic decisions and not the full implementation of the framework. Another interesting research direction would be to examine the 'Transport chain generation' module in more detail. First, we may look into differences in use of transport chains between different actors. Therefore, more research has to be done into the decision making process of these actors. Behavioural experiments needs to be conducted to be able to capture the actions of the different actors. Secondly, a better formulation of the total logistic costs involved and more specifically the difference in transport costs between the actors, may improve the module. More insight in the cost structure of carriers and forwarders may lead to a more realistic representation of the transport chain formation. Finally, the need exists to gather detailed data to be able to model on a microscopic level and implement the proposed framework.

Chapter 4

A practical implementation of the freight transportation framework on Flanders

4.1 Introduction

In this chapter, the freight transportation framework of chapter 3 is applied on Flanders. A first application of the framework on a small test sample of ten zones is discussed. An inside is gained into the working of the framework and into potential problems when implementing the framework on a country-size scale. As the framework is still in a conceptual phase not all elements are yet in place. Only the parts which are already functioning are used in the chapter. Next to the construction of transport chains, the integration of logistic decisions made by the forwarder concerning consolidation of freight flows may be simulated. To see the effect of changes in certain parameters in the Logistic module, a sensitivity analysis is conducted.

The chapter is organized as follows. The Logistic module of this framework is applied to the region of Flanders in section 4.2. Starting from the disaggregation step used on the input data, all steps in the Logistic module are calculated up to the consolidation decisions of a forwarder. In section 4.3 a sensitivity analysis of certain parameters in the framework is presented. Finally, conclusions are drawn and options for future work are suggested.

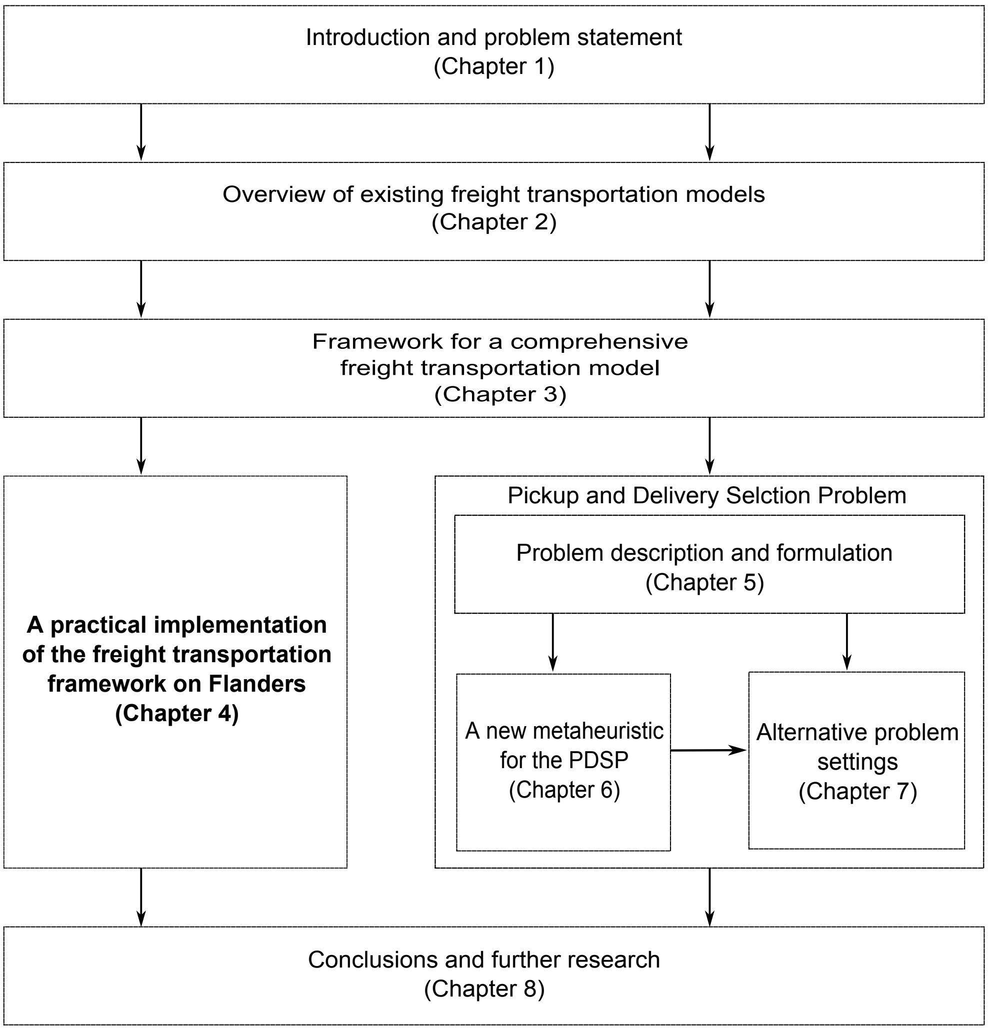

Figure 4.1: Outline of the thesis - Chapter 4

4.2 Worked example of the Logistic module for Flanders

In this chapter, only the Logistic module of the framework in figure 3.2 will be further elaborated. This module starts after the Market module and will take the PC flows between the firms as given. Also the Network assignment will be left out of this thesis. As for now, the PC flows are on a zonal level, because the Generation and Market modules are not yet in place. Instead a disaggregation step is inserted, to create firm-to-firm flows. This is demonstrated in the following subsection for the region of Flanders.

In the rest of this section, the different steps of the Logistic module are explained. The decisions of the forwarder are modelled separately at the end of this section in paragraph 4.2.5. Interactions with carriers are not yet incorporated in this example, this will be discussed in the second part of this thesis (chapters 5 to 7). The goal is to include these actors, so that transport rate negotiations between firms and carriers or forwarders may be simulated. Hence, a firm may choose between the service of a carrier or use, if present, his own transport fleet. Furthermore, an option is inserted to rely on forwarders for the organization and execution of the transport orders. This implies that a forwarder will be held responsible, not solely for carrying out the transport, but also for the choice of an appropriate transport chain and the consolidation options of combining several clients.

4.2.1 The region of Flanders

Figure 4.2: Intermodal freight terminals in Belgium (Macharis and Pekin, 2010)

To illustrate the conceptual Logistic module, it is applied to the region of Flanders, the northern part of Belgium. The 308 communities (LAU 2 (Eurostat, 2012)) in Flanders are used as zones in the model. However, to keep calculation efforts within reach a first example is applied on only ten communities selected from the 308 communities in Flanders. Selecting only ten zones allows the testing of the logistic decisions module, while limiting calculation efforts. The zones are selected based on their geographical location (two within each province, NUTS 2 (Eurostat, 2012)) and the number of firms within the zone. The zones are: Genk, Sint-Truiden, Antwerp, Mechelen, Leuven, Zaventem, Gent, Aalst, Bruges and Courtray. The main goal is to identify potential problems within the framework, before implementing it on a larger scale. For that reason only a small test sample is used.

To start the Logistic module, information is needed on the PC flows between the different zones. These flows are divided into nine matrices corresponding to the nine different NST/R (category 7 and 8 are combined) commodity categories. The NST/R classification is a standard goods classification for transport statistics composed of ten categories, which is often used in Europe (see table 4.1). In this worked example only category 0 (Agricultural produce) is considered. Furthermore, data on the network structure of the different transport modes and the location of the terminals is needed. Figure 4.2 shows the location of the different terminals in Belgium. In table 4.2 the different terminals, harbours and airports in Belgium used in the Logistic module are listed.

Table 4.1: NST/R categories

NST/R	**commodities**
0	Agricultural products and live animals
1	Foodstuffs and animal fodder
2	Solid mineral fuels
3	Petroleum products
4	Ores and metal waste
5	Iron, steel and non-ferrous metals (including semimanufactured products)
6	Crude and manufactured minerals, building materials
7	Fertilizers
8	Chemical products
9	Vehicles, machinery and other goods

Table 4.2: Terminals in Flanders

Category	Location	Transport modes
Habours	Gent	IWW, Rail, Road, Sea
	Seabruges	IWW, Rail, Road, Sea
	Antwerp	IWW, Rail, Road, Sea
	Ostend	IWW, Road, Sea
Trimodal terminals	Genk	IWW, Rail, Road
	Meerhout	IWW, Rail, Road
	Brussels	IWW, Rail, Road
	Willebroek	IWW, Rail, Road
IWW terminals	Deurne	IWW, Road
	Herent	IWW, Road
	Grimbergen	IWW, Road
	Wielsbeke	IWW, Road
	Avelgem	IWW, Road
Rail terminals	Genk	Rail, Road
	Muizen	Rail, Road
	Antwerp	Rail, Road
	Antwerp habour	Rail, Road
	Courtray	Rail, Road
Airports	Zaventem	Air, Road
	Ostend	Air, Road, Rail
	Liege	Air, Road

4.2.2 Disaggregation step

To integrate logistic decisions in a freight transportation model, the logistic decisions are best modelled on a microscopic scale. This allows the representation of the different actors and their decisions. Therefore, in a first step the data of the PC flows, which are on an aggregated zonal level, need to be disaggregated to firm-to-firm flows. To do this, the steps of the ADA-model of Ben-Akiva and de Jong (2008) are applied.

In the ADA-model the main decision protocol at a disaggregated level instead of an aggregated level.

Between two zones only a fraction from all the potential relationships, between senders and receivers of a certain commodity, is actually realized. This is due to the fact that not all firms do business with each other. To calculate the actual number of firm-to-firm (F2F) relations of commodity k between two zones (r and s), the following formula is used:

$$F2F_k \; relations = F_k \cdot P_{kr} \cdot C_{ks} \tag{4.1}$$

$$With, F_k = \frac{N_k}{\sum_s C_{ks}} \tag{4.2}$$

where, F_k is the fraction of actually realised links between senders and receivers of two zones, P_{kr} is the number of producers of commodity k in a zone r, C_{ks} is the number of consumers of commodity k in a zone s and N_k is the number of receivers per sender for commodity k. More information on this method may be found in de Jong et al. (2008).

The disaggregation step is applied to Flanders, for the flows between Genk and Bruges. In table 4.3 the yearly zonal flow (PC flow) between Genk and Bruges is 918,87 tonnes of agricultural products. Based on the actual number of firms in the different zones, the model assumes for the simulation that there are 122 agricultural producers in Genk and 34 agricultural consumers in Bruges. This leads to a total of 4148 potential relationships, which will not all be realised. Considering 20 receivers per sender, the actual number of relations can be calculated. The total number of customers in Flanders for NST/R category 0 are 1970 firms.

$$F_k = \frac{20}{1970} \approx 1\% \tag{4.3}$$

$$\text{F2F}_k\text{relations} = 1\% \cdot 122 \cdot 34 = 42 \tag{4.4}$$

This leads to 42 firm-to-firm relations in the agricultural sector between Genk and Bruges. These 42 relations will be selected at random from the 4148 potential relationships. The 918,87 tonnes of yearly flow are proportionally divided between the 42 realised links, according to the size of the firms involved.

The input data necessary for this step are the PC flows between two zones for each of the different NST/R categories, as in table 4.3. Furthermore, the number of producers and consumers from each commodity category in each zone is required. Also the size of the firms (annual turnover or number of employers) is needed to divide the PC flows into firm-to-firm flows based on their size. Finally, the number of receivers per sender needs to be given to calculate the fraction of realised links.

Table 4.3: PC flows in NST/R 0 (in tonnes)

	Genk	**St-Truiden**	**Antwerp**	**Mechelen**	**Leuven**	**Zaventem**	**Gent**	**Aalst**	**Bruges**	**Courtray**
Genk	497,82	298,59	3546,53	600,75	697,33	219,8	1791,52	602,14	918,87	580,9
St-Truiden	262,36	157,37	1869,12	316,61	367,51	115,84	944,18	317,34	484,27	306,15
Antwerp	3102,69	1861	22104,07	3744,24	4346,19	1369,93	11165,79	3752,9	5726,93	3620,5
Mechelen	829,46	497,51	5909,2	1000,97	1161,89	366,23	2985,01	1003,28	1531,01	967,89
Leuven	1001,83	600,9	7137,2	1208,98	1403,35	442,34	3605,33	1211,78	1849,17	1169,03
Zaventem	707,39	424,3	5039,6	853,67	990,91	312,34	2545,73	855,64	1305,7	825,45
Gent	2628,17	1576,38	18723,49	3171,6	3681,49	1160,41	9458,1	3178,93	4851,05	3066,78
Aalst	476,67	285,91	3395,86	575,23	667,71	210,46	1715,4	576,56	879,83	556,22
Bruges	2210,5	1325,86	15747,98	2667,57	3096,43	976	7955,03	2673,74	4080,13	2579,41
Courtray	1007,33	604,2	7176,42	1215,63	1411,06	444,77	3625,14	1218,43	1859,33	1175,45

Table 4.4: Number of realised firm-to-firm links

	Genk	**St-Truiden**	**Antwerp**	**Mechelen**	**Leuven**	**Zaventem**	**Gent**	**Aalst**	**Bruges**	**Courtray**
Genk	25	13	231	37	38	48	97	28	42	34
St.-Truiden	13	7	122	19	20	25	51	15	22	18
Antwerp	231	122	2133	337	347	441	898	258	386	314
Mechelen	37	19	337	53	55	70	142	41	61	50
Leuven	38	20	347	55	56	72	146	42	63	51
Zaventem	48	25	441	70	72	91	186	53	80	65
Gent	97	51	898	142	146	186	378	108	162	132
Aalst	28	15	258	41	42	53	108	31	47	38
Bruges	42	22	386	61	63	80	162	47	70	57
Courtray	34	18	314	50	51	65	132	38	57	46

As output of this step flows are given at a firm-to-firm level for each of the nine commodity categories and for each combination of two zones. In table 4.4 the results for the firm-to-firm flows for NST/R category 0 are given.

4.2.3 Transport chain generation module

Within the Logistic module, a separate module is responsible for the creation of the different transport chains. It is run separately, before the logistic decision making process. This 'Transport chain generation' module is based on the ADA-model of Ben-Akiva and de Jong (2008).

The module makes a Total Logistic Cost (TLC) function for each of the transport chains. The TLC function consists of an ordering cost O, inventory cost I, capital cost of the goods in transport Y and in inventory K and transport cost T. The first four cost components depend on the commodity category. The transport cost is carrier specific and is based on the distance travelled. The TLC of commodity k transported between firm m in zone r to firm n in zone s, with a shipment size q using transport chain l is:

$$G_{rskmnql} = O_{kq} + T_{rskql} + Y_{rskl} + I_{kq} + K_{kq} \tag{4.5}$$

The optimal transfer points within each predefined transport chain (possible combinations between the transport modes) are determined, based on the TLC function. In the module different transfer points are checked in each predefined transport chain. The transfer point that has the minimum TLC is maintained. This procedure will be executed for each combination of zones and commodity types. The transfer chains calculated in this module will later be used by firms and forwarders to determine the optimal manner to ship their goods. In this step, an average transport rate is used, as well as the most common vehicle/vessel type, for a commodity category. The transport rate may be later adjusted by simulating price negotiations with carriers, to arrive at the real transport cost. Because these price negotiations depend on the barging power of the firm, they are not included in the 'Transport chain generation' module. The results of this module are used by firms as an initial starting point.

The transport modes used for Flanders are road (light road and heavy road), rail and inland waterways (IWW). Transport by air and sea is only considered for export and import. The load capacity of each of these transport modes is known for the different commodity categories. In this limited example a single vehicle/vessel type per transport mode is considered. The resulting 30 transport chains are given in appendix A, as presented in section 3.5.2. The transport chains that do not start or end with road transport are only possible for zones where a rail/inland waterway terminal is located.

In the 'Transport chain generation' module, transport chains are built between the different zones taken into account average shipment sizes for each commodity category. Later these shipment sizes are adjusted to the specifications of the yearly transport orders between firms, for each specific firm-to-firm relation. Not all transport chain options are allowed for every combination of zones and commodity category. Between some zones certain options will not be available.

In the rest of this section the TLC calculations are shown. As an example, this is worked out for the transport of agricultural goods between Genk and Bruges, and only for the heavy road - rail - heavy road transport chain. An average shipment size q of 1,48 tonnes is used to determine the transfer points. The average shipment size is based on the total yearly flow between all zones divided by the total amount of realised links between all zones. This gives the average yearly flow per realised link. Within the 'Transport chain generation' module a monthly shipment is considered, the average yearly flow is divided by 12 to arrive at the average shipment size used in the calculations. The yearly demand Q is 21,88 tonnes for the firm-to-firm link under consideration. From all the possible transfer points the terminals of Meerhout and Ostend leads to the lowest TLC, so these transfer points are used in this example. Other possibilities are shown in tables 4.8 and 4.9. An overview of the symbols used in this section and their description may be found in the list of symbols at the beginning of this thesis.

In the 'Transport chain generation' module additional data is used. First of all, the different kind of transport chain types that are considered and the terminal locations that may serve as transhipment point are required to build the transport chains. To calculate the TLC information on the NST/R categories, the value of the goods and average shipment size is needed. Furthermore, order cost, interest rate, warehouse cost and transport costs of each mode are required. For each link the travelling distance and time between two zones is given for each transport mode. Finally, data on capacity, (un)loading cost and frequency of the different transport modes is needed. The necessary input is given in table 4.5 and table 4.6. For each transport mode used in the Logistic module the capacity and costs are summarised in table 4.5. Also the frequency of service of each mode is given. This is used to calculate the waiting time for each transport mode. Table 4.6 gives the value of the commodities and their average shipment size for each NST/R category.

To determine the TLC per year, first the frequency of shipments is calculated and rounded up to the next integer number. This leads to a frequency of $Q/q =$

Table 4.5: Transport modes: capacity and costs

Transport mode	**Capacity (tonnes)**	**Transport cost (€/Km)**	**(un)loading cost (€/tonne)**	**Frequency (per week)**
Light Road	1,5	0,5	1	50
Heavy Road	27	1	2	10
Ship (sea)	2500	20	0,4	3
Train	1200	15	0,4	15
Vessel (IWW)	1000	9	0,4	15
Plane (air)	100	15	1	5

Table 4.6: NST/R: value and shipment size

Category	**Value (Euro/tonne)**	**Average shipment size (tonnes)**
0	442	1,48
1	672	68,4
2	60	6,4
3	983	289,12
4	163	2,5
5	941	26,29
6	50	262,98
7/8	1364	221,84
9	1437	4,64

$21,88/1,48 \approx 15$ shipments. The **order costs** is $o * f$ or $55 * 15 = 825$€ for one year.

To calculate the **transport cost**, the following formula is used:

$$[D_{ph} * TC_{hr} + D_{mh} * TC_r * [q/(0,75 * Cap_r)] + D_{eh} * TC_{hr} + q * (4 * L_{hr} + 2 * L_r)] * f \quad (4.6)$$

The assumption is made that for rail/IWW transport the transport cost are proportional to the actual capacity used. The module starts with a 75% fill level. This fill level is later on adjusted to the actual fill level in an iterative process, based on the decisions of the actors involved. This assumption is only valid if the rest of the capacity of the train/vessel is occupied by other firms and the cost may be shared.

The next cost component is the **capital cost of goods in transit**. To determine the time during which goods are in transit, a sum is made of the travel time (heavy road and rail transport) and the waiting time for a vehicle or train to be available. This sum is represented by the Total Transport time (TT). Further, the interest rate, d, and value of the goods, v, is needed. This gives the following formula:

$$\frac{TT * d * v * Q}{365 * 24} \tag{4.7}$$

This cost component has only a limited influence on the TLC. Especially for small shipment sizes with low value density, this cost is negligible.

For the **inventory cost**, the cost to store half of the shipment size (average inventory size) is calculated based on a percentage of the goods value:

$$\frac{q}{2} * w * v \tag{4.8}$$

Finally, the **capital cost of the inventory** is calculated. This is based on the same interest rate as for the capital cost of goods in transit.

$$\frac{q}{2} * d * v \tag{4.9}$$

A summary of all the costs is given in table 4.7. This procedure has to be repeated for all the possible transport chains and their transfer points. Only the transfer points with the lowest TLC are maintained for the next step.

Table 4.7: TLC: heavy road - rail - heavy road

Order cost	825 €
Transport cost	1174,36 €
Capital cost of goods in transit	1,15 €
Inventory cost	65,42 €
Capital cost of inventory	13,08 €
TLC(per year)	**2079,01 €**

Detailed calculations for the TLC of the different possible transhipment points for the transport chain ‘Heavy road - Rail - Heavy road’ are given in tables 4.8 and

4.9. Three different terminal options are investigated for the transhipment between road and rail. The combination of the terminals of Meerhout and Ostend leads to the lowest TLC.

Table 4.8: Heavy road - Rail - Heavy road: different terminal options

Heavy Road:	Genk - Meerhout:	Distance:	34,13 km
		Travel time:	30,90 min
		Waiting time:	8,6 hours
Rail:	Meerhout - Ostend:	Distance:	190,12 km
		Travel time:	142,59 min
		Waiting time:	5,6 hours
Heavy Road:	Ostend - Bruges:	Distance:	27,6 km
		Travel time:	19,98 min
		Waiting time:	8,6 hours
Q = 21,88 tonnes	q = 1,48 tonnes		
Total Logistics Cost (in Euro):	Order cost	= 825€	
	Transport cost	= 1174,36€	
	Capital cost in transit	= 1,15€	
	Inventory cost	= 65,42€	
	Capital cost of inventory	= 13,08€	
	TLC(per year)	**= 2079,01€**	
Heavy Road:	Genk - Willebroek:	Distance:	88,63 km
		Travel time:	73,09 min
		Waiting time:	8,6 hours
Rail:	Willebroek - Ostend:	Distance:	118,63 km
		Travel time:	88,98 min
		Waiting time:	5,6 hours
Heavy Road:	Ostend - Bruges:	Distance:	27,6 km
		Travel time:	19,98 min
		Waiting time:	8,6 hours
Q = 21,88 tonnes	q = 1,48 tonnes		
Total Logistics Cost (in Euro):	Order cost	= 825€	
	Transport cost	= 1953,93€	
	Capital cost in transit	= 1,14€	
	Inventory cost	= 65,42€	
	Capital cost of inventory	= 13,08€	
	TLC(per year)	**= 2846,60€**	

Table 4.9: Heavy road - Rail - Heavy road: different terminal options (continue)

Heavy Road:	Genk - Meerhout:	Distance:	34,13 km
		Travel time:	30,90 min
		Waiting time:	8,6 hours
Rail:	Meerhout - Gent:	Distance:	133,84 km
		Travel time:	100,38 min
		Waiting time:	5,6 hours
Heavy Road:	Gent - Bruges:	Distance:	50,67 km
		Travel time:	43,05 min
		Waiting time:	8,6 hours
Q = 21,88 tonnes	q = 1,48 tonnes		
Total Logistics Cost (in Euro):	Order cost	= 825€	
	Transport cost	= 1494,87€	
	Capital cost in transit	= 1,14€	
	Inventory cost	= 65,42€	
	Capital cost of inventory	= 13,08€	
	TLC(per year)	**= 2399,50€**	

The result of this step is a list of 30 transport chains between each combination of the ten zones and for each of the nine commodity categories. In our small scale set up this could lead to 24300 possible transport chains built, depending on the availability of a rail/inland waterway terminal for each zone. For each of these transport chains the optimal route and transfer points are set, based on an average shipment size.

One problem encountered with this method, is that the transfer points chosen within a transport chain depend on the average shipment size used to calculate the TLC. Starting with a small shipment size sometimes leads to favouring short main haulage distances, when consolidation is not possible. If the shipment size is changed in a later step, the chosen transfer points may no longer be optimal. So the initial shipment size chosen for each NST/R category is important. This is also shown in the sensitivity analysis in section 4.3. When the 'Transport chain generation' module has run, the transfer points are fixed for the remainder of the Logistic module. To overcome this problem for each pair of zones, three transport chains with the lowest TLC are further used in the Logistic module. This allows seeing changes in the cost structure in a later step, when shipment size is variable during the minimization of the

TLC (see section 4.2.4). This is especially useful when differences in TLC are minimal. The consolidation phase of the forwarder also works with these three transport chains (as described in section 4.2.5).

4.2.4 Determining an optimal shipment size

The results from the disaggregation step of section 4.2.2 are PC flows at a firm-to-firm level, which represent the shipments between senders and receivers. When the framework is fully operational these flows are obtained from the Market module. For each shipment, given as a yearly flow, sender and receiver have to decide who is responsible for the transport. The actor that will be responsible for the transport has to decide on the transport chain used and the appropriate shipment size. For our example of transport of agricultural commodities from Genk to Bruges the selected firms have to determine who is going to be responsible for the transport. Mostly, this will be the sender, or the firm that owns a personal transport fleet. Based on the list of the possibly transport chains from the 'Transport chain generation' module, between Genk and Bruges for the agricultural commodity category, calculations are made.

The 'Transport chain generation' module works at the level of zones and not at the level of individual firm-to-firm flows. Hence, all firms within the same zones and the same commodity type will have the same set of feasible transport chains. They will not necessarily choose the same transport chain because their yearly firm-to-firm flows are of different size. In this section the optimal shipment size for the firm is determined, whereas previously an average shipment size was used. The transport chains generated in the 'Transport chain generation' module will serve as a starting point. For each of the available transport chains created in the 'Transport chain generation' module, a shipment size is determined. At this moment, interactions between firms and carriers or forwarders are not considered. This implies that the transport rate is the same for each firm. If a firm opts to outsource the transport decisions to a forwarder, this actor will be responsible for choosing a transport chain. So, after the 'Transport chain generation' module the forwarder is contacted. He determines the optimal transport chain for each of his customers, afterwards consolidation options may be investigated. Based on common legs in the transport chains of different firms, economies of scale may be achieved by consolidating shipments. This is further discussed in section 4.2.5. In a later addition to the model the interaction with carriers will be integrated (see chapters 5 to 7 for the decisions of a carrier). This allows representing price negotiations and different transport rates depending on the offer bids of the carriers.

In the heavy road - rail - heavy road transport chain between Genk and Bruges with the rail link between Meerhout and Ostend, the optimal shipment size is determined. This is done according to method of de Jong and Ben-Akiva (2007). The TLC for different frequencies is calculated. The frequency leading to the lowest TLC is used to determine the optimal shipment size. Here the traditional economic order quantity of Harris (1913) is not used, because it does not take into account the influence of transport costs on the shipment size. In this case the transport rate of the train depends on the shipment size. For the firm-to-firm link studied in this example the yearly demand is 21,88 tonnes. For this yearly demand a shipment size of 7,29 tonnes gives the lowest TLC of 1000,05€ (table 4.10). So if in the final decision it is opted to use the heavy road - rail - heavy road transport chain, the yearly demand should be divided into shipment sizes of 7,29 tonnes, with a frequency of three shipments per year. When the economic order quantity would have been used a shipment size of 11,60 tonnes is found which corresponds to a TLC of 1104,72€.

Table 4.10: Optimal shipment size

Frequency	**Shipment size**	**TLC**
1	21,88 tonnes	1540,27€
2	10,94 tonnes	1076,74€
3	**7,29 tonnes**	**1000,05€**
4	5,47 tonnes	1020,07€
5	4,38 tonnes	1078,78€

4.2.5 Consolidation options of a forwarder

In this section attention is drawn to the consolidation options of a forwarder. As a starting point it is assumed that the forwarder has already calculated the TLC of each transport chain and this for each of his customers similar as is section 4.2.3. For each customer the three chains with the lowest TLC are considered for consolidation. Two consolidation methods are integrated in the framework as presented in section 3.5.3. First, the forwarder will attempt to consolidate shipments that have the same main haulage, constructing a connected hubs system. In the second option the forwarder will create a corridor by consolidating the common parts of the main haulage of several shipments.

4.2.5.1 Constructing a connected hubs system

As a forwarder considers terminal consolidation, only transport chains with a rail or inland waterways leg are qualified for consolidation by a forwarder. The forwarder sorts the three transport chains with the lowest TLC that are maintained for each customer, based on main haulage. They may be consolidated, if two or more shipments have a common transport leg. It is shown for the rail transport link in the example at hand, between Meerhout and Ostend.

In the initial run of the Logistic model it is assumed that trains and vessels are filled for 75% of their capacity. In the consolidation phase this level is compared with reality. If the fill level changes due to consolidation or because fewer firms make use of a certain link, it is adapted and fed back into to module to recalculate the TLC. The capacity of a train is 1200 tonnes. This means that in order to reach a fill level of 75%, it assumed that initially a train is filled with 900 tonnes.

Table 4.11: Changes in fill level due to consolidation via connected hubs

Fill level	**Used train capacity**	**Transport cost**	**TLC**
75%	900 tonnes	447,07€	1000,05€
80%	960 tonnes	442,73€	995,72€
85%	1020 tonnes	438,91€	991,90€
90%	1080 tonnes	435,51€	988,50€
95%	1140 tonnes	462,47€	985,46€
100%	1200 tonnes	429,73€	982,72€

In table 4.11 results of several levels of consolidation are given. The 75% fill level is the initial situation as in section 4.2.4. As more and more shipments, that use the terminals of Meerhout and Ostend for their main haulage via rail, are consolidated the fill level increases and the transport cost goes down. Also the TLC decreases as only the transport cost changes and all other cost components remain unchanged. If possible the forwarder should strive after a fill level of 100%, as this leads to the lowest transport cost. The transport cost decreases by 3,9% if the train can be fully loaded, compared to the initial 75%. Although this may seem as a minor change, it has to be kept in mind that the shipment size under consideration is only 7,29 tonnes. With a higher shipment size and with several deliveries per year, cost savings could add up and become more significant.

4.2.5.2 Constructing a corridor

Another possibility for the forwarder is to set up a corridor system by combining several shipments of his clients. Therefore, he may either look for shipments that have the same begin terminal or end terminal. In the example the shipments are sorted based on their begin terminal. The same procedure applies if a corridor is built when shipments are sorted based on the same end terminal. The construction of a corridor is performed after the forwarder has checked the possibilities of the connected hubs system. Shipments that are not eligible for consolidating via a common main haulage link are used to construct a corridor. In this system shipments are only consolidated for a part of the main haulage. Due to this consolidation procedure transport cost will go down because of a higher fill level, on the other hand capital cost of goods in transit may go up as goods are longer on their way due to multiple stops. The disadvantages of complex bundling systems like a corridor are also discussed in Kreutzberger (2010). Next to the longer routes, the longer operational time and potential additional exchange of load units at intermediate nodes implies higher costs.

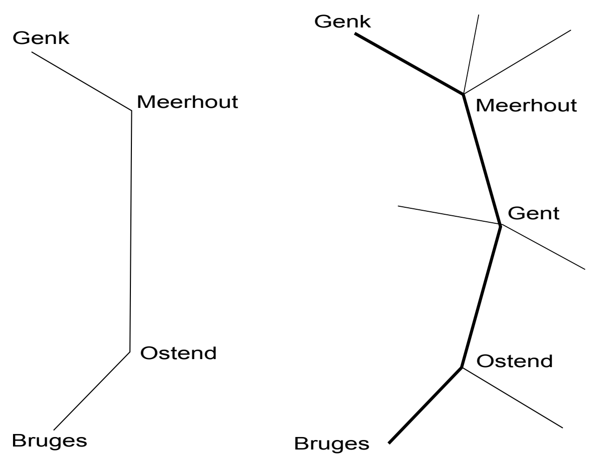

Figure 4.3: Consolidation via a corridor

In figure 4.3 the corridor constructed for the shipment between Genk and Bruges is shown. On the left the original transport chain is given with a railway connection between Meerhout and Ostend as main haulage. On the right, the constructed corridor is presented. For the shipment between Genk and Bruges the main haulage via rail is split into two sections. A stop is added in the terminal of Gent. The first part reaches a fill level of 95% due to this action. Also the second part has a higher fill level and uses 85% of the total capacity of the train. The detailed cost calculations of the TLC in case of a constructed corridor may be found in table 4.12. The total distance travelled by train increases from 190,12km to 219,65km as the train has to make a slight detour to make a stop in Gent. Also the travel time increases due to the extra distance travelled and due to the stop in Gent. For each stop an extra waiting time of 15 minutes is added for loading and unloading the train. This extra travel time has an influence on the capital cost of goods in transit. As can be seen from the calculations in table 4.12 the total logistic cost decreases slightly to 996,90€. The higher travel distance, the extra travel time and the small shipment size under consideration, lead to only a minor improvement in the TLC.

Table 4.12: TLC for the link Genk - Bruges with consolidation via a corridor

Heavy Road:	Genk - Meerhout:	Distance:	34,13 km
		Travel time:	30,90 min
		Waiting time:	8,6 hours
Rail (part 1):	Meerhout - Gent:	Distance:	133,84 km
Fill level = 95%		Travel time:	100,38 min
		Waiting time:	5,6 hours
Rail (part 2):	Gent - Ostend:	Distance:	85,81 km
Fill level = 85%		Travel time:	64,36 min
		Transfer time:	0,25 hours
Heavy Road:	Ostend - Bruges:	Distance:	27,6 km
		Travel time:	19,98 min
		Waiting time:	8,6 hours
Q = 21,88 tonnes	q = 7,29 tonnes		
Total Logistics Cost (in Euro):	Order cost	= 165€	
	Transport cost	= 443,88€	
	Capital cost in transit	= 1,18€	
	Inventory cost	= 322,37€	
	Capital cost of inventory	= 64,47€	
	TLC(per year)	**= 996,90€**	

4.3 Sensitivity analysis of the Logistic module

A sensitivity analysis can be useful in model development to determine how changes in the input parameters influence the output of the model. Several sources of uncertainty may be present in a model. A sensitivity analysis investigates how these uncertainties are spread throughout the model and which parameters are more sensitive to changes. In the presented framework several parameters can be recognized. First of all, the shipment size, q, in which goods are shipped to the customer. Next, several cost parameters exists, such as the order cost, o, the yearly interest rate, d, the value of the goods, v, the warehouse cost, w, and the transport prices of road, rail and IWW transport. A sensitivity analysis is performed to see the influences of these parameters onto the outcome of the model.

The presented parameters are changed one by one to see the influence on the 'Transport chain generation' module. It is checked whether changing these parameters leads to other transport chains becoming more attractive. For the sensitivity analysis, transport chains are build for 53 chosen links between the ten selected zones. NST/R category 1 is used in this analysis. For this NST/R category the initial average shipment size, q, is larger than the capacity of the road transport vehicles (see table 4.6). This means that several trucks need to be used for each shipment, the effect of this is studied as well. A 2^2 factorial design (Law, 2007) is developed, in which the yearly demand, Q, and the total distance between sender and receiver are the two factors studied. For each of the four factorial points two links are selected from the list of 53 constructed links to represent the high and low values. The 53 constructed links together with the selected links for the sensitivity analysis can be found in appendix B.

Within the 'Transport chain generation' module 30 transport chain options exists (appendix A). However not all of these chains will be used in the sensitivity analysis. First of all, the chains containing transport via sea or air are removed, because these chains are only used for import or export and not for transport within Flanders. Furthermore, the different links for consolidated road transport are removed, leaving 11 out of the 30 possible transport chains. Not every selected zone has access to a rail or IWW terminal, this is only available for Genk, Antwerp, Courtray and Gent. This means that six chains are considered for all of the eight selected links: light road, heavy road, light road - rail - light road, heavy road - rail - heavy road, light road - IWW - light road and heavy road - IWW - heavy road. For the links Courtray - Genk and Courtray - Antwerp an extra chain is added with a direct rail link.

From the sensitivity analysis it may be concluded that the parameter o had no influence on the outcome of the model. The order cost is linked to the frequency of shipment, which remains unchanged. For all the different transport chains the yearly order cost is the same. When the order cost o is altered, all transport chains are influenced in the same way and no changes are made in the choice of the optimal transport chain. Parameters d and v have only a limited, non-significant, influence on the total logistic cost of the different transport chains. The capital cost of goods in transit and the capital cost of the inventory represent only a small share of the total logistic costs of the transport chains. These costs are related to the parameters d and v and do not have a significant influence on the transport chain choice. This may be due to the fact that these parameters are represented in all transport chains and alter these chains in the same way. The parameter w is represented in the inventory cost. On a yearly basis this cost is equal for all transport chains, as it does not depend on the means of transport. This means that also this parameter does not influence the choice of the optimal transport chain. For the selected shipment size q and the individual transport prices of the different transport modes an influence is noted. This is further discussed in this section.

In table 4.13 the results for parameter q are given. The first column indicates the link. In the second and third column the optimal transport chain is given for different values of q. For each link different values for q are inserted to calculate the effect on the TLC and to establish breakpoints. From the table it is clear that the shipment size has an influence on the optimal transport chain. The first two links have a direct rail opportunity, which becomes attractive for large shipment sizes. For the links with a high distance (first four links) the combination of road and rail/IWW transport is the most attractive for small shipment sizes. This may be explained by the consolidation assumption that is made for transport via rail and IWW. When rail or IWW transport is combined with pre and end haulage, it is assumed that the capacity of the train or vessel is shared among the clients with an initial fill level of 75%. This makes these transport modes cheaper for small shipment sizes, as only a small share of the transport cost is paid. Due to the larger distance for these first four links the advantage is more explicit and leads to cheaper transport chains than the direct road link. When shipment size increases, more trucks are required to deliver the goods to the rail terminal and the cost increases. For the links with a low distance (last four links) light road is mostly the best option for small shipment sizes and heavy road for larger shipment sizes. The transport rate and the rate for (un)loading light road are lower than those of heavy road. This makes light road the preferred transport mode for small shipment sizes. As the shipment size increases the capacity of light road is insufficient and more trucks need to be used, this makes heavy road more appealing despite the higher transport cost. For the links Gent - Bruges (1) and Mechelen - Antwerp (2), the combination with IWW or rail transport is again the optimal transport chain with the lowest cost. No clear difference is noted between the links with a high yearly demand and the links with a low yearly demand.

Table 4.13: Sensitivity analysis of the shipment size

Link	**value for q (in tonnes)**	**Optimal transport chain**
Courtray - Antwerp	$q \leq 12$	Light Road - rail - Light Road
	$q = 13$	Heavy Road - rail - Heavy Road
	$14 \leq q \leq 238$	Heavy Road
	$q \geq 239$	Direct rail
Courtray - Genk	$q \leq 22$	Light Road - rail - Light Road
	$23 \leq q \leq 274$	Heavy Road
	$q \geq 275$	Direct rail
Antwerp - Bruges (1)	$q \leq 4$	Light Road - IWW - Light Road
	$5 \leq q \leq 11$	Heavy Road - IWW - Heavy Road
	$q \geq 12$	Heavy Road
Bruges - Antwerp (2)	$q \leq 4$	Light Road - IWW - Light Road
	$5 \leq q \leq 11$	Heavy Road - IWW - Heavy Road
	$q \geq 12$	Heavy Road
Gent - Aalst	$q \leq 3$	Light Road
	$q \geq 4$	Heavy Road
Gent - Bruges (1)	$q \leq 4$	Light Road - IWW - Light Road
	$q \geq 5$	Heavy Road
Mechelen - Antwerp (2)	$q \leq 10$	Heavy Road - rail - Heavy Road
	$q \geq 11$	Heavy Road
Mechelen - Zaventem	$q \leq 3$	Light Road
	$q \geq 4$	Heavy Road

The results from the sensitivity analysis of the heavy road transport cost, TC_{hr}, are summarized in table 4.14. The Logistic module takes a transport cost of 1€ (table 4.5) for heavy road transport. When the shipment size is 68,4 ton (table 4.6), a direct link with heavy road transport is the preferred transport chain in all cases (table 4.13). If TC_{hr} is increased different transport chains become more attractive as can be seen in table 4.14. For the links with a high distance the necessary increase in the heavy road transport cost, before choosing another transport chain, is rather small compared to the links with a low distance. For the first category the transport price is still less than 2€, while in the links with a low distance the transport cost should increase to more than 4€. Transport via rail or IWW is more attractive for larger distances.

Table 4.14: Sensitivity analysis of the heavy road transport cost

Link	**value for TC_{hr} (in euro)**	**Optimal transport chain**
Courtray - Antwerp	$TC_{hr} \leq 1,70$	Heavy Road
	$1,71 \leq TC_{hr} \leq 1,76$	Heavy Road - rail - Heavy Road
	$TC_{hr} \geq 1,77$	Light Road - rail - Light Road
Courtray - Genk	$TC_{hr} \leq 1,02$	Heavy Road
	$TC_{hr} \geq 1,03$	Light Road - rail - Light Road
Antwerp - Bruges (1)	$TC_{hr} \leq 1,95$	Heavy Road
	$1,96 \leq TC_{hr} \leq 3,37$	Heavy Road - IWW - Heavy Road
	$TC_{hr} \geq 3,38$	Light Road - IWW - Light Road
Bruges - Antwerp (2)	$TC_{hr} \leq 1,94$	Heavy Road
	$1,95 \leq TC_{hr} \leq 3,26$	Heavy Road - IWW - Heavy Road
	$TC_{hr} \geq 3,27$	Light Road - IWW - Light Road
Gent - Aalst	$TC_{hr} \leq 6,23$	Heavy Road
	$TC_{hr} \geq 6,24$	Light Road
Gent - Bruges (1)	$TC_{hr} \leq 4,31$	Heavy Road
	$TC_{hr} \geq 4,32$	Light Road - IWW - Light Road
Mechelen - Antwerp (2)	$TC_{hr} \leq 5,65$	Heavy Road
	$TC_{hr} \geq 5,66$	Light Road - rail -Light Road
Mechelen - Zaventem	$TC_{hr} \leq 5,51$	Heavy Road
	$TC_{hr} \geq 5,52$	Light Road

The influence from the transport price for rail transport is less explicit within the considered links. Only two out of the eight links had a direct rail link. Furthermore, with the shipment size of 68,4 ton heavy road is the most advantageous for all links as seen in table 4.13. When the shipment size is held constant and the price of rail transport is changed only the decision of the first two links is influence as seen in table 4.15. For all the other links heavy road remains the best transport chain. This may be explained when looking at the total logistic cost, within this cost the transport cost is the only component that changes when altering the rail transport cost. In, for example, the transport chain heavy road - rail - heavy road between Courtray and Genk rail transport takes up 24,85% of the total transport cost. The loading and unloading cost of heavy road transport on the other hand takes 64,68%. The rest of the cost is split between the (un)loading cost of rail transport and the transport via road, respectively 6,47% and 4%. This proportion is more or less the same for the other links. Hence changing the transport price of rail transport has only a limited influence on the TLC calculated within the 'Transport chain generation' module.

Table 4.15: Sensitivity analysis of the rail transport cost

Link	**value for TC_r (in euro)**	**Optimal transport chain**
Courtray - Antwerp	$TC_r \leq 4,69$	Direct rail
	$TC_r \geq 4,70$	Heavy Road
Courtray - Genk	$TC_r \leq 3,13$	Direct rail
	$3,14 \leq TC_r \leq 14,22$	Light Road - rail - Light Road
	$TC_r \geq 14,23$	Heavy Road

The sensitivity analysis of the IWW transport price shows the same pattern as rail transport prices. This time no direct IWW link exists and only for the link between Courtray and Genk a change is noticed (table 4.16). In the other links direct heavy road transport has the lowest TLC, no matter what the transport price is for IWW. In the heavy road - IWW - heavy road transport chain between Courtray and Genk, the share of IWW transport cost in the total transport cost is 21,44%. For the heavy road pre and end haulage this share is 7,32%. Again loading and unloading the heavy trucks takes up most of the transport cost, 64,77%. The (un)loading cost of the vessel is 6,48% of the total transport cost.

Table 4.16: Sensitivity analysis of the IWW transport cost

Link	**value for TC_{iww} (in euro)**	**Optimal transport chain**
Courtray - Genk	$TC_{iww} \leq 5,81$	Heavy road - IWW - Heavy road
	$TC_{iww} \geq 5,82$	Heavy Road

From the previous analysis it has become clear that the transport prices and the shipment size used to construct the transport chains have an influence on the 'Transport chain generation' module. Before further developing the proposed framework in a fully working freight transportation model a study needs to be conducted to set the correct transport prices. To overcome the influence of the initial shipment size on the chosen transport chain, several transport chains may be compared by the different actors in the next step of the Logistic module. In this step the transport chains of the 'Transport chain generation' module serve as a starting point and the shipment size is adapted to the needs of the firms involved. More transport chains (for example a top three) could be considered by the decision making actor. Then the effect of the shipment size is seen for all these chains. It may be that the best initial transport chain is not the best transport chain when the shipment size is adapted to the yearly demand of the firm. This was already stated in section 4.2.3. Future research may also look at the cost sharing mechanisms in rail and IWW transport and introduce a minimum transport price. This may exclude the effect of having very low transport prices when shipment size is small. At this moment when shipment size is small only a small share of the transport cost needs to be paid by the firm. This encourages the transport via rail or IWW for small shipment sizes. Finally, the price of (un)loading trucks needs to be further checked as this takes up the largest part in the intermodal transport chains. The transport prices of rail and IWW transport have only a limited influence within intermodal transport chains due to the high loading costs of trucks and the cost sharing mechanism due to consolidation. Future research should look at using transhipment costs instead of separating the (un)loading of the truck and the (un)loading of the train or vessel into two movements with separate costs.

4.4 Conclusions and further research

In this chapter the Logistic module of a new freight transportation framework is applied for a small selection of communities in the region of Flanders, Belgium. One of the advantages of this freight transportation framework in regard to other existing models in Belgium is the integration of logistic decisions on a firm level. Furthermore, the interactions between actors are studied within a multimodal network. Although the framework is still in a conceptual phase some points for attention may be formulated.

Difficulties are to be expected when enlarging the scale of the model, due to an exponential growth in calculations and processing time. This needs to be addressed before the framework may be implemented on a country-size scale. Further research needs to be conducted on the scale of the model. Inside in how many actors are required for the modelling of freight flows in Flanders needs to be gained. For this scaling experiments are to be conducted. As the framework is based on the interactions between the different actors future behaviour experiments may reveal more insight in the reactions of actors to policy measures. To get a better grip on the reactions and interactions of actors is of key importance for the framework. For this the decisions of the carrier is one aspect that needs to be studied. In the upcoming chapters 5 to 7 the selecting, scheduling and routing decisions of a carrier are modelled in more detail.

In this chapter, case study results of Flanders revealed that within the 'Transport chain generation' module the initial shipment size used to determine the transfer points of the different transport chains may have a large impact on the total logistic cost. More insight in the cost structure of carriers and forwarders may lead to a more realistic representation of the transport chain formation and may improve the module. Future research may also involve a study on the total logistic cost function, as some elements like safety stock are not represented yet. Furthermore, the consolidation options of a forwarder presented in the framework are an interesting concept for further research. Within the available literature on international modelling trends consolidation options are seldom studied. Consolidation decisions at terminals are part of the task of a forwarder, because he is responsible for several clients and manages larger freight flows. The consolidation of different commodity categories has to be investigated as legal and practical limitations may arise. Two different consolidation types are considered in the framework, either using a connected hub system or constructing a corridor. Other consolidation options need to be further explored.

Sensitivity analysis shows that transport prices and shipment size are the main parameters influencing the optimal transport chain. Gathering specific data for these elements seems to be necessary and a field study should be conducted. In this field study attention should be given to the (un)loading cost of the different transport modes and price sharing mechanisms for trains or vessels used by several clients. The cost of (un)loading trucks takes up a great share of the total transport cost within intermodal transport chains. Furthermore, the sensitivity analysis revealed that multimodal transport is the preferred transport chain for small shipment size. Introducing a minimum cost for the use of transport via rail or IWW or a different construction of the pricing schemes for these transport modes may overcome this problem. Hence a better representation of the actual cost in intermodal transport seems to be required.

Finally, the need exists to gather detailed data to be able to model on a microscopic level and implement the proposed framework. Not only for the Logistic module but also for the integration with the other modules in the framework these data collections need to be conducted. Future research should conduct a market study and interviews with the different agents involved.

Chapter 5

Pickup and delivery selection problem: Problem description and formulation

5.1 Introduction

The previous chapters focus on freight transportation models and the construction of a new conceptual framework. A key agent in this conceptual framework is the carrier. Chapters 5 to 7 focus on the decisions of the carrier (figure 5.1). The operational planning of every day decisions made by carriers is studied. Chapter 5 will serve as an introduction for chapters 6 and 7, as both of these chapters work with the presented model.

This chapter proposes a novel modelling approach for incorporating carrier decisions in an activity-based framework. The decisions of the carrier are formulated as a selective pickup and delivery problem (PDSP). This is a novel approach to model logistic decisions in models with the objective to explain and predict freight flows. One of the important decisions a carrier has to make is whether or not to accept a transport request in order to maximize his profit. The selection of requests in a paired pickup and delivery problem is not often studied in literature, to the author's knowledge only Schönberger et al. (2002) investigated this problem before. Next to this decision, the carrier also needs to schedule the transport orders that are accepted into the different vehicles and construct a routing plan. Both decisions are part of the

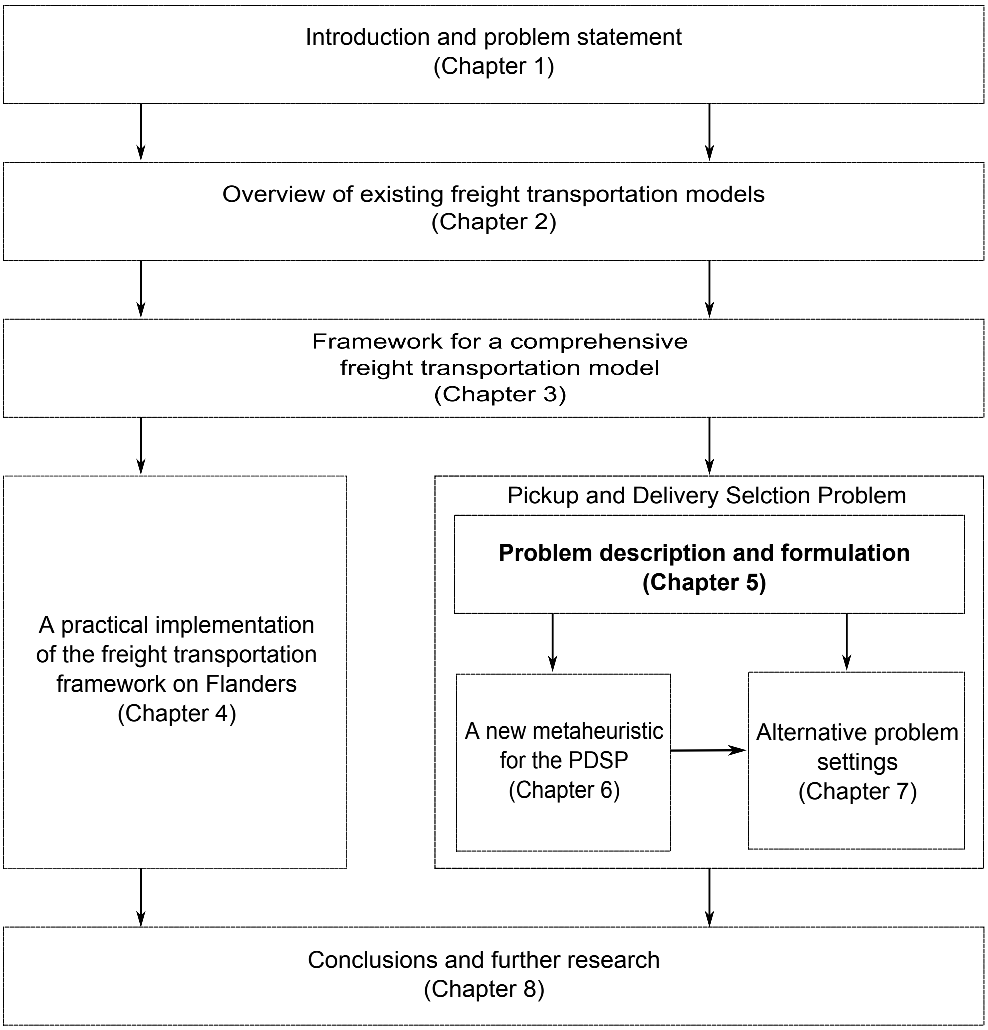

Figure 5.1: Outline of the thesis - Chapter 5

Logistic module of the framework. This allows a better representation of the influence of carrier decisions within an activity-based freight transportation model.

This chapter will particularly focus on the formulation of the PDSP. To fully grasp the problem at hand a detailed description is given in section 5.2. In section 5.3, an overview of related literature to the PDSP is given. Literature on existing vehicle routing problems with profit and other price collection problems are studied together with tradition pickup and delivery problems. The model formulation of this specific PDSP of the carrier is presented in section 5.4. To end, conclusions are drawn in section 5.5. Solution methods to solve the PDSP are proposed in chapter 6. A tabu-embedded simulated annealing algorithm is developed and applied on benchmark instances. Alternative problem settings of the PDSP are given and solved in chapter 7.

5.2 Problem description

Several actors are involved with the transport of goods. To model freight transport, the different actors involved in the decision making process have to be represented. In chapter 3 a conceptual framework is presented to model freight transport. The key actors in this framework are firms, carriers, and forwarders. These actors allow the model to work on an activity-based level, focusing on the different activities of each actor. The decision making process of carriers is one of the key aspects in modelling logistic decisions in a behaviour based transportation model (see section 3.5.1). When modelling at an activity-based level, the behaviour of carriers has to be taken into account. One of the decisions a carrier has to make is whether or not to accept transport requests he receives. Furthermore, he needs to plan the sequence of pickups and deliveries to optimize the use of his vehicles given time and capacity limitations.

A carrier faces the daily problem of optimally scheduling his transport orders. Each day a carrier receives transport requests from his clients, which have to be executed within a certain time period. To obtain a maximal profit, the carrier has to group certain orders and create an optimal sequence of paired pickup and delivery tasks. In literature, this problem is called a pickup and delivery problem (PDP). Within a PDP the assumption mostly made is that all requests have to be fulfilled. In reality a carrier may refuse a transport order, when he believes this order is not profitable. Sometimes non-profitable orders are accepted, due to reasons of competition or long-term commitment to a client. In that case a carrier accepts the transport order which is less or non profitable, because it will generate other requests with a profit high enough to offset the loss of the first transport order. Multi-period decisions will be studied in chapter 7. In our conceptual framework (figure 3.2) only current requests are taken into account and the possible loss of future requests is ignored. Actors take decisions for one simulation period at a time. If a request is accepted, it will generate revenue when the transport is completed. When a carrier has to decide whether to accept a certain request, the problem is defined as a Pickup and Delivery Selection Problem (PDSP). This problem has been introduced by Schönberger et al. (2002) and will form the object of this chapter.

5.3 Related literature

The PDP is a generalization of the vehicle routing problem (VRP), which is a generalization of the travel salesman problem (TSP) (Mitrović-Minić, 1998). All of these problems have been widely investigated and numerous extensions have been developed. In a VRP generally all trip requests either originate or terminate at the depot. In a PDP the trip requests are made between two locations that are outside the depot. In this chapter the division between paired and unpaired pickup and delivery points is used as in Parragh et al. (2008). Pickup and delivery vehicle routing problems are characterised with unpaired pickup and delivery locations. In this case an identical load is considered, and each unit picked up may be used to serve a delivery request. A classical pickup and delivery problem on the other hand, has paired pickup and delivery locations. Every request is associated with a paired origin and destination location and a specified load. The problem described in section 5.4 considers paired pickup and delivery points.

In this section a review of existing literature is made. The focus is on a specific case of the PDP, the pickup and delivery selection problem. In a PDSP not all transportation requests have to be fulfilled. A carrier receives transportation requests during the entire day. When new requests are received, a decision has to be made whether the carrier will take the responsibility of the transport or not. The PDSP is NP-hard as it is a generalization of the travelling salesman problem. In literature this problem is not often investigated, but several variations on the problem exist. Two main bodies of routing literature are relevant for the PDSP. On the one hand VRP with profits and on the other hand literature concerning PDP. The PDP is more relevant to the problem presented, however profit maximization has been more applied to VRP. In the next subsection first several vehicle routing problems with profits are presented, as the PDSP may be seen as a variation of these problems. Next, techniques used on PDP are discussed which might be useful for the PDSP (subsection 5.3.2). To end this section the available literature on PDSP and variants of the problem are given (subsection 5.3.3).

5.3.1 VRP with profits

Feillet et al. (2005) give an overview of the TSP with profits. A distinction is made between three problem types, depending on the objective function. A first problem is called the profitable tour problem (PTP), which has as objective to simultaneously find a tour that minimizes travel cost and maximizes the collected profit. The problem studied in this paper, the PDSP, may be situated in this category. The second problem, the orienteering problem (OP), has as objective to maximize the collected profit while travel costs do not exceed a preset maximum cost. This last constraint is also known as the knapsack constraint. The last problem is known as the prize-collecting TSP (PCTSP). Here the collected profit is defined as a constraint, ensuring that the profit may not be smaller than a preset value. This has to be achieved while minimizing travel costs.

Also vehicle routing problems exist for which it is not necessary to visit every node on the graph. The VRP with profits is the extension of a TSP with profits to multiple vehicles. Aksen and Aras (2005) study the single-depot capacitated VRP with profits and time deadlines (VRPPTD), in which it is not necessary to visit all customers. Their objective is to find the number and routes of vehicles to maximise the total profit. They propose an iterative marginal profit analysis method (iMPA) to solve this problem. First, the given problem instance is solved as a VRP with time deadlines using simulated annealing (SA). For the current set of routes iMPA is applied until the marginal profit of each remaining customer is positive. The iMPA computes for the current set of routes each customer's marginal profit. These values are sorted in nondecreasing order. If the marginal profit of the customer with the lowest marginal profit is positive, then iMPA is stopped. Otherwise, the customer is deleted from the current route. This is repeated for all customers with a negative marginal profit. Empty routes are removed. If iMPA modifies the set of visited customers, the process is repeated. Starting with a new set of customers, the VRP is again solved with SA. When the iMPA does not modify the set of visited customers, the profit of all routes is checked. The heuristic stops when the profit of all routes is positive. Otherwise, for each route with a nonpositive total profit the customer with the lowest marginal profit is dropped until the total profit of the route becomes positive. In Thorson et al. (2004) Integrative Freight Market Simulation (IFMS) is presented, in which a multiple vehicle routing problem with profits and competition (MVRPPC) is used. Three main differences with traditional multivehicle routing problems may be noticed. First, competition in the form of multiple carriers is incorporated into the process. Second, instead of minimizing cost, the objective is to maximize profits. Third, trucks leave and return to their home bases empty, as they are hired from external carriers. The solution method takes a "cluster first, route second" approach in which the clustering phase combines a geometric clustering with a generalized assignment problem (GAP). The routing is performed using tabu search. The Multiple Tour Maximum Collection Problem (MTMCP) of Butt and Ryan (1999), is closely related to the VRP with profits. Due to limited availability of time not all nodes may be visited. Only nodes which give the highest contribution in terms of profit are selected. An optimal solution procedure for the MTMCP is described. This procedure is based on a generalized set-partitioning formulation and uses constraint branching and tour storage techniques to improve solution time.

5.3.2 Pickup and delivery problem

The pickup and delivery problem is used to find optimal routes, for a fleet of vehicles, to satisfy a set of transportation requests. Almost every practical PDP problem is restricted by several time constraints (Mitrović-Minić, 1998). First, time windows determine when a load may be picked up or delivered at a certain location. Next, drivers of vehicles are restricted in their use by time windows. In most countries drivers may only drive a certain amount of time and are obligated to respect rest moments. When executing a PDP, pairing and precedence constraints have to be satisfied. The pairing constraint demands that both pickup and delivery of the load have to be executed by the same vehicle. The precedence constraint requires that the pickup is performed before the corresponding delivery of the load. In this section the main characteristics of paired or one-to-one pickup and delivery problems are presented. This means that each request originates at a single location and is meant for another destination (Cordeau et al., 2008).

Pickup and delivery problems may be divided into dynamic and static problems (Savelsbergh and Sol, 1995). In a dynamic problem not all request are known in advance, but may be received during the entire simulated period. Routes are constructed with the requests known at that time. When a new transportation request becomes available at least one route has to be adjusted. In a static problem all requests are known when the routes are constructed and no later adjustments to the planning are required. In this chapter the PDSP is defined as a static problem, with all requests known in advance.

Within the PDP various objective functions are used, depending on the purpose or criteria of the research. In Savelsbergh and Sol (1995) an overview is given. The most common objective functions used by single vehicle problems are mainly related to minimizing duration, completion time, travelled time or client inconvenience. Problems with multiple vehicles mostly try to minimize the number of vehicles or maximize profit, this while minimizing the distance travelled or the travel time. This is also the case in Li and Lim (2001) their objective function exists of four elements. First the number of vehicles is minimized, than total travel cost and total schedule duration and finally the drivers' total waiting time is minimized. The maximization of profit, leads us to the pickup and delivery selection problem, which is only rarely applied within PDP.

Next, the main solution techniques used in PDP are presented, as they may be helpful to solve the PDSP. Metaheuristics were designed in order to attack complex and difficult combinatorial optimization problems that arise in many practical areas (Mitrović-Minić, 1998). Nanry and Barnes (2000) present one of the first metaheuristics for Pickup and Delivery Problems with Time Windows (PDPTW). The authors make use of a reactive tabu search which alternates between three move neighbourhoods. The first local search operator tries to move a pair from its current route to another route. In the second move neighbourhood pairs are exchanged between two different routes. The last one polishes routes by moving individual nodes forward or backward in their routes. The heuristic is tested on instances up to 50 requests. Li and Lim (2001) use a hybrid metaheuristic to solve their own benchmark instances. A simulated annealing algorithm is used combined with tabu search. The simulated annealing algorithm restarts from the current best solution after several iterations without any improvement. After K restarts without improvement the algorithm is ended. The visited solutions are recorded into a tabu set to avoid cycling. A large neighbourhood search is proposed by Bent and Van Hentenryck (2004) to solve the PDPTW. In their objective function the number of routes created and the total travel cost is minimized. The heuristic makes use of a two-stage hybrid algorithm. The first stage uses a simulated annealing algorithm to minimize the number of routes by only relocating pairs of customers. In a second stage the total travel cost is minimized by means of a large neighbourhood search. Also Ropke and Pisinger (2006) propose a large neighbourhood search. The objective function consists of three elements: distance travelled, time spent by each vehicle and number of requests in the request bank. If a request may not be assigned to a vehicle, it is placed in the request bank. For the neighbourhood search they apply three different request removal heuristics and two insertion heuristics. Requests are removed from a route either based on their similarity (shaw removal heuristic), their cost (worst removal heuristic) or at random (random removal heuristic). To insert the requests either a basic greedy heuristic is used choosing the request with the lowest overall cost or a regret heuristic based on the regret value of not inserting the request in his best route. In the adaptive large neighbourhood search, removal and insertion heuristics are chosen on a roulette wheel selection principle, with weights assigned to each heuristic. Xu et al. (2003) expand the problem by including extra real-life constraints, such as multiple time windows, compatibility constraints and maximum driving time restrictions. A column generation heuristic is used to solve the problem.

5.3.3 Pickup and delivery selection problem

Only few research articles investigate **Paired pickup and delivery problems** in which profits determine the acceptance of an order. The PDSP adds complexity to the traditional PDP as it requires selecting which subset of nodes in the graph to visit, as well as determining the order of visits in each tour. Another difficulty is added when the nodes are also restricted by time windows. Schönberger et al. (2002) consider the PDP in which not all nodes have to be visited to maximize profit. In this problem orders may be less-than-truckload. A hybrid algorithm is presented to solve the problem. The hybrid algorithm is composed of a genetic algorithm that is seeded by a parallel route construction heuristic. The construction heuristic generates a feasible solution by assigning requests to vehicles based on their order on a time axis. Requests that violate the capacity or time window restrictions are removed from the routes. After the construction heuristic, improvements are made using a genetic algorithm. Schönberger (2005) divides requests into two categories: tactical requests and operational requests. **Tactical request** acceptance problems require a general decision about the future acceptance of different requests. Mostly, this type comprises all requests of a certain customer. Due to the long-term acceptance of certain requests, it may be necessary to require medium- or long-term investments for additional transport or transhipment resources. The general acceptance is recommended only if the agreed revenues cover the sum of necessary investment and operation costs. In **operational request** acceptance problems, the carrier company has to decide about the acceptance of particular requests, which are not part of long-term contracts. Such a request is accepted if expected revenues cover expected additional costs caused by this additional request. If a carrier refuses a customer demand, it may be expected that also all other requests of this customer are lost for this carrier. According to Schönberger (2005) lost revenues cannot be adequately incorporated into the calculation of the profitability of a request. This is further studied in chapter 7 with the introduction of a multi-period PDSP. In our problem statement (Section 5.4) we focus on the acceptance of operational requests. In Arda et al. (2008), a profitable PDP with time windows is presented. The authors study orders of full truckload and try to maximize global profit while respecting time windows. To solve this NP-hard problem genetic algorithms are used. First a parent of an ordered set of transportation orders is made. A feasible solution can be extracted by choosing successively the first order that fits the time windows constraints. Schönberger et al. (2002) and Arda et al. (2008) use homogenous vehicle fleets and propose static models. They do not take into account a fixed cost of using an additional vehicle. Also Frantzeskakis and Powel

(1990) investigate the PDSP. In their case a dynamic aspect is added and only full truckloads are considered. The carrier decides which loads he will accept or refuse and how many vehicles to relocate in order to maximize the total expected profit over a planning horizon.

Verweij and Aardal (2003) study in their merchant subtour problem the selection of optimal locations to buy and sell products. A selection is made so that the merchant may optimize his profit. The problem is a variation of the PDSP, in which only a single vehicle is considered.

Kleywegt and Papastavrou (1998) propose a problem in which transport is done between terminals in long haul shipments. Vehicles are either at a terminal or en route between two terminals. The selection of clients happens at a terminal after which their loads are consolidated into vehicles and direct transport to a terminal is conducted. This leads to a full truckload problem in which clients are concentrated at terminals and not spread out in the area.

In Ting and Liao (2012) a selective pickup and delivery problem (SPDP) is formulated. This may be seen as a variant of the PDSP in the case of **unpaired pickup and delivery nodes**. In the SPDP the constraint that all pickup nodes must be visited is relaxed. The objective is to find the shortest route for visiting all delivery nodes, without necessarily visiting all the pickup nodes as the nodes are not paired and only a single commodity is taken into account. The problem is solved using a memetic algorithm that allows to simultaneously deal with the selection of pickup nodes and the visiting order of nodes.

Another option within the PDP instead of not visiting all nodes is to outsource some of the requests to a third party logistic player. Schönberger (2005) investigates the possibility to make use of a logistic service provider (LSP). In this case all requests are divided between either the own vehicle fleet or the LSP. Routes have to be established for the own vehicles and the sum of charges to be paid for all externalized requests has to be minimized. Krajewska and Kopfer (2009) also study a PDP where the carrier has the possibility to outsource transport requests. They make use of a tabu search algorithm to solve their Integrated Transportation Planning Problem (ITPP). The main difference with other studies that include outsourcing is the use of three different outsourcing types instead of one. A first group of subcontractors works nearly exclusively for the carrier and is paid on tour basis. The second group of exclusively employed subcontractors is paid on a daily basis. The last group consists of independent subcontractors which are not employed exclusively.

This chapter offers the following novelties compared to existing research. The traditional PDP is extended to a PDSP by allowing a selection of transportation requests. This leaves the carrier with the option to discard transportation requests which lead to a lower total profit. Next to the planning and scheduling of vehicles into routes as in a classical PDP, a selection within the transportation requests has to be made. The problem at hand considers more than one commodity and paired pickup and delivery locations. This is different to the study of Ting and Liao (2012) where a single commodity is considered and pickup and delivery are unpaired. Furthermore, multiple vehicles are considered and transport loads are less-than-truckloads. In the study of Verweij and Aardal (2003) only a single vehicle is assumed and in the work of Arda et al. (2008), Frantzeskakis and Powel (1990) and Kleywegt and Papastavrou (1998) full truckloads are investigated. The paired pickup and delivery locations, together with the multiple vehicles and less-than-truckload requests make the PDSP very hard to solve. The only paper that studies a PDSP with similar problem characteristics but in a different problem context is Schönberger et al. (2002). However, the authors apply a different solution strategy than the one proposed in chapter 6 and the described benchmark data are not available. Their heuristic results are not compared to exact solutions or lower bounds and reported results are only briefly described. This hinders the possibility to compare computational results. In the remainder of this chapter the model is formulated in section 5.4.

5.4 Problem formulation

In this section a mathematical representation of the problem is given. First, the key characteristics of a PDSP are described. Next, all symbols that are used are presented and the objective function and corresponding constraints are formulated. The problem is defined as a static PDSP problem. The formulation is an adaptation of the PDPTW formulation of Mitrović-Minić (1998) and is extended to include the selection of requests.

5.4.1 Key characteristics of a PDSP

To represent logistic decisions within an activity based freight transportation model (chapter 3), the decisions of a carrier have to be modelled. First, the key characteristics related to this problem are presented. This allows formulating a PDSP model in the next subsection.

First of all, not all requests have to be accepted. Every fulfilled request leads to revenue. If a request is accepted, a reward is achieved when the transport is done successfully. For every request a time window is assigned to the pickup and delivery location. In the problem definition at hand, only hard time windows are considered. A request consists of less-than-truckloads. Furthermore, pickup has to occur before delivery of each request (Precedence constraint) and pickup and delivery have to be performed by the same vehicle (Pairing constraint). In our model multiple vehicles are used and it is assumed that capacity is the same for all vehicles. All vehicles depart from and return to a depot of the carrier. Finally, travel costs and travel times for each link are known and assumed to be constant.

5.4.2 Introduction of symbols

Requests A carrier receives a set P of requests. Because the set of requests is equal to the number of pickup locations the same symbol is used in both cases. Each request $r \in P$ consists of a pickup location p_i, a delivery location d_{i+n}, a quantity to be shipped q_i and a revenue Rev_i if the request is completely satisfied. So each request is given as a quadruple, $r = \{p_i, d_{i+n}, q_i, Rev_i\}$. The quantity q_i may either be a positive or negative number, depending on the type of operation, either a pickup or a delivery task.

Locations Three different types of locations may be distinguished, each with their own time window. A set of pickup locations $P = \{1, ..., n\}$ and a set of delivery locations $D = \{n+1, ..., 2n\}$ are included, each with an earliest operation time e_i, a latest operation time l_i and a quantity q_i that needs to be shipped or delivered. A single depot O is available, where each vehicle starts and ends his route. If this is a start location, the depot is denoted as node 0. For an end location the notation $2n+1$ is used for the node.

Network A network $G(A, N)$ is given, with $N = P \cup D \cup O$, the set of nodes and A a set of undirected arcs. Within the network the distance between two nodes i and j is given as d_{ij}. The travel cost ct, expresses the charge for travelling a single distance unit. The cost to travel a certain link is expressed as $ct \cdot d_{ij}$. The last variable on the network is t_{ij} which stands for the time needed to travel from node i to node j.

Vehicles The carrier has a given homogenous fleet K of own vehicles. Each vehicle k has a maximum capacity of Q_{max}. Vehicles are bound in time by their driver, who is subject to legal driving time restrictions. Only the total amount of driving hours is checked, not the daily rest requirements. Making the assumption that a carrier has the same amount of drivers as vehicles, each vehicle has a start time s_k and a finish time f_k. The difference between f_k and s_k may not exceed the legal driving time of the driver. To keep track of the content of the vehicle, so that it will not exceed the maximum capacity, load variables L_i^k are introduced.

Operations A vehicle has to perform several operations on its route. Each pickup and delivery task takes a certain amount of operation time ot_i to perform per unit that needs to be handled. The total time a vehicle spends at the pickup or delivery location, can be found as follows: $ot_i \cdot q_i$. Due to the hard time windows applied at each pickup and delivery location, a vehicle cannot start his pickup operation until after time e_i. The vehicle is allowed to arrive earlier at the location, but must then wait until the start of the time window. A vehicle may never arrive to a location after the end of the time window l_i. Different waiting protocols may be defined depending on the solution heuristic used. It may be preferred to drive first and wait at the arrival location or to wait first at the previous location and then drive. The empirical study of Mitrović-Minić and Laporte (2004) shows that the wait first strategy has the potential to build shorter routes compared to drive first in case of dynamic planning problems. Waiting at the starting positions results in more requests being known at the time they leave and a better potential to optimize the route. On the other hand the study revealed that the wait first strategy requires much more vehicles for the same set of locations. Therefore, a new waiting strategy (advanced dynamic waiting) was introduced. Here the drive first and wait first strategy are combined by serving locations in one service zone according to the drive first strategy and apply the wait first strategy between different service zones. This strategy was able to outperform the common used drive-first waiting strategy (Mitrović-Minić and Laporte, 2004). For static vehicle routing, as the problem at hand, drive first is the most commonly used waiting strategy and will be used for the PDSP.

Variables For this problem two groups of binary variables are defined.

$$\begin{aligned} X_{ij}^k &= \text{binary flow variables} \\ &= 1 \text{ if vehicle } k \text{ travels from } i \text{ to } j \\ Y_i^k &= \text{binary request acceptance variables} \\ &= 1 \text{ if vehicle } k \text{ performs request } i \end{aligned}$$

Next to these binary variables, two groups of continuous variables are introduced.

$$\begin{aligned} T_i^k &= \text{time variables} \\ &= \text{time of vehicle } k \text{ after node } i \text{ is served} \\ L_i^k &= \text{load variables} \\ &= \text{load of vehicle } k \text{ after serving node } i \end{aligned}$$

5.4.3 Objective function

The objective of the PDSP is to maximize the profit collected along the vehicle tours. Profit is defined as the sum of the total revenue collected on all the tours minus the total cost of performing the tours.

$$Profit = Revenue - Cost$$

For the revenue (Rev) a table is created which stipulates the price of the transport order in function of the distance to be travelled. In chapter 7 a different revenue model for the carrier is proposed. The total revenue is found by accumulating all revenues of the requests that are accepted and executed (equation (5.1)).

$$Rev_{tot} = \sum_{k \in K} \sum_{i \in P} Rev_i \cdot Y_i^k \tag{5.1}$$

The total cost (C_{tot}) is calculated as the sum of the costs of each link travelled by a certain vehicle k. In this case the cost is only related to the distance being travelled. No fixed cost component is enclosed for the use of a vehicle. The assumption is made that a carrier has a fixed vehicle fleet at his disposition and no extra cost is imposed for the use of the vehicles.

$$C_{tot} = \sum_{k \in K} \sum_{i \in N} \sum_{j \in N} ct \cdot d_{ij} \cdot X_{ij}^k \tag{5.2}$$

The objective function which needs to be maximized is:

$$\max \left[Rev_{tot} - C_{tot} \right] \tag{5.3}$$

$$\max \sum_{k \in K} \left[\sum_{i \in P} Rev_i \cdot Y_i^k - \sum_{i \in N} \sum_{j \in N} ct \cdot d_{ij} \cdot X_{ij}^k \right] \tag{5.4}$$

5.4.4 Constraints

In this section the constraints to which the objective function is subjected are formulated. The constraints are grouped according to their function.

Flow conservation constraint This constraint (5.5) is introduced to make sure that vehicles entering a location will also leave this location.

Vehicle constraints Each vehicle starts and ends his tour in the depot O. If a vehicle is not used it stays at the depot. This is represented by restrictions (5.6) and (5.7). Every request may only be executed by at most one vehicle (5.8). Constraint (5.9) states that a vehicle cannot load more freight than its maximum capacity. To keep track of the load of a vehicle at a certain moment, the following constraints (5.10) and (5.11) are necessary. Each vehicle leaves and arrives back at the depot empty.

Time window constraints Each node has to be served within its time window. The start of the operation, as well as the end of the operation has to fall within the time window (5.12). This is similar to the time windows defined in Mitrović-Minić (1998) and Schönberger and Kopfer (2004). To keep track of time, a time variable is introduced. To start, the time variable is set equal to the start time of the vehicle (5.13). A vehicle may not exceed his finish time (5.14). The time variable is increased after every operation. The time after service at a certain node, is found by adding the travelling time and operation time to the time variable after serving the previous node. Also the time windows have to be respected, so that the arrival time at a node may not precede the earliest operation time allowed on that location. This is specified in constraint (5.15). Due to the time window constraint on T_i^k, it is assured that the operation does not start before e_j.

Pairing and precedence constraints If a request is performed, then vehicle k has to finish its operations at the pickup location i before he can visit the associated delivery location $n + i$. This is known as the precedence constraint (5.16). It is not allowed to split a request over more vehicles. A vehicle has to perform both the pickup and the delivery activity. This is known as the pairing constraint ((5.17) and (5.18)).

In the formulation given on the next page big M-values are used, where M needs to be a sufficient large number. However, the value of the big M is best kept as small as possible. For this reason two different M-values are considered. In the examples given in the next chapter this depends on the data set used. For constraint 5.11 M_1 is set to the maximum load capacity of the vehicles. In constraints 5.15 and 5.16 the maximum length of a working day is considered for M_2.

$$\sum_{\substack{j=1 \\ j\neq i}}^{N} X_{ij}^k - \sum_{\substack{j=1 \\ j\neq i}}^{N} X_{ji}^k = 0 \qquad \forall i \in N, \forall k \in K \qquad (5.5)$$

$$\sum_{j\in P} X_{0j}^k \leq 1 \qquad \forall k \in K \qquad (5.6)$$

$$\sum_{i\in D} X_{i(2n+1)}^k \leq 1 \qquad \forall k \in K \qquad (5.7)$$

$$\sum_{k=1}^{K} Y_i^k \leq 1 \qquad \forall i \in P \qquad (5.8)$$

$$L_i^k \leq Q_{\max} \qquad \forall i \in N, k \in K \qquad (5.9)$$

$$L_0^k = 0 \qquad \forall k \in K \qquad (5.10)$$

$$L_j^k - L_i^k - \mid q_j \mid \geq -M_1 \cdot (1 - X_{ij}^k) \qquad \forall i, j \in N \wedge i \neq j, \forall k \in K \qquad (5.11)$$

$$e_i + ot_i \cdot \mid q_i \mid \leq T_i^k \leq l_i \qquad \forall i \in N \backslash O, \forall k \in K \qquad (5.12)$$

$$T_0^k = s_k \qquad \forall k \in K \qquad (5.13)$$

$$s_k \leq T_i^k \leq f_k \qquad \forall i \in N, \forall k \in K \qquad (5.14)$$

$$T_i^k + t_{ij} - T_j^k + ot_j \cdot \mid q_j \mid \leq (1 - X_{ij}^k) \cdot M_2 \qquad \forall i, j \in N, \forall k \in K \qquad (5.15)$$

$$T_i^k + t_{i(n+i)} - T_{n+i}^k \leq (1 - Y_i^k) \cdot M_2 \qquad \forall i \in P, \forall k \in K \qquad (5.16)$$

$$\sum_{j\in N\backslash O} X_{ij}^k = Y_i^k \qquad \forall i \in P, \forall k \in K \qquad (5.17)$$

$$\sum_{j\in N\backslash O} X_{j(n+i)}^k = Y_i^k \qquad \forall i \in P, \forall k \in K \qquad (5.18)$$

$$X_{ij}^k \in \{0, 1\} \qquad \forall i, j \in N, \forall k \in K \qquad (5.19)$$

$$Y_i^k \in \{0, 1\} \qquad \forall i \in P, \forall k \in K \qquad (5.20)$$

$$T_i^k, L_i^k \geq 0 \qquad \forall i \in N, \forall k \in K \qquad (5.21)$$

5.5 Conclusions

In this chapter the decisions of a carrier in a freight transportation model is studied. A pickup and delivery selection problem is formulated to represent the decisions of a carrier. The problem is defined on an operational planning level, this is a novel technique for modelling carriers in transportation models. The focus is on the selection and routing of transport requests done by carriers. The selection of paired pickup and delivery request in order to maximize profits is only seldom studied in literature. To solve the PDSP solution heuristics are developed and tested on benchmark data in chapter 6. Problem variants to the PDSP are formulated and solved in chapter 7.

Chapter 6

Pickup and delivery selection problem: A new metaheuristic for the PDSP

6.1 Introduction

In the previous chapter, an operational planning problem of carriers in freight transportation models is presented. A solution approach using simulated annealing combined with tabu search is proposed in this chapter (figure 6.1). This metaheuristic allows a more thoroughly search for the optimum solution than local search algorithms and prevents the solution to get stuck in a local optimum. To test the proposed algorithm two sets of benchmark data are used. First, the benchmark data of Li and Lim (2001) is adapted so that it may be used for the PDSP. Because the data of Li and Lim (2001) was originally designed for a PDP with time windows, the results may not be fully compared. To further test the algorithm new benchmark data sets are created using a full factorial design. Some smaller instances are generated from our new benchmark data to be solved to optimality. Also the effect of relaxing time windows within the benchmark data set is studied.

The chapter is organized as follows. In sections 6.2 and 6.3 the insertion heuristic and local search operators are given. Two examples are used to show the working of the algorithm in section 6.4. An experimental design to test the algorithm is set up in section 6.4.3. Next, in section 6.5 the tabu-embedded simulated annealing

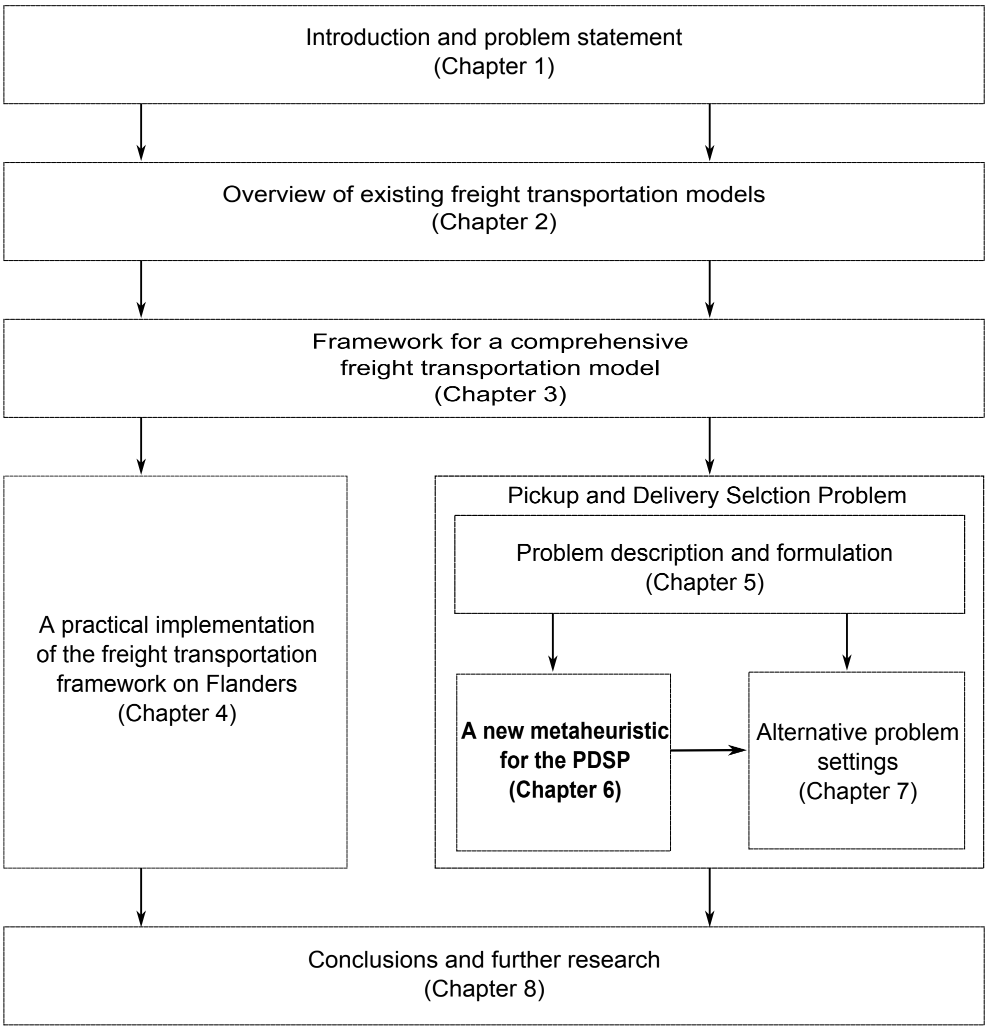

Figure 6.1: Outline of the thesis - Chapter 6

metaheuristic is presented in detail. The results of the algorithm on the benchmark data of Li and Lim (2001) and on the new benchmark data are discussed afterwards. Finally, conclusions are drawn in section 6.6.

6.2 Insertion heuristic

An insertion heuristic is used to generate an initial solution for the PDSP, which will be improved later by a local search heuristic. The insertion heuristic assigns requests to routes by means of a parallel insertion procedure. In the PDSP more transport requests are available than the carrier is able to accept with its fixed vehicle size. Hence all vehicles will be used. Therefore, it is opted to use a parallel insertion heuristic. With a sequential approach the high number of transport requests would take longer to asses one by one in order to find the best request to insert. Besides the danger of creating too many routes does not exist in this case, as the number of vehicles is limited and all vehicles will be used. The heuristic starts with only one vehicle. The goal is to have an initial solution which is feasible. Allowing infeasible solutions will increase the run time and add extra complexity to the algorithm. Therefore, it is opted to only check for feasible solutions. Some checks for infeasibility, such as time window violations, may be performed during the algorithm. This will eliminate certain routing options and decreases the run time. Future research may consider allowing infeasible solutions to see if this may approve the solutions found. The initial solution found by the insertion heuristic is further improved by four local search operators described in section 6.3.

For each route the following data are tracked during the execution of the heuristic procedure: the total revenue and total cost of a route, which requests are already accepted by the carrier, the order in which the requests are performed and the total load of the vehicle after serving a node. Also time data are collected, such as the earliest possible arrival time and the latest allowed arrival time at a node and the time after which the node is served (T_i).

First all requests are sorted in increasing order based on the start time of the pickup node. The first request of the ordered list is inserted in the first vehicle if it is profitable, otherwise the request is not served and the next request in the ordered list is considered. If the request is profitable, pickup and delivery are inserted directly after each other into the route of the first vehicle. After inserting the request, the parameters of the route mentioned above are updated. The total cost is increased with the extra distance necessary to complete the request times the cost per kilometer. The earliest starting time et_i a vehicle can start service in node i, depends on the earliest starting time of the previous node j:

$$et_i = Max\{et_j + ot_j \cdot |q_j| + t_{ji}; e_i\} \tag{6.1}$$

The next request in the ordered list is inserted in the best route in which a feasible insertion is possible. The best route is the route that causes the highest increase in profit when inserting the request. If the request can be inserted into one of the current routes, the pickup and delivery nodes are placed in the position leading to the highest profit. Both nodes are inserted independently and are not required to be placed next to each other. Every possible insertion point is checked, taking into account the precedence constraint and removing infeasible links due to time window constraints. If the request cannot be inserted in an existing route, a new vehicle is added. The pickup and delivery node of the request are inserted as first items of this route, if the request is profitable. Vehicles are added as long as the maximum number of vehicles allowed is not reached. When no profitable insertion is possible and all vehicles are in use, the request remains unserved for now.

To determine the best route for inserting a request, the profit of each vehicle is calculated after inserting the current request at its lowest cost position. To calculate the profit of a route, the difference between total revenue and total cost is taken. The cost is based on the distance travelled to serve a request. If a new route is profitable, the time windows of the current request are checked. This is done in two phases, first the pickup node is checked and afterwards the delivery node. If both nodes are served within their time window and the total route is profitable, the request can be inserted into the route. This is done for each route. The route with the highest increase in profit is selected to insert the current request.

At the end of the insertion heuristic, parameters of the route are calculated. First, lt_i is specified. This is the latest possible moment a vehicle may arrive in node i that still allows the service of the node to be completed in time. After that, T_i, the time after service for each node i, is calculated.

Calculation of lt_i, starts at the end of the route and calculates back to the first node. The latest possible arrival time of a vehicle k at node i, with node j as the next node in the route is equal to:

$$lt_i = Min\{lt_j - t_{ij}; l_i\} - ot_i \cdot |q_i| \tag{6.2}$$

For T_i, the program starts at the first node of the route and works forward to the end node (depot). The time T_i after serving node i is:

$$T_i = Max\{T_j + t_{ji}; e_i\} + ot_i \cdot |q_i| \tag{6.3}$$

The initial solution generated by the insertion heuristic is first optimized with the REORDER operator (figure 6.2). The operator tries to lower costs by reordering the nodes within the existing routes. As no new requests are added, the revenue remains the same. Hence to increase the profit, the cost for executing a route has to go down. The cost is lowered when total distance, the only cost driving factor, decreases. The operator tries to improve the original route by serving pickup points earlier in the route and delivery nodes later. In one iteration a single node is reordered, either a pickup node or a delivery node. A node is only moved by a single place at the time. This ensures that the precedence constraint is respected. Nodes are only reordered in the route if it leads to a lower cost and the solution is still feasible. This is checked by means of three tests:

- The first test checks whether the capacity of the vehicle is not exceeded at any point in time during the execution of the route. Changes in capacity are recalculated for the new route.
- A second test checks whether the two nodes which are reordered are still served within their time windows. These two nodes are located next to each other and are only switched from place.
- Finally, the cost of the new route is compared with the cost of the original route. This is done by comparing the distance before and after the two nodes that are interchanged. The distance between the two nodes is in both directions the same and thus stays the same in the new route.

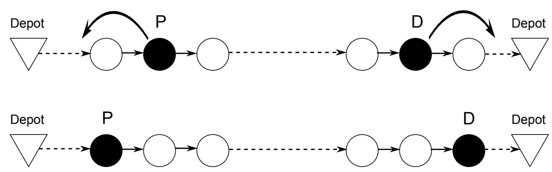

Figure 6.2: REORDER operator

At the end of the improvement heuristic described in section 6.3 this operator is repeated in a post-optimization phase. Algorithm 1 gives the pseudocode for the insertion heuristic. PostOptimize() is used to refer to the REORDER operator.

6.3 Improvement heuristic

Four local search operators are defined to improve the initial solution, as explained in the following subsections. A distinction may be made between classical PDP search operators and search operators specifically developed for the PDSP. The classical PDP search operators used in our local search algorithm are SHIFT and EXCHANGE, which are similar to the local search operators of Li and Lim (2001). The other two search operators are constructed specially for the PDSP and are referred to as INSERT and SWITCH.

Algorithm 1 Insertion heuristic

```
Order requests based on opening time window of the pickup node
Set number of vehicles to 1
for i = 1 → each request do
  if first request then
    if Profit(vehicle1) > Cost(vehicle1) then
      Insert pickup_i and delivery_i node after each other in first vehicle
      - Update revenue and transport cost of route
      - Update load factor: L_i^k
      - Update time data: et_i, lt_i and T_i^k
    else
      Request remains unserved: Y_i = 0
    end if
  else
    set Δ = 0
    for j = 1− > number of vehicles in use do
      Set ProfitFor = to profit route_j
      Place pickup_i and delivery_i point at lowest cost position in route_j
      Set ProfitAfter = to profit route_j
      if (ProfitAfter − ProfitFor) > Δ then
        Set Δ = ProfitAfter − ProfitFor
        Set BestVehicle = j
      end if
    end for
    if Δ > 0 then
      Place request at lowest cost position in vehicle_BestVehicle
    else
      Add vehicle: as long as max. number of vehicles not reached
      if Profit > Cost then
        Insert pickup_i and delivery_i node after each other in new vehicle
        - Update revenue and transport cost of route
        - Update load factor: L_i^k
        - Update time data: et_i, lt_i and T_i^k
      else
        Request remains unserved: Y_i = 0
      end if
    end if
  end if
end for
PostOptimize(S)
```

6.3.1 EXCHANGE operator

The EXCHANGE operator (figure 6.3) is applied to all possible combinations of two routes. For two selected routes the requests with the lowest marginal profit in each route are removed from the route. These requests are exchanged between the routes and reinserted in the position with the lowest cost in the other route. Marginal profit is computed as follows: the difference is taken between the revenue of the request and the extra costs for performing the request. As cost is related to the distance, the sum is taken over the links necessary to perform the request minus the links that are replaced. If the total profit of the routes is higher after the EXCHANGE operation the solution is stored, otherwise the original routes are placed back.

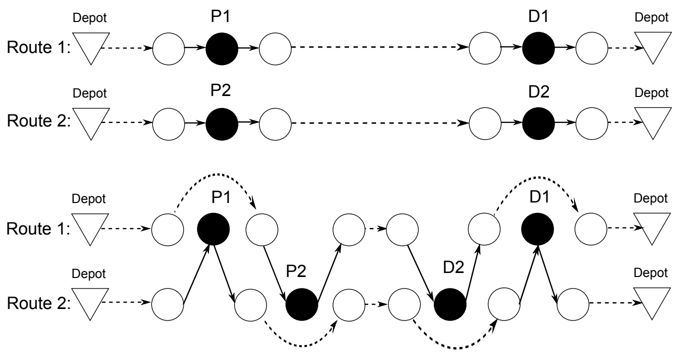

Figure 6.3: EXCHANGE operator

6.3.2 SHIFT operator

A second operator tries to put the request with the lowest marginal profit from a selected route in another route. All routes are selected one by one to see if the SHIFT operator (figure 6.4) may be applied to the route. The marginal profit is defined analog as in the EXCHANGE operator. The request with the lowest marginal profit is removed from the route. In a next step, the SHIFT operator checks whether this request may be placed in another existing route. A first accept strategy is applied. The operator stops when it finds a route to insert the request, which results in a higher total profit and satisfies all constraints. If the selected route is empty after this operation and unserved requests are still left, the INSERT operator is used to put unserved requests into the empty route. This is explained in the next section. If no unserved request is inserted in the route, the vehicle remains at the depot. This allows the SHIFT operator to reduce the number of routes.

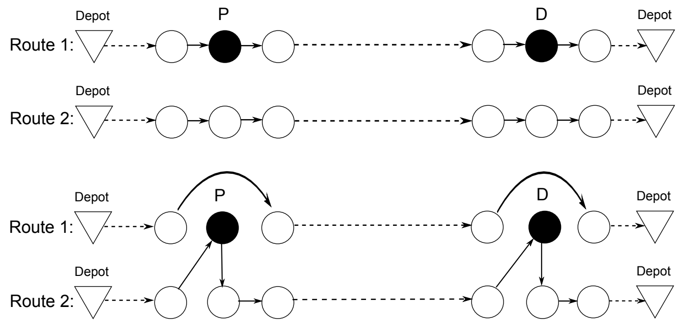

Figure 6.4: SHIFT operator

6.3.3 INSERT operator

The INSERT operator (figure 6.5) is applied to all routes. From the list of unserved requests, a request is selected to be inserted into the route. All feasible positions to insert the request in the route are listed. An insertion is feasible if time windows and vehicle capacity are not violated. For each request the pickup node has to be visited before the delivery node. If inserting the request leads to a higher profit for the route considered, the request is inserted in the position with the lowest cost. The operator stops when no unserved request can be added to the route to increase profit. The next route is now considered for applying this operator.

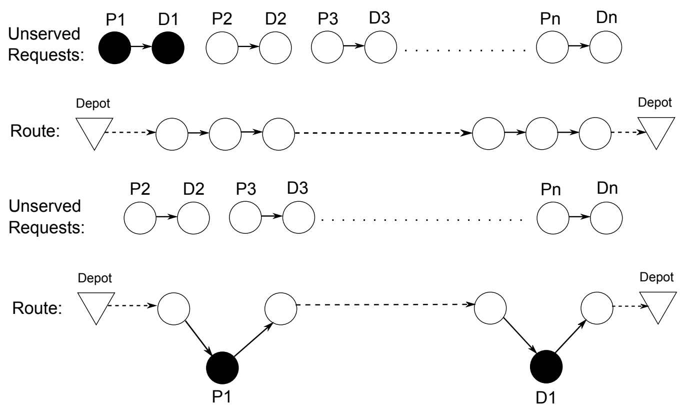

Figure 6.5: INSERT operator

6.3.4 SWITCH operator

The SWITCH operator (figure 6.6) removes the request with the lowest marginal profit from the selected route and replaces it with an unserved request. These requests are switched if this results in a higher total profit. In a first step, the marginal profit for each request within the selected route is calculated. Marginal profit is computed as explained in section 6.3.1. The request with the lowest marginal profit is removed from the route and will no longer be served by the carrier. A second step finds an unserved request to be inserted into the route in his lowest cost position. This step is analog to the INSERT operator. If switching both requests leads to a higher total profit, the requests are replaced, otherwise another unserved request is considered. If no unserved request may be inserted profitably, the original route is restored.

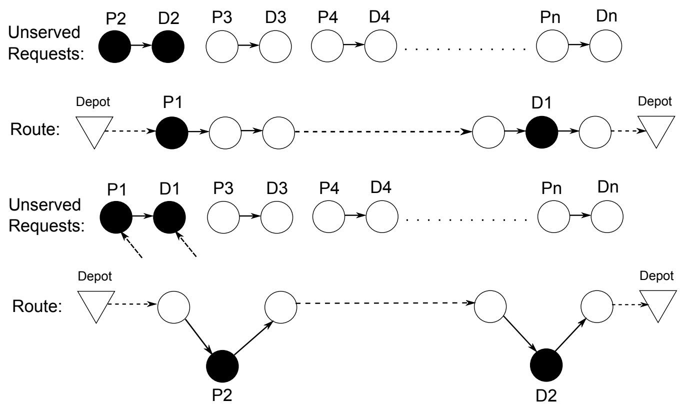

Figure 6.6: SWITCH operator

The local search operators are implemented according to the sequence in figure 6.7. First, the INSERT operator is used to perform more requests by inserting unserved requests to routes. Next, the SWITCH operator improves the current solution by replacing low profit requests with unserved requests that lead to a higher profit. Finally, the EXCHANGE and SHIFT operators try to find better combinations of requests by switching either two requests between routes or moving a single request to another route. Moreover, the SHIFT operator may reduce the number of vehicles used. These four local search operators are iterated until no further improvement may be found. Afterwards, the REORDER operator is applied in a post-optimization phase to improve the routing of the vehicles.

The working of the improvement heuristic is shown in algorithm 2. First, an

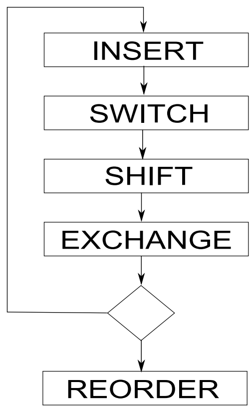

Figure 6.7: Improvement heuristic

initial solution S is generated with the insertion heuristic. This solution is further improved with the post-optimization operator (REORDER), which is indicated with PostOptimize(S). A loop is created over the four local search operators as long as an improvement in the profit is found ($Profit1$ not equal to $Profit2$). Each of these local search operators are applied to all vehicles in the solution one by one. At the end of the loop the post-optimization operator is repeated.

6.4 Experimental results

Results of experiments using the insertion and improvement heuristic of the previous sections are presented here. First, a numerical example is shown. To demonstrate the mechanisms of the improvement heuristic the benchmark data of Li and Lim (2001) are adopted to our problem setting in section 6.4.2. Next, new benchmark data including all characteristics of PDSP are defined based on a full factorial design in section 6.4.3. All experiments are conducted on a Intel Core Duo 2.4 GHz laptop with 4 GB RAM.

6.4.1 Numerical example

The insertion and improvement heuristics are demonstrated on a numerical example. In this example a carrier receives ten requests. The carrier has only three vehicles and limited time (eight working hours) to serve requests, so a selection has to be made to maximize his profit. Each vehicle has a capacity of 90 units, no fixed vehicle cost

Algorithm 2 Improvement heuristic

```
S = InsertionHeuristic
PostOptimize(S)
Set Profit1 = 0
while end! = 1 do
  Profit2 = sum of profit of the vehicles
  if Profit2 = Profit1 then
    end = 1
  else
    Profit1 = Profit2
    for vehicle1 from 0 to maximum vehicles do
      Apply INSERT to vehicle1
    end for
    for vehicle1 from 0 to maximum vehicles do
      Apply SWITCH to vehicle1
    end for
    for vehicle1 from 0 to maximum vehicles do
      Apply SHIFT to vehicle1
    end for
    for vehicle1 from 0 to maximum vehicles-1 do
      for vehicle2 from 1 to maximum vehicles and vehicle1! = vehicle2 do
        Apply EXCHANGE between vehicle1 and vehicle2
      end for
    end for
  end if
end while
PostOptimize(S)
output S
```

is assumed. All nodes are located in an area of 25 km^2. Travel cost per kilometer is 30 cent and travel time is set to one minute per kilometer. Table 6.1 presents the ten received requests. The location of the depot is shown in the first line. In the last column, the corresponding delivery (pickup) node is given. The X- and Y-coordinate of each node is expressed in kilometers. Time and revenue are all given with three decimal digits. Results are rounded to two decimals.

Table 6.1: Requests

Node i	X (km)	Y (km)	e_i (min)	l_i (min)	ot_i (min)	q_i	Rev_i (€)	d_{i+n} $\backslash p_{j-n}$
0	14,243	18,985	0	480,000	0	0	0	0
1	13,267	2,812	91,119	230,299	1	84	18,512	11
2	18,304	14,271	190,551	270,660	2	21	10,384	12
3	24,806	2,011	314,873	365,691	1	36	32,752	13
4	3,764	17,876	211,250	283,966	1	37	28,020	14
5	18,730	5,362	224,379	291,805	2	30	19,588	15
6	8,599	2,742	176,713	301,382	1	68	38,994	16
7	1,266	9,648	276,080	332,147	1	33	28,560	17
8	21,060	19,717	142,647	184,429	1	12	45,920	18
9	6,005	7,138	24,806	160,839	1	79	9,556	19
10	23,094	5,845	97,414	213,116	2	44	27,406	20
11	16,203	11,591	368,776	457,346	1	-84	18,512	1
12	21,017	9,844	293,167	394,083	2	-21	10,384	2
13	8,647	4,669	379,147	471,459	1	-36	32,752	3
14	17,753	18,653	345,306	466,285	2	-37	28,020	4
15	21,346	14,801	363,550	447,522	2	-30	19,588	5
16	22,402	16,513	321,987	433,348	1	-68	38,994	6
17	15,493	10,884	349,513	467,538	2	-33	28,560	7
18	1,171	8,245	368,705	434,431	2	-12	45,920	8
19	4,351	11,621	241,958	406,952	2	-79	9,556	9
20	14,363	16,407	317,033	394,740	1	-44	27,406	10

6.4.1.1 Optimal solution

Due to the limited size of the problem a global maximum can be found with the program LINGO 10.0 (see table 6.2). The optimal solution has a total profit of 120,54 €. All routes are feasible and all requests are served within their time window and within a single working day. Requests 1,2,5,7 and 9 are rejected by the carrier.

Table 6.2: Optimal solution

Route 1:	0 - 8 - 3 - 18 - 13 - 0
Route 2:	0 - 6 - 16 - 0
Route 3:	0 - 10 - 4 - 20 - 14 - 0

6.4.1.2 Insertion heuristic

All requests are listed based on the earliest time window of the pickup node. The ranked list is given in table 6.3. Requests are then assigned to routes based on profitability and pickup and delivery nodes are placed in their best position in the route. Results are shown in table 6.4. Route 1 has a total driving time of 412,29 minutes, route 2 takes 460,43 minutes to get back to the depot and route 3 takes 391,09 minutes. This is all well below the allowed time of 480 minutes (eight working hours). The total profit of the initial solution is 33,67 €.

Table 6.3: Ranked list of requests

Pickup i	Delivery $i+n$	e_i
9	19	24806
1	11	91119
10	20	97414
8	18	142647
6	16	176713
2	12	190551
4	14	211250
5	15	224379
7	17	276080
3	13	314873

Table 6.4: Initial solution numerical example 1

Route 1:	0 - 9 - 19 - 0
Route 2:	0 - 1 - 11 - 0
Route 3:	0 - 10 - 2 - 12 - 20 - 0

6.4.1.3 Improvement heuristic

After finding the initial solution, the local search operators presented in section 6.3 are applied. As the initial solution has only one request in most routes the EXCHANGE and SHIFT operators will not change the initial solution. The INSERT operator does not alter the initial solution in the first iteration. This is expected as the insertion heuristic was not able to include any more requests. The last operator, SWITCH, removes the request with the lowest marginal profit from the route and replaces it with a better unserved request. This is performed for each route, leading to three new routes, with a total profit of 69,57 € (table 6.5).

Table 6.5: Best solution found after first iteration of the improvement heuristic

Route 1:	0 - 3 - 13 - 0
Route 2:	0 - 4 - 14 - 0
Route 3:	0 - 10 - 5 - 20 - 15 - 0

The improvement heuristic is then repeated. Again, because of the low number of requests in each route, the EXCHANGE and SHIFT operators do not improve the best solution found. This can be explained since these operators are designed to improve routes in classic pickup and delivery problems and are not suited to make a request selection. Running the INSERT operator again changes the first route to the optimal route (table 6.2): 0 - 8 - 3 - 18 - 13 - 0, the other routes are left unchanged. Total profit is 109,10 €. Finally, the SWITCH operator leads to the optimal solution as presented in table 6.2. Total profit increases to 120.54 €. Total operation time of route 1 is 458,97 minutes, route 2 takes 398,51 minutes to reach the depot and the last route takes 442,62 minutes. In this case the post-optimization operator REORDER does not further alter the solution.

After executing the improvement heuristic twice, the heuristic reaches the optimal solution from subsection 6.5.4. All routes are feasible and the optimal solution was found in less than one second.

6.4.2 Li and Lim (2001) runs

For the PDSP, as defined in this chapter, no ready-to-use benchmark data is available. None of the available benchmark data for PDP include revenues. In this section, the benchmark data created by Li and Lim (2001) are adopted. These instances can be found on the following website: http://www.sintef.no/pdptw. The best known results of these instances can also be found on this website. Four researches (Li and Lim (2001); Bent and Van Hentenryck (2004); Ropke and Pisinger (2006); Hasle and Kloster (2007)) and the results of the software TetraSoft are combined to give the best known results. However, the data of Li and Lim (2001) are generated for a standard PDP so they are adapted to suit the PDSP at hand. This is done in the next subsection.

Due to the different objective functions for the PDP and the PDSP, the benchmark data of Li and Lim (2001) does only allow a limited comparison of the results from our heuristic. Therefore, only twelve instances from the benchmark data are selected. Li and Lim (2001) provided benchmark data with 100, 200, 400, 600, 800 and 1000 nodes. Here instances of 100 or 200 nodes are considered, to keep computational efforts within reach. The benchmark data is divided in three categories based on the geographical location of the nodes, which may be either clustered, randomly distributed or a mix of the two. In each category the first two instances are selected, both for the 100 nodes and the 200 nodes, leading to twelve instances.

In a first step one instance is chosen and worked out as an example. Instance LR101 of the problem category LR1 is chosen for this example. The LR1 category has randomly distributed customers and a tight time window width. 53 requests can be found in LR101, 25 vehicles with a capacity of 200 units are available. Travel cost and travel time are both set to a single unit per kilometer. The best known result is reported for each problem instance on the website. For instance LR101 the best known result is found in 2001 by Li and Lim (2001). This solution uses 19 vehicles and has a total distance of 1650,80 km.

6.4.2.1 Data preparation

As the benchmark data from Li and Lim (2001) are created for the PDP, the goal of this example is to test the heuristic on his ability to schedule selected requests into feasible routes while minimizing the total distance travelled. The number of vehicles used is not minimized, because the use of a vehicle is considered as a fixed cost in the PDSP. The instances are adapted, to ensure that all requests are selected in the PDSP. This allows a comparison between the results of the PDSP with the results of PDP. First a revenue is assigned to each request. A sufficiently high number is chosen to make sure all requests are profitable and selected by the carrier. The time window is enlarged with the service time as the definition of time windows by Li and Lim (2001) is slightly different from our problem setting in which a node has to be served within the time window. In Li and Lim (2001) the vehicle only needs to start service within the time window. Finally, the requests are reordered. All pickup nodes are listed first, followed by the corresponding delivery nodes.

6.4.2.2 Insertion heuristic

The insertion heuristic uses 23 vehicles and all requests are served. The total distance of all 23 routes is 2025,03 km. The goal of the numerical example is to test whether the heuristic can achieve good results in combining all requests into optimal route schedules. For this reason total distance is compared instead of total profit. Furthermore, all requests have to be accepted to be able to compare the results with the best known solution of the benchmark data. The resulting routes after application of the insertion heuristic can be found in table 6.6.

6.4.2.3 Improvement heuristic

Starting from the initial solution, the improvement heuristic is repeated until no further improvement may be found. The results after each iteration are given in table 6.7. After three iterations no further improvements can be reached and the improvement heuristic stops. The final solution is feasible and places all requests in only twenty vehicle routes. The total distance is 1693,48 km. This solution has a gap of 2,6% in total distance with the best known solution of 19 vehicles and a total distance of 1650,80 km. In subsection 6.4.2.4 reasons to explain this gap are given. The best solution of the heuristic is given in table 6.8. The insertion and improvement heuristics together run around two seconds.

Table 6.6: Initial solution of instance LR101

Route 1:	0 - 32 - 2 - 46 - 55 - 85 - 99 - 0
Route 2:	0 - 50 - 22 - 6 - 75 - 103 - 59 - 0
Route 3:	0 - 5 - 58 - 23 - 76 - 0
Route 4:	0 - 25 - 47 - 7 - 78 - 100 - 60 - 0
Route 5:	0 - 35 - 34 - 88 - 87 - 0
Route 6:	0 - 42 - 1 - 54 - 95 - 0
Route 7:	0 - 12 - 40 - 45 - 65 - 93 - 98 - 11 - 64 - 0
Route 8:	0 - 17 - 14 - 67 - 70 - 39 - 92 - 0
Route 9:	0 - 13 - 66 - 21 - 29 - 82 - 74 - 0
Route 10:	0 - 51 - 52 - 24 - 77 - 105 - 104 - 0
Route 11:	0 - 19 - 26 - 72 - 3 - 79 - 56 - 0
Route 12:	0 - 20 - 10 - 63 - 73 - 31 - 84 - 0
Route 13:	0 - 16 - 15 - 68 - 69 - 0
Route 14:	0 - 37 - 41 - 90 - 94 - 0
Route 15:	0 - 28 - 8 - 81 - 61 - 0
Route 16:	0 - 9 - 62 - 43 - 96 - 0
Route 17:	0 - 4 - 49 - 57 - 102 - 0
Route 18:	0 - 44 - 97 - 30 - 83 - 0
Route 19:	0 - 36 - 89 - 0
Route 20:	0 - 48 - 101 - 18 - 71 - 0
Route 21:	0 - 33 - 86 - 0
Route 22:	0 - 53 - 106 - 0
Route 23:	0 - 27 - 80 - 38 - 91 - 0

6.4.2.4 Other Li and Lim (2001) instances

For the twelve instances chosen out of the Li and Lim (2001) data set results are shown in table 6.9. The number of vehicles used is on average higher in our heuristic compared to the best known solutions. This may be explained by the fact that in the objective function of Li and Lim (2001) priority is given to the minimization

Table 6.7: Overview different iterations

Iteration	Vehicles	Distance	Gap
0 (insertion heuristic)	23	2025,03 km	22,7%
1	23	1848,19 km	12%
2	22	1735,96 km	5,2%
3	20	1693,48 km	2,6%

Table 6.8: Best found solution

Route 1:	0 - 2 - 47 - 33 - 55 - 100 - 86 - 0
Route 2:	0 - 50 - 22 - 6 - 75 - 103 - 59 - 0
Route 3:	0 - 5 - 24 - 77 - 58 - 23 - 76 - 0
Route 4:	0 - 16 - 48 - 101 - 69 - 0
Route 5:	0 - 34 - 4 - 49 - 57 - 102 - 87 - 0
Route 6:	0 - 13 - 66 - 27 - 80 - 38 - 91 - 0
Route 7:	0 - 12 - 40 - 45 - 65 - 93 - 98 - 11 - 64 - 0
Route 8:	0 - 17 - 14 - 67 - 70 - 39 - 92 - 0
Route 9:	0 - 51 - 52 - 7 - 105 - 60 - 104 - 0
Route 10:	0 - 19 - 26 - 72 - 3 - 79 - 56 - 0
Route 11:	0 - 20 - 10 - 63 - 73 - 30 - 83 - 0
Route 12:	0 - 37 - 41 - 90 - 94 - 0
Route 13:	0 - 28 - 81 - 0
Route 14:	0 - 1 - 9 - 54 - 62 - 31 - 84 - 0
Route 15:	0 - 42 - 44 - 97 - 43 - 96 - 95 - 0
Route 16:	0 - 35 - 36 - 88 - 89 - 0
Route 17:	0 - 15 - 68 - 18 - 71 - 0
Route 18:	0 - 25 - 46 - 8 - 78 - 99 - 61 - 0
Route 19:	0 - 32 - 53 - 106 - 85 - 0
Route 20:	0 - 21 - 29 - 82 - 74 - 0

of the number of vehicles and only secondly to minimization of the total distance travelled. In the PDSP the objective is to minimize cost. The cost of the vehicle fleet is considered as fixed and not included in the objective function. Furthermore, the improvement heuristic is adapted for a selection problem and is not ideal for a classical PDP. As all requests have to be accepted, the INSERT and SWITCH operators cannot be fully used for solving the instances of Li and Lim (2001). The only operator able to reduce the number of vehicles is SHIFT as it moves one request out of a route into an existing route, which may create empty routes. Looking at the total distance travelled the best known result is achieved twice (LC101 and LC1_2_1). In one case (LR1_2_2) the total distance travelled is less than the best known result, but the number of vehicles used is higher. Run time is between 2 and 12 seconds for small instances (+-50 requests) and between 41 and 227 seconds for larger instances (+-100 requests). The longer run time for the instances with 100 requests may be explained by the number of requests as well as the large number of initial vehicles (50 vehicles) available to solve the problem. As the local search operators are applied to all vehicles one by one.

Table 6.9: Li and Lim (2001) runs

Instance	**Best known**		**Improvement heuristic**		**Gap**	
	Vehicles	**Distance**	**Vehicles**	**Distance**	**Vehicles**	**Distance**
LC101	**10**	**828.94**	**10**	**828.93**	**0**	**0%**
LC102	10	828,94	11	912,17	1	10%
LR101	19	1650,8	20	1693,48	1	2,6%
LR102	17	1487,57	19	1584,21	2	6,5%
LRC101	14	1708,8	16	1752,73	2	2,6%
LRC102	12	1558,07	14	1678,08	2	7,7%
LC1_2_1	**20**	**2704,57**	**20**	**2704,51**	**0**	**0%**
LC1_2_2	19	2764,56	22	3081,40	3	11,4%
LR1_2_1	20	4819,12	25	5389,37	5	11,8%
LR1_2_2	**17**	**4621,21**	**23**	**4550,88**	**6**	**-1,5%**
LRC1_2_1	19	3606,06	22	4178,93	3	15,9%
LRC1_2_2	15	3673,19	19	3775,99	4	2,8%

6.4.3 New benchmark data for the PDSP

To test the heuristic, benchmark data for the PDSP consisting of different problem classes are created. A full factorial design was set up with five characteristics, which were each tested for their high and low values. First, the number of requests can be 50 (-) or 100 (+). A second factor is the width of the time windows for each node. The numbers are randomly generated either between 0 and 30 minutes plus service time (-) or between 30 and 60 minutes plus service time (+). The third factor, the capacity of the vehicle is 40 (-) or 70 (+) units. The coordinates of the nodes are randomly chosen from an area of 25 km^2 (-) or 50 km^2 (+). Finally, the maximum number of vehicles allowed is 10 (-) or 15 (+). The resulting 32 classes are shown in table 6.10.

The depot is located randomly in the area and the maximum duration of a route is a single working day of eight hours or 480 minutes. Shipment sizes of the requests are randomly chosen between zero and 30. Service time is randomly chosen between one and three minutes. For the experiments in chapter 6 the revenue is set to four times the distance between pickup and delivery. Later in chapter 7 a different revenue model for the carrier is investigated.

The heuristic is tested for a single instance in each problem class. Run time is between one second and five seconds for the classes with 50 requests and between two seconds and 24 seconds for the classes with 100 requests. The run time is lower than the runs of the benchmark data of Li and Lim (2001), this may be explained by the lower number of vehicles available (10/15 vehicles instead of 25/50 vehicles) An overview of the results is presented in appendix C together with the results of the metaheuristic from section 6.5. Columns two and three show the results of the improvement heuristic, respectively the total profit made and the total number of requests left unserved. In column four, the run time is given. As may be seen from the results, the number of unserved requests is lower in the last 16 classes. This was expected as the number of vehicles available increases with five from 10 to 15 vehicles. Also profit is higher for these last classes. In general the profit and number of unserved requests are dependent on the total number of requests and the number of vehicles available.

Table 6.10: Overview of problem classes

Class	**F1**	**F2**	**F3**	**F4**	**F5**	**Class**	**F1**	**F2**	**F3**	**F4**	**F5**
1	-	-	-	-	-	17	-	-	-	-	+
2	+	-	-	-	-	18	+	-	-	-	+
3	-	+	-	-	-	19	-	+	-	-	+
4	+	+	-	-	-	20	+	+	-	-	+
5	-	-	+	-	-	21	-	-	+	-	+
6	+	-	+	-	-	22	+	-	+	-	+
7	-	+	+	-	-	23	-	+	+	-	+
8	+	+	+	-	-	24	+	+	+	-	+
9	-	-	-	+	-	25	-	-	-	+	+
10	+	-	-	+	-	26	+	-	-	+	+
11	-	+	-	+	-	27	-	+	-	+	+
12	+	+	-	+	-	28	+	+	-	+	+
13	-	-	+	+	-	29	-	-	+	+	+
14	+	-	+	+	-	30	+	-	+	+	+
15	-	+	+	+	-	31	-	+	+	+	+
16	+	+	+	+	-	32	+	+	+	+	+

6.5 Tabu-embedded Simulated Annealing (TSA) algorithm for the PDSP

In this section the development of a metaheuristic for the PDSP is discussed. First, the metaheuristic created for the PDSP is explained and the parameters are set in section 6.5.1. After this, experimental results of the metaheuristic are shown in sections 6.5.2 and 6.5.3. To further improve the solutions found in section 6.4, an algorithm is constructed incorporating the local search operators described in section 6.3. The algorithms are programmed using C^{++}. This heuristic should be reasonably fast, robust and able to handle large problems. In this section we use the notation LocalSearch to refer to the improvement heuristic and PostOptimize to refer to the REORDER operator. The symbols used in the different algorithms are given in the list of symbols at the begin of this thesis.

The heuristic is based on the tabu-embedded simulated annealing algorithm of Li and Lim (2001). The algorithm starts with the insertion heuristic to create a first feasible solution (S_{best}). This solution is further improved by the improvement heuristic. Instead of repeating the tabu search until the procedure terminates, it is restarted from the current best solution (S_{best}) after several iterations ($STOP$) without any improvement. At the same time the global annealing temperature, T, is reset. After a number of restarts (K) without any improvement the algorithm is ended. The generation of new best solutions (S'_{best}) is done via the TABU(S) algorithm (see algorithm 4). To avoid cycling, the visited solutions are recorded into a tabu set, which contains the total profit of a solution. Since the probability of two different solutions having the same total profit is very small, it is sufficient to only keep track of total profit. The Tabu-embedded Simulated Annealing (TSA) algorithm is given in algorithm 3.

Algorithm 3 TSA algorithm

Empty tabu set
Set $gNoImpr = 0$
Set S_{best} to initial solution from insertion heuristic
S_{best} = PostOptimize(S_{best})
S_{best} = LocalSearch(S_{best})
while $gNoImpr < K$ **do**
  $S = S_{best}$
  S'_{best} = TABU(S)
  if $Profit(S'_{best}) > Profit(S_{best})$ **then**
    Set S_{best} to S'_{best} and $gNoImpr = 0$
  else
    $gNoImpr = gNoImpr + 1$
    reset T to T_0
  end if
end while
output S_{best}

Algorithm 4, TABU(S), tries to find a new local optimum (S'_{local}) with the help of the SHUFFLE (S) algorithm. A random feasible solution (S') is generated with the SHUFFLE(S) algorithm, which is not in de tabu set. In de TABU(S) algorithm this random solution (S') is further optimized with the help of the LocalSearch function.

This leads to a new local optimum (S'_{local}), which is compared to the current local optimum (S_{local}). If it performs better the new local optimum is stored in S_{local} and given as an output of the TABU(S) algorithm. If the current local optimum (S_{local}) is not improved the search continues with the new found local optimum (S'_{local}). The algorithm repeats itself until no improvement is found for a certain amount of iterations ($STOP$).

Algorithm 4 TABU(S)

Set $S_{local} = S$
Set $NoImpr = 0$
while $NoImpr < STOP$ **do**
  $S' = SHUFFLE(S)$, with S' not in tabu set
  $S'_{local} = LocalSearch(S')$
  $S'_{local} = PostOptimize(S'_{local})$
  if $Profit(S'_{local}) > Profit(S_{local})$ **then**
    Set S_{local} to S'_{local} and $NoImpr = 0$
  else
    $NoImpr = NoImpr + 1$
  end if
  Set $S = S'_{local}$
end while
output S_{local}

The SHUFFLE(S) function (algorithm 5) acts as a diversification strategy to escape from local optima. First, two random routes are chosen. After that, a random local search operator (SHIFT, EXCHANGE, INSERT, SWITCH) is performed on both of the chosen routes. However, it is no longer required to have a higher profit after performing the local search operator as within the improvement heuristic. To allow extra diversification from the current local optimum an extra operator is added, DELETE. The operator, DELETE, removes the request with the lowest marginal profit from the selected route. If a feasible solution (S') is found, of which the total profit is not in the tabu set, it is either accepted or rejected. This is based on the difference in profit between the current solution (S) and the new found solution (S'). If the difference is positive, hence a higher profit is obtained in the new solution, the probability (*prob*) of accepting the solution is set to one. Else the probability is set to the exponential of the difference, Δ, divided by the annealing temperature, T. Whether or not the new feasible solution (S') is accepted is then determined using a random number. When the new solution (S') is accepted it is stored in the tabu set and the annealing temperature (T) is decreased with the factor δ. If the new solution (S') is not accepted S is set equal to S' and the SHUFFLE(S) function is repeated. Hence to rejected solution (S') is used as input to find a new neighbour. Restarting the search from the current solution allows to find a more diverse solution (S') of the solution (S) with which it started. This means that the DELETE operator may act several times within the SHUFFLE(S) function and multiple requests may be removed. The function is given in algorithm 5.

Algorithm 5 SHUFFLE(S)

```
while end! = 1 do
  S' ← Get a random neighbour of S which is not in tabu set:
      -Generate two random numbers to determine the chosen routes.
      -Randomly selected a local search operator or DELETE.
      -Get a random neighbour of S using the selected operator.
      -Check whether the random neighbour is in tabu set.
  Δ = Profit(S') − Profit(S)
  if Δ ≥ 0 then
    prob = 1
  else
    prob = e^(Δ/T)
  end if
  if random (0,1) ≤ prob then
    accept S'
    record S' into tabu set
    Update temperature: T = δ · T
    Set end = 1
  else
    S = S'
  end if
end while
output S'
```

Although the TSA algorithm is inspired by the work of Li and Lim (2001), some clear differences exists between the two algorithms. First of all, the TSA algorithm as proposed in this section makes use of four different local search operators instead of two. Furthermore, the DELETE operator is added to the SHUFFLE(S) function.

Within the TABU(S) algorithm Li and Lim (2001) apply a route reduction step after the implementation of the SHUFFLE(S) function. This is not considered in the TSA algorithm of this thesis, as reducing the number of vehicles is not an objective of the PDSP. Another main difference is the use of an improvement heuristic instead of a descent local search (DLS) as by Li and Lim (2001). The DLS checks all the solutions in the neighbourhood, the solution with the minimum objective cost will act as the initial solution for repeating the DLS procedure. This is performed for each local search operator separately and repeated until no improvement is found. The improvement heuristic of section 6.3 does not consider all possible solutions and put the four local search operators in a loop which is repeated.

6.5.1 Parameter setting

Several parameters are used in the TSA algorithm presented in section 6.5. In order to optimize results a sensitivity analysis is used to select the parameter values. The parameters which will be considered in the analysis are:

- K: Stopping condition of the general metaheuristic
- $STOP$: Stopping condition of $TABU(S)$
- T_0: Initial global annealing temperature
- δ: Factor for decreasing T

For these parameters the following initial values are considered: K is set to three, $STOP$ to four, T_0 is 50 as chosen by Li and Lim (2001) and δ equal to 0,97.

For the sensitivity analysis a subset of problems is selected. A 2^{k-p} fractional factorial design is applied to select 16 problem classes. In our case a 2^{5-1} fractional factorial design is applied, which has a resolution of V (Law, 2007). A certain subset of size 2^{5-1} is chosen of all 2^5 design points. Table 6.11 lists the selected problem classes. For each of the selected problem instances three independent runs of the TSA algorithm are performed for the sensitivity analysis.

The parameter K indicates how many times the general search is restarted without finding an improvement. Analysis is done for values from one up to five runs. In figure 6.8 the vertical axis represents the average gap between the total profit of a solution and the one found by the local search heuristic, as there is no upper bound to compare our results with. As may be seen in figure 6.8 the largest improvement is found between the values of two and three. The improvement between three and four runs is rather small but computation time increases sharply with each step. Therefore

Table 6.11: 2^{5-1} fractional factorial design

Problem class	F1	F2	F3	F4	F5
17	-	-	-	-	+
2	+	-	-	-	-
3	-	+	-	-	-
20	+	+	-	-	+
5	-	-	+	-	-
22	+	-	+	-	+
23	-	+	+	-	+
8	+	+	+	-	-
9	-	-	-	+	-
26	+	-	-	+	+
27	-	+	-	+	+
12	+	+	-	+	-
29	-	-	+	+	+
14	+	-	+	+	-
15	-	+	+	+	-
32	+	+	+	+	+

it is opted to limit the general algorithm to three runs without any improvement. With the $STOP$ parameter the number of runs of the $TABU$ search is set. The outcome of the sensitivity analysis is represented in figure 6.9. Better average solutions are found when the number of runs is increased, after four runs the extra improvement is small. As the computation time increases with the number of runs, $STOP$ is set to four. Only a small improvement of the average solution is generated when five runs are allowed. The sensitivity analysis on the initial temperature T_0 is shown in figure 6.10. In Li and Lim (2001) a temperature of 50 is chosen. For the sensitivity analysis T_0 is varied between 40 and 60 with intervals of size two. Although changes in temperature have only a limited impact on solution quality, the best solutions are found with T_0 equal to 54. Finally, a sensitivity analysis for δ, the factor for decreasing the initial temperature, is generated. Values between 0,90 and 0,99 are considered with intervals of 0,1. Changes in the average solution are little, only a small peak may be seen with the value of 0,96. For further analysis this value is used. Both the values of T and δ

have only a small impact on solution quality. The values chosen offers on average the best results, although differences are small.

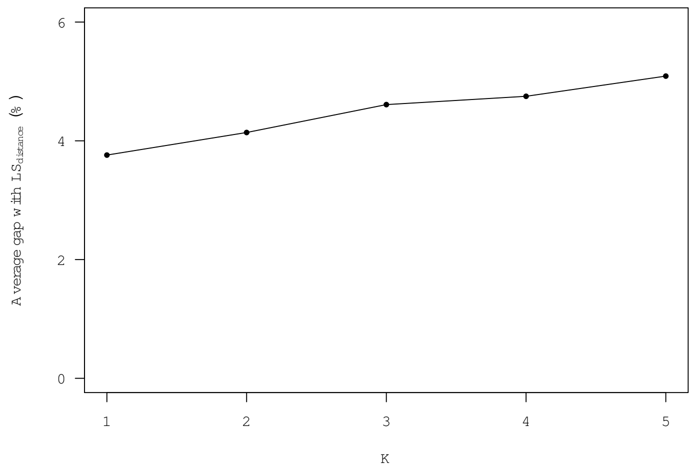

Figure 6.8: Sensitivity analysis of parameter K

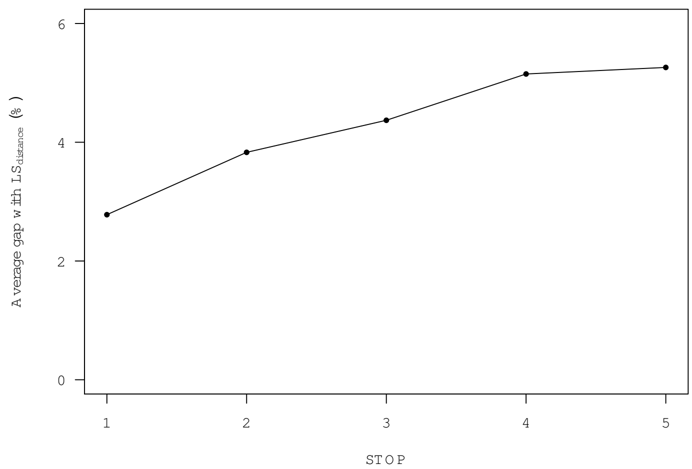

Figure 6.9: Sensitivity analysis of parameter $STOP$

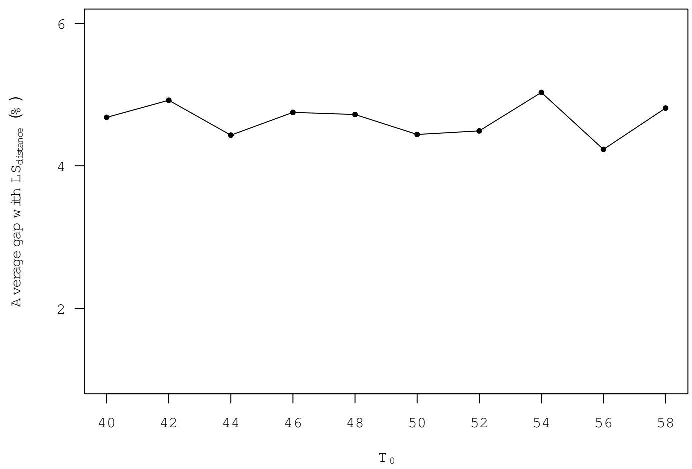

Figure 6.10: Sensitivity analysis of parameter T_0

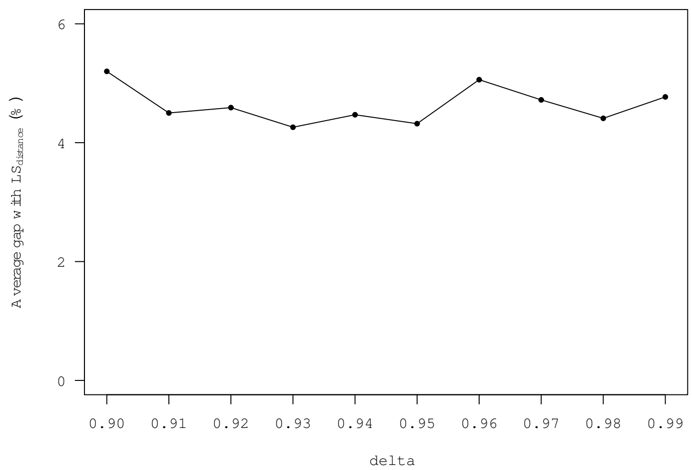

Figure 6.11: Sensitivity analysis of parameter δ

6.5.2 Experimental results: Li and Lim (2001) benchmark instances

Although the metaheuristic is developed to solve the PDSP and does not take into account the number of vehicles used, it achieves good results for the benchmark instances of Li and Lim (2001). The results can be found in table 6.12. Six of the twelve chosen instances are solved to their best known solution. In two other instances the total distance travelled is lower than the best known solution, but the number of vehicles used is higher. As the metaheuristic only minimizes the distance travelled and not the number of vehicles used, it is a better solution for the PDSP. For the PDP as considered by Li and Lim (2001) the objective is first to minimise the number of vehicles and only secondly the distance travelled. In the PDSP we consider a carrier with a fixed vehicle fleet and an excess of transport requests. The assumption is made that the fixed costs of the vehicle fleet remains the same whether they are used or not. This means that all vehicles will be used in order to accept as many requests as possible and optimize the profit. Hence, the heuristic will always minimize the distance and not the number of vehicles used. The remaining four instances have a gap in distance with the best known solution of less than 3,6%.

Table 6.12: Metaheuristic results for Li & Lim (2001)

Instance	**Best Known**		**TSA algorithm**		**Gap**	
	Vehicles	**Distance**	**Vehicles**	**Distance**	**Vehicles**	**Distance**
LC101	**10**	**828,94**	**10**	**828,92**	**0**	**0%**
LC102	**10**	**828,94**	**10**	**828,92**	**0**	**0%**
LR101	**19**	**1650,8**	**19**	**1650,76**	**0**	**0%**
LR102	**17**	**1487,57**	**17**	**1487,53**	**0**	**0%**
LRC101	14	1708,8	15	1715,15	1	0,4%
LRC102	12	1558,07	14	1606,48	2	3,1%
LC1_2_1	**20**	**2704,57**	**20**	**2704,57**	**0**	**0%**
LC1_2_2	19	2764,56	19	2774,50	0	0,4%
LR1_2_1	20	4819,12	22	4991,17	2	3,6%
LR1_2_2	**17**	**4621,21**	**21**	**4326,55**	**4**	**-6,4%**
LRC1_2_1	**19**	**3606,06**	**19**	**3607,57**	**0**	**0%**
LRC1_2_2	**15**	**3673,19**	**19**	**3298,62**	**4**	**-10,2%**

6.5.3 Experimental results: New benchmark instances

In appendix C the results of the TSA algorithm are compared with the results of the local search heuristic of section 6.4.3. The total profit and the number of unserved requests are presented separately. The gap between the local search and the TSA algorithm is given in columns six and seven. The algorithm runs between 22 seconds and 162 seconds for the 50-request classes and between the 163 seconds and 1009 seconds for the 100-request classes. The TSA algorithm is able to improve all of the 32 classes defined. Improvements in profit range from 1,65% to 34,84%. The number of unserved requests went down with maximum eight requests. In one case (class 26) the number of unserved requests increased with one, but this resulted in a higher profit. The advantage of better constructed routes was higher than the additional profit of accepting an extra request. In general the largest improvements are made in the classes with 100-requests. Because the search area is larger, as more requests remains unserved, a metaheuristic may lead to better results than a local search heuristic. Also the classes with 10 vehicles have larger improvements than the classes with 15 vehicles. This again may be explained by the fact that more requests remains unserved when there are less vehicles.

The full factorial design of the benchmark data allows determining the main and interaction effects of the different problem characteristics. This is represented in table 6.13. All of the main interaction effects are positive. This means that a higher level of the factor has a positive effect on the profit of the carrier. The largest influence on the obtained profit stems from increasing the number of requests, followed by increasing the area where the nodes are located. When more transport requests are available a higher profit may be obtained. Also in a larger area the pickup and delivery node may be further away from each other resulting in higher revenue for the carrier. The smallest effect is noted when the capacity of the vehicle is expanded. The interaction effects between the factors on the profit are all positive, except for two: the interaction between the number of requests and the capacity of the vehicles and the interaction between the capacity of the vehicle and the number of available vehicles. These factors should have opposite signs in order to have a higher profit. The same analysis can be done for the percentage of requests that remain unserved. The largest main effect is now found by decreasing the number of requests and by increasing the number of vehicles. This was expected as less transport requests and more vehicles to serve clients will result in fewer clients to be refused. Notice that the number of transport requests has an opposite effect of the profit gained by the carrier. Factors two and three are better put on their high levels as this decreases the number of unserved requests, while the area which is studied is best kept small. The largest interaction effect is found by combining the width of the time windows with the capacity of the vehicles. This interaction effect is negative and is hence better to have these factors at the same level to be able to accept the most requests.

Table 6.13: Main and interaction effects of the problem characteristics

Main effect	Profit	Requests	Interaction effect	Profit	Requests
- factor 1	1584,24	21,13%	- factor 1-2	241,05	0,75%
- factor 2	693,12	-9,50%	- factor 1-3	-120,01	2,50%
- factor 3	188,15	-3,75%	- factor 1-4	348,51	0,75%
- factor 4	1485,33	10,00 %	- factor 1-5	256,96	-0,50%
- factor 5	475,66	-14,25%	- factor 2-3	261,58	-4,63%
			- factor 2-4	426,14	-1,13%
			- factor 2-5	188,51	-1,63%
			- factor 3-4	138,07	2,13%
			- factor 3-5	-123,19	0,36%
			- factor 4-5	200,62	-0,87%

6.5.4 Optimal solutions of selected new benchmark data

For the benchmark data created in this section no upper bound was established. To further evaluate the quality of the TSA algorithm, six reduced instances of our classes are tried to be solved to optimality. The optimization software AIMMS is used to generate the optimal solutions of the instances. Within the first six classes of our benchmark data the first 25 requests are selected together with five vehicles. AIMMS is able to find an optimal solution for four instances (class 1, 2, 5, 6), for the other two instances (class 3 and 4) no optimal solution is found. In Table 6.14 the optimal solution is compared with the local search and the TSA algorithm. All classes could be solved to optimality with the TSA algorithm. For class two even the local search was able to find the optimal solution. The TSA algorithm is able to find the optimal solution within a few seconds, where AIMMS take several minutes to solve the instances. The local search heuristic has a run time of less than one second.

Table 6.14: Optimal solutions

Class	Optimal solution		Time	Local Search		TSA algorithm		Time
	Profit	Unserved requests		Profit	Unserved requests	Profit	Unserved requests	
1	547,36	40%	3144,37	504,73	32%	547,36	40%	2
2	546,60	44%	215,66	546,60	44%	546,60	44%	0
5	501,65	28%	890,28	375,19	40%	501,65	28%	3
6	640,35	32%	334,97	545,88	36%	640,35	32%	4

6.5.5 Relaxing time windows on the PDSP

Within the activity-based framework of chapter 3 there exists room for negotiation between the different actors. Until now the assumption made in this chapter is that time windows are fixed and imposed by the clients of the carrier. Asdemir et al. (2009) show in their paper that dynamic pricing based on the time of delivery may allow the carrier to better manage their transport cost. Furthermore, it allows spreading the demand of clients throughout the day. In this section this option is investigated by relaxing the time windows in our own benchmark data set. When a carrier has the possibility to negotiate time windows imposed by the clients he might further optimize his operations and serve more clients or obtain a higher profit. In appendix D the results of the PDSP without time windows are given.

Table 6.15 compares the outcome of the PDSP without time windows with the PDSP with time windows. It can be seen that for all the classes a higher profit can be obtained when no time windows are applied. Furthermore, more requests are accepted which lead to a lower percentages of unserved requests. The increase in profit is on average 10,89% and the percentages of unserved requests drops on average with 7,25%. These results are interesting for the framework as an economic impulse may be given when time windows are part of a negotiation context. It allows carriers to accept more clients and obtain a higher total profit. Within the freight transportation framework it probably won't be possible to relax the time windows completely, but having some room for negotiation will allow the carrier to arrange their vehicle routes more freely. Hence, when implementing the PDSP into the freight transportation framework of chapter 3 future research should be conducted. A feedback loop should be allowed between carriers and their clients. This will enable negotiation opportunities about time windows. Besides, the option to charge different prices based on the imposed time windows, as seen by Asdemir et al. (2009), has to be further investigated. This may allow stimulating clients to change their order.

Table 6.15: Comparing the PDSP with and without time windows

Class	**Profit**	**Unserved requests**	**Class**	**Profit**	**Unserved requests**
1	5,38%	-6%	17	5,21%	-4%
2	6,17%	-2%	18	5,57%	-10%
3	9,13%	-6%	19	3,95%	-4%
4	14,21%	-12%	20	7,87%	-10%
5	11,38%	-16%	21	7,70%	-2%
6	17,16%	-6%	22	11,48%	-10%
7	8,97%	0%	23	5,83%	-2%
8	21,27%	-13%	24	13,01%	-10%
9	13,09%	-2%	25	7,08%	-4%
10	12,58%	-8%	26	12,47%	-5%
11	10,45%	-10%	27	1,05%	-6%
12	15,27%	-5%	28	10,53%	-10%
13	16,97%	-10%	29	5,74%	-6%
14	13,84%	-6%	30	23,87%	-10%
15	12,98%	-18%	31	7,52%	-2%
16	18,48%	-8%	32	12,17%	-9%

6.6 Conclusions and further research

After formulating the selection problem in chapter 5, solution heuristics are developed in this chapter. First, an insertion heuristic is created, together with five local search operators. New local search operators (INSERT, SWITCH) were developed to handle the selection of profitable transport requests in a PDSP. Afterwards, a tabu-embedded simulated annealing algorithm was used as metaheuristic to further improve the results. The objective is to maximize the total profit reached by selecting and executing transport requests. The number of vehicles used is considered as fixed. The metaheuristic approach offers high quality solutions for the benchmark data of Li and Lim (2001). The algorithm was thoroughly tested with the help of 32 carefully chosen instances. A full factorial design was set up with five characteristics, which were each tested for their high and low values. Furthermore, the TSA heuristic is applied on a few small instances. For each of these instances the optimal solution is known and the TSA heuristic was able to solve them to optimality. To end, the effect of relaxing time windows on the selection of requests is studied. In chapter 7 problem variants to the PDSP are defined. These variants are inspired by some practical considerations, which carriers could face in real life.

In first instance future research should be aimed at improving the scalability of the algorithm. At the moment the improvement heuristic takes up a significant amount of time as the local search operators are looped and applied on each vehicle within each iteration. Besides, the improvement heuristic is called several times within the TSA algorithm. A reduction in the run time of the improvement heuristic would allow the algorithm to run faster. If not all options are considered within each run of a local search operator this would speed up the heuristic and allow larger instances to be solved. Also allowing infeasible solutions may be considered as this might further improve the solutions found by the TSA algorithm. Furthermore, the implementation of the PDSP within the freight transportation framework needs to be further studied. The negotiation between carriers and clients may incorporate the width of the time windows as well as transportation rates. In chapter 7 these transportation rates are studied.

The PDSP can be further investigated as a separate problem within operational research, without the context of a freight transportation framework. Future research could extend the PDSP to include multiple vehicle types and different commodity types. It should be tested how the algorithm may be adapted and how consolidation limitations within vehicle routes could be integrated. For some commodity types it may be infeasible to be transported together or certain vehicle types cannot be used, like for example refrigerated goods. Furthermore, a dynamic version of the PDSP may be studied in which not all requests are known in advanced. This will allow carriers to apply the model in practice, without the freight transportation framework. A dynamic version of the algorithm should be developed, in which the information of new or adjusted requests becomes available during the planning period.

Chapter 7

Pickup and delivery selection problem: alternative problem settings

7.1 Introduction

In the previous chapters 5 and 6 the PDSP is introduced and solved by means of a tabu-embedded simulated annealing algorithm. This chapter takes a closer look at several assumptions made in the PDSP. Problem variants of the PDSP are defined and examples are worked out to see how the algorithm may be applied. These problem variants are inspired by certain situations a carrier may encounter in real life. The modified assumptions in the PDSP will lead to simulating realistic problems of a carrier. The different aspects of the problem variants are introduced in this chapter. An in-depth analysis of each variant is performed by means of examples.

The outline of this chapter is as follows. First, in section 7.2 the PDSP is extended with compulsory requests which cannot be refused. The influence of incorporating a fixed cost for the usage of vehicles within the PDSP is studied in section 7.3. Next, options to outsource some requests to a logistic service provider (LSP) are investigated in section 7.4. In section 7.5 an alternative revenue model for the carrier is proposed. A last problem variant that is considered is the multi-period PDSP of section 7.6. Difficulties encountered with defining a multi-period variant of the PDSP are presented and a small test case is considered. To end, conclusions and suggestions

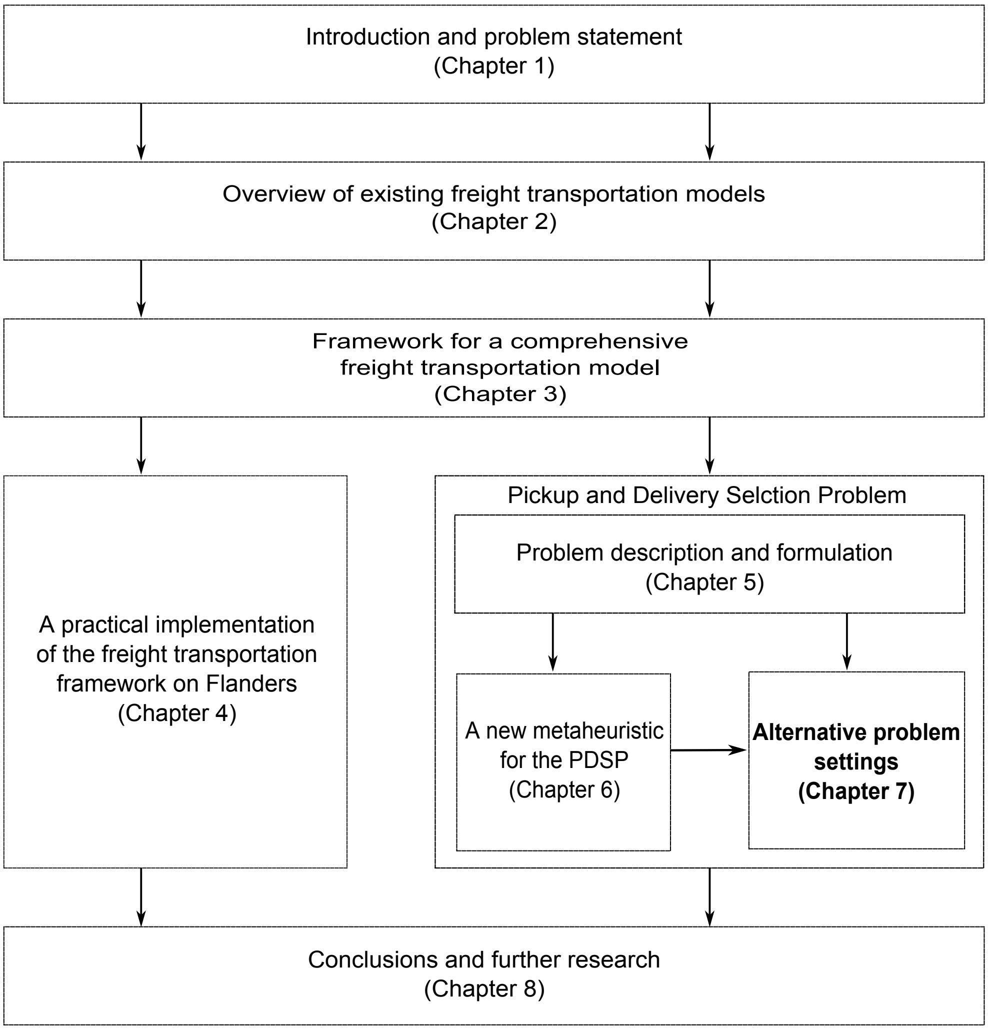

Figure 7.1: Outline of the thesis - Chapter 7

for further research are given in section 7.8.

7.2 Pickup and delivery selection problem with compulsory requests

The PDSP as defined in chapter 5 makes the assumption that the carrier has the liberty to refuse all transport requests which are not profitable. However, in real life it could happen that there exist a number of fixed clients which you may not refuse because of long-term contracts. These long-term contracts are also represented in the freight transportation framework of chapter 3. The problem is extended to a pickup and delivery selection problem with compulsory requests (PDSPCR).

For the problem formulation of the PDSPCR the following alterations are made to the formulation of the PDSP (see section 5.4). Constraint (5.8) is replaced by constraint (7.1) and a new constraint (7.2) is added to the formulation.

$$\sum_{k=1}^{K} Y_i^k \leq 1 \qquad \forall i \neq i^{comp} \in P \tag{7.1}$$

$$\sum_{k=1}^{K} Y_{i^{comp}}^k = 1 \qquad \forall i^{comp} \in P \tag{7.2}$$

with i^{comp}, for a compulsory request. It has to be noted that for all other constraints and for the objective function, the following is valid: $i^{comp} \subset i \in P$.

The modifications to the TSA algorithm necessary to solve the PDSPCR are explained in section 7.2.1. In section 7.2.2 an example is solved and discussed.

7.2.1 Modifications to the TSA algorithm

To cope with compulsory requests, alterations to the TSA algorithm of chapter 6 have to be made. First of all, the insertion heuristic is adapted. It is no longer obligated for each request to have a positive impact on the profit of a route. Furthermore, the insertion of compulsory requests has to be ensured. A list is created, which contains all compulsory requests. The insertion heuristic starts with placing the requests from this list into vehicle routes. Here, only the feasibility concerning time windows and vehicle capacity are taken into account. For the first compulsory request to be inserted into a route it is not checked whether or not this request is profitable. Subsequently compulsory requests are inserted into the most profitable place in an existing route. This will lead to a higher overall profit or a lower loss within a route. Again, as in the original insertion heuristic, pickup and delivery are inserted separately at their best location keeping in mind the preceding constraint. If a compulsory request cannot be inserted in an existing route at a profitable place, a new vehicle is added as long as vehicles are still available. The first compulsory request of a new route may either lead to a profit or a loss. Later compulsory requests are at a first stage inserted at the most profitable place in an existing route. When all available vehicles are in use and still some compulsory requests remain unserved, they are inserted at the first available place regardless the profit or loss it will generate. When all compulsory requests are inserted, the remaining requests are selected until all vehicles are fully used or no request can be inserted at a profit. Requests which are not compulsory are only inserted if the total profit gained increases.

Some of the local search operators need to be adapted as well. Compulsory requests may only be interchanged between routes or moved from one route to another route. They are not allowed to leave the solution and have to be served by one of the available vehicles. For this reason the SWITCH operator (section 6.3.4) is changed. Only requests which are not in the list of compulsory requests can be removed from a route. If a compulsory request would be selected for removal, it is skipped and the next request is removed instead. This ensures that compulsory requests will stay in the solution and the corresponding client is served.

A final alteration is needed within the TSA algorithm itself. The SHUFFLE(S) algorithm uses the DELETE operator. Because compulsory requests are not allowed to leave the solution and to be added to the list of unserved requests, this operator is changed slightly. Every time a compulsory request is chosen for removal the next non-compulsory request is removed instead.

This altered version of the TSA algorithm will be used in the further analyses of this section and is indicated as CR-TSA.

7.2.2 Numerical examples

The same six reduced instances as in section 6.5.4 of the previous chapter are used here to compare the results of the CR-TSA algorithm. For each of these instances the first five requests are considered as compulsory. In this section one instance is worked out in detail, the results of the other instances are given at the end of this section in table 7.4. All experiments in this chapter are conducted on a Intel Core Duo 2.4 GHz laptop with 4 GB RAM.

7.2.2.1 PDSPCR instance of class 1

The first instance as generated in section 6.4.3 is used in this numerical example. This instance is reduced to the first 25 requests instead of all 50 requests, to allow the optimization software AIMMS to solve the instance optimally. The nodes are randomly distributed over an area of 25 km^2. All requests have to be served within one working day of eight hours, or within 480 minutes. Five vehicles are used instead of ten, each with a capacity of 40 units. The operation time is randomly chosen between one and three minutes per unit. In tables E.1 and E.2 of appendix E the requests received by the carrier are listed. This is the same instance as used in section 6.5.4. Table 7.1 gives the solution found by the altered insertion heuristic. Requests one to five are compulsory and are inserted as first, each time a compulsory request cannot be inserted in an existing route, a new vehicle is added. This was the case for requests one, two, three and five. Request four was inserted at the best possible location in one of the existing routes, at that moment only routes one to three were created. Afterwards the non compulsory requests are inserted. They are first sorted based on the time window of the pickup node. The total profit of this solution is 409,30€.

Table 7.1: PDSPCR: Insertion heuristic

Route 1:	0 - 19 - 24 - 44 - 49 - 1 - 26 - 0
Route 2:	0 - 14 - 2 - 4 - 29 - 27 - 7 - 32 - 39 - 0
Route 3:	0 - 3 - 18 - 28 - 23 - 43 - 48 - 0
Route 4:	0 - 5 - 21 - 46 - 30 - 0
Route 5:	0 - 12 - 10 - 37 - 15 - 40 - 35 - 0
Unserved requests:	6, 8, 9, 11, 13, 16, 17, 20, 22, 25

The improvement heuristic is able to achieve a solution with a profit of 446,97€, as given in table 7.2. Compulsory requests are not allowed to leave the solution, but they may be moved between routes. This is done with request four, which is now part of route four. Other requests, such as request 21, may be removed from the solution.

Table 7.2: PDSPCR: Improvement heuristic

Route 1:	0 - 24 - 49 - 1 - 26 - 0
Route 2:	0 - 19 - 44 - 14 - 2 - 27 - 7 - 32 - 39 - 0
Route 3:	0 - 3 - 18 - 28 - 23 - 43 - 48 - 0
Route 4:	0 - 5 - 6 - 4 - 29 - 31 - 30 - 0
Route 5:	0 - 12 - 10 - 37 - 15 - 40 - 35 - 0
Unserved requests:	8, 9, 11, 13, 16, 17, 20, 21, 22, 25

After the CR-TSA algorithm the optimal solution (see table 7.3), as obtained with

AIMMS, is found in less than three seconds. A total profit of 511,26€ is achieved. A comparison may be made with the optimal solution without compulsory requests as given in table 7.6. Only route one is different, as all compulsory requests except request one were already accepted in the solution of the PDSP. In the case of the PDSPCR, request 25 is replaced with request one, resulting in a lower profit.

Table 7.3: PDSPCR: Optimal solution of instance one

Route 1:	0 - 19 - 44 - 1 - 26 - 0
Route 2:	0 - 14 - 2 - 8 - 27 - 33 - 39 - 0
Route 3:	0 - 3 - 18 - 28 - 7 - 32 - 43 - 0
Route 4:	0 - 5 - 17 - 4 - 29 - 30 - 23 - 42 - 48 - 0
Route 5:	0 - 24 - 12 - 49 - 37 - 15 - 40 - 0
Unserved requests:	6, 9, 10, 11, 13, 16, 20, 21, 22, 25

7.2.2.2 Optimal solutions of the PDSPCR

Reduced instances for the first six classes are solved with AIMMS to find their optimal solution. Within each instance the first five requests are compulsory requests. For the instances of class three and four AIMMS was not able to solve the problem to optimality. The results of the other four classes are given in table 7.4. The optimal solution is compared with the results of the improvement heuristic (see section 6.3) and the CR-TSA algorithm. The CR-TSA algorithm was not able to find the optimal solution for class two, leading to a gap between the optimal profit and the profit found with the CR-TSA algorithm of 0.6%. All other classes are solved to optimality in considerably less time than AIMMS. The CR-TSA algorithm is able to show large increases in objective function value compared to the local search heuristic. The improvements in total profit range from 8.5% for class two to 35.9% for class five. The number of unserved requests stayed the same for class one and decreases for classes five and six. In class two the number of unserved requests went up and at the same time the profit increases. This means that the gains of making shorter routes is higher than the gains of the additional profit for inserting an extra request. The local search heuristic has a run time of less than one second for all instances.

Table 7.4: Optimal solutions of the PDSPCR

Class	Optimal solution		Time	Local search		CR-TSA		Time
	Profit	**Unserved requests**		**Profit**	**Unserved requests**	**Profit**	**Unserved requests**	
1	511,26	40%	1600,73	446,97	40%	511,26	40%	3
2	473,21	48%	268,91	434,52	48%	470,49	52%	1
5	409,82	32%	579,78	301,52	40%	409,82	32%	2
6	602,23	32%	677,98	483,99	40%	602,23	32%	3

7.2.2.3 Different percentages of compulsory requests

In the previous examples five out of the 25 requests were considered as compulsory requests or 20% of all requests. In business it is often the case that only a small share of your clients is responsible for the larger part of your profit. This effect is known as the Pareto principle, were 80% of the results stem from 20% of the causes. In this section the influence of different percentages of compulsory requests is studied, to see if the heuristic is able to provide good results and whether larger shares can still be managed.

In table 7.5 results are shown for the different percentages of compulsory requests. The analysis starts with 20% and goes up to 48% of all requests, or five till 12 compulsory requests for each class. For the classes 1, 2, 5 and 6 the results of the CR-TSA algorithm are compared with optimal solution found by AIMMS. In case the problem was not feasible this is indicated with “nf”. With 52% compulsory requests or 13 out of 25 requests the problem was no longer feasible for all classes. It has to be noticed that the benchmark data was not developed to be able to accept all requests. In this analysis the first number of transport requests of the set are taken as compulsory requests. It might be possible that another combination of requests is feasible. Furthermore, the more requests become compulsory the more the PDSP evolves to a traditional PDP with 100% compulsory requests

For the cases with 40% and 44% no solution was found by the CR-TSA algorithm for class 1. This may be explained by the way the initial solution is constructed. All compulsory requests have to be inserted in the initial solution, when this is not possible the heuristic stops. Future research may look at an alternative method to create this initial solution without the requirement to have all compulsory requests already in place. This will lead to a infeasible initial solution which needs to be further optimized to have a feasible outcome. Also the CR-TSA algorithm could consider allowing infeasible solutions which are repaired later on in the heuristic. The other runs with the CR-TSA algorithm gives good results regardless of the percentages of compulsory requests. For class 1 and 5 the algorithm was able to find the optimal solution in all cases. In class 2 a difference is noticed for the first two runs of respectively 0,6% and 1,6%. In class 6 the runs with 28% and 32% of compulsory requests show a gap of 3,5%.

Table 7.5: Percentages of compulsory requests

CR	**Class 1**		**Class 2**		**Class 5**		**Class 6**	
	CR-TSA	AIMMS	CR-TSA	AIMMS	CR-TSA	AIMMS	CR-TSA	AIMMS
20%	511,26	511,26	470,49	473,21	409,82	409,82	602,23	602,23
24%	503,60	503,60	465,66	473,21	409,82	409,82	602,23	602,23
28%	503,60	503,60	448,40	448,40	409,82	409,82	541,09	560,45
32%	503,60	503,60	nf	nf	371,01	371,01	541,09	560,45
36%	490,09	490,09	nf	nf	371,01	371,01	518,75	518,75
40%	/	442,57	nf	nf	371,01	371,01	nf	nf
44%	/	401,53	nf	nf	346,70	346,70	nf	nf
48%	nf	nf	nf	nf	346,70	346,70	nf	nf

7.3 Pickup and delivery selection problem with fixed vehicle cost

In the problem definition of the PDSP used in chapters 5 and 6 a fixed vehicle cost is not considered. It is assumed that a carrier has a fixed amount of vehicles at his disposal to execute requests. This is a reasonable assumption when looking at short run operational decisions. Decisions on the number of vehicles in the fleet of the carrier are mostly tactical decisions and the cost of the vehicles is considered in the long run. Furthermore, it is supposed that a carrier has to pay his drivers regardless whether they operate a vehicle or not. This means that his cost structure does not change when a vehicle is used and hence no fixed vehicle cost is induced. Both Schönberger et al. (2002) and Arda et al. (2008) do not take into account a fixed vehicle cost. In this section this assumption is relaxed. For each vehicle that is executing a route a fixed vehicle cost is added to the total operating cost of the carrier. The carrier has to consider whether or not a vehicle will be performing a route. Only when the profit obtained from a route is high enough to cover the fixed vehicle cost the route will be constructed. This might lead to accepting less transport requests from clients.

Including a fixed vehicle cost to the PDSP leads to a different objective function. Each time a route is assigned to a vehicle, an additional cost is subtracted from the total profit made by the carrier. The objective function that needs to be maximized is the following:

$$\max \sum_{k \in K} \Big[\sum_{i \in P} Rev_i \cdot Y_i^k - \sum_{i \in N} \sum_{j \in N} ct \cdot d_{ij} \cdot X_{ij}^k - \sum_{j \in N} C_{veh} \cdot X_{0j}^k \Big] \tag{7.3}$$

where C_{veh} is the fixed vehicle cost of a vehicle. If a vehicle is being used, it has to leave the depot and there exists one link from the depot, X_{0j}^k, that is equal to one.

7.3.1 Modifications to the TSA algorithm

The TSA algorithm, as constructed in chapter 6, allows generating the routes which lead to the highest possible profit. At the end of the TSA algorithm the carrier needs to check whether the total profit of a certain route is sufficient to pay the fixed vehicle cost. If this is not the case, this vehicle will not be used. At that moment no other combination of requests will lead to a route with a higher profit since the most profitable routes are already formed. Therefore, adding a fixed vehicle cost may lead to less routes being constructed and as a consequence less requests might be accepted. When a vehicle is removed, it is possible that the requests that were in this route are better placed in one of the remaining vehicle routes instead of current requests in that route.

To incorporate a fixed vehicle cost, additional steps are added to the TSA algorithm. The modified TSA algorithm is given in algorithm 6 on page 161. As in section 6.5 PostOptimize() indicates the REORDER operator is applied and LocalSearch() is used to refer to the improvement heuristic. First, the insertion heuristic and post-optimization operator are run. Afterwards the fixed cost of the vehicles is added to each of the existing routes. In a third step the TSA algorithm is used as in chapter 6. This will lead to the most profitable routes given the fixed vehicle cost. Step four checks whether all routes are profitable. If a route is not profitable it is removed and the requests from these routes are stored in a separate list. As the TSA algorithm should lead to the most profitable routes, no other routes could be constructed with the unserved requests that will lead to profitable routes after the subtraction of the fixed vehicle cost. Hence, as one of the initial constructed routes is not profitable, fewer vehicles will be used in the optimal solution. Next, the TSA algorithm is rerun taken the previous solution (without the unprofitable routes) as an input. However, this time only the remaining vehicles are considered. Maybe in the first run of the algorithm putting the requests into the route of the removed vehicle leaded to the highest profit, but the request could also be inserted in an existing route with a lower profit margin. This lower profit margin may still be higher than the one of the requests inserted in the route at this moment. For this reason, the requests removed from a deleted route together with the other unserved requests are considered for insertion in one of the remaining routes during the second run of the adapted TSA algorithm. For the INSERT operator only removed requests from the unprofitable routes which were stored in a separate list are used. The SWITCH operator takes all unserved requests into consideration. Because fewer routes are considered, the run time of the second TSA algorithm is lower than the first run. Finally, the profit of the routes is again tested and the improvement heuristic (section 6.3) is applied. This algorithm will be referred to as TSA*.

7.3.2 Numerical example

In this section the instance as described in section 7.2.2 is used. A comparison is made between the solution with and without the fixed vehicle cost.

When no fixed vehicle cost is incurred, AIMMS was able to solve the instance in 52,41 minutes. The optimal profit is 547,36€ and the constructed routes together with the unserved requests are given in table 7.6.

Table 7.6: PDSP: Optimal solution of reduced instance 1

Route 1:	0 - 19 - 44 - 25 - 50 - 0
Route 2:	0 - 24 - 12 - 49 - 37 - 15 - 40 - 0
Route 3:	0 - 5 - 17 - 4 - 29 - 30 - 23 - 42 - 48 - 0
Route 4:	0 - 14 - 2 - 8 - 27 - 33 - 39 - 0
Route 5:	0 - 3 - 18 - 28 - 7 - 32 - 43 - 0
Unserved requests:	1, 6, 9, 10, 11, 13, 16, 20, 21, 22

Algorithm 6 TSA* algorithm: with fixed vehicle cost

```
Empty tabu set
Set gNoImpr = 0
Set S_best to initial solution from insertion heuristic
S_best = PostOptimize(S_best)
Add fixed vehicle cost to each route
S_best = LocalSearch(S_best)
while gNoImpr < K do
  S = S_best
  S'_best = TABU(S)
  if Profit(S'_best) > Profit(S_best) then
    Set S_best to S'_best and gNoImpr = 0
  else
    gNoImpr = gNoImpr + 1
    reset T to T_0
  end if
end while
Remove unprofitable routes
Set gNoImpr = 0
while gNoImpr < K do
  S = S_best
  S'_best = TABU(S)
  if Profit(S'_best) > Profit(S_best) then
    Set S_best to S'_best and gNoImpr = 0
  else
    gNoImpr = gNoImpr + 1
    reset T to T_0
  end if
end while
Remove unprofitable routes
S_best = LocalSearch(S_best)
output S_best
```

When a fixed vehicle cost of 60€ is added for each vehicle used, AIMMS (see table 7.7) finds a total profit of 308,56€ in a run time of 237,89 seconds. As expected the total profit is lower.

Table 7.7: Fixed vehicle cost of 60€

Route 1:	0 - 19 - 44 - 14 - 2 - 8 - 27 - 33 - 39 - 0
Route 2:	0 - 24 - 18 - 12 - 49 - 37 - 15 - 40 - 43 - 0
Route 3:	0 - 5 - 6 - 4 -29 - 31 - 30 - 7 - 23 - 32 - 48 - 0
Route 4:	/
Route 5:	/
Unserved requests:	1, 3, 9, 10, 11, 13, 16, 17, 20, 21, 22, 25

Due to the additional vehicle cost two routes less are constructed. The three remaining routes are all adapted due to the fixed vehicle cost. In the second route an additional request (18) is added. This request was first served by route five, which is now removed. If we look at the difference in profit between the two routes (route two of table 7.6 and of table 7.7) the profit is lower in the second route. Within the optimal solution the route has a total profit of 132,88€, where the profit now is 98,47€. This may be expected because an additional vehicle cost of 60€ is added. However, when the fixed vehicle cost is left out, the profit increases to 158,47€, which is higher than the original profit. This means that in first instance it was better to serve request 18 in route five. When adding the vehicle cost this route was no longer profitable. Still inserting request 18 in route two led to a higher profit than leaving this request unserved. The same applies to request seven of deleted route number five. When adding this request into route three it is now longer optimal to serve request 17, this request is replaced by request six. Request three of the removed route remains unserved. From route four, which is removed because it was no longer profitable, all requests were able to be inserted in route one. Due to this, request 25 is removed from route one. In total 12 requests remain unserved, compared to the ten requests in the solution without the fixed vehicle cost. This means that only two additional requests are left unserved, when two routes with a total of six requests are removed.

The TSA* algorithm was able to find the optimal solution of table 7.7, this within three seconds. Although the TSA* algorithm was able to find the optimal solution for this instance, other solutions found show great variation. This may be due to the moment when the profitability of the routes is tested. If a route at that moment is profitable it is not deleted and another solution is obtained. In addition, routes with a low profit are not deleted, although this may sometimes lead to better solutions.

Hence when the found solution, before checking the profitability, is not the optimal solution great variations are found in the end solution. The effect of the random numbers used in the TSA algorithm is enlarged by checking the profitability at one moment in time and then repeating the TSA algorithm. A slight difference between two solutions after the first run, may become a large difference in the end solution. Future research should look at introducing a new local search operator that tries to reduce the number of used vehicles and insert the accepted requests into other existing routes. This may allow constantly checking the fixed cost and profitability of the vehicle routes, instead of only removing unprofitable routes after a TSA run. Furthermore, this removes the need to repeat the TSA algorithm twice.

7.4 Pickup and delivery selection problem with an LSP

In order to increase the number of transport requests that are accepted, a carrier may outsource requests to a logistic service provider (LSP). The consideration has to be made whether a request is performed with the vehicle fleet of the carrier, outsourced to a LSP or refused. This definition is different than the problem of Schönberger and Kopfer (2004) where all requests are divided between the carrier and the LSP and none remain unserved.

In Kopfer and Wang (2009) a vehicle routing problem is studied, which allows subcontracting a part of the requests to external carriers. For each request it has to be decided whether it is conducted with own sources or with a carrier. Their results show great cost savings by allowing subcontracting. Also Bolduc et al. (2007) consider the possibility to outsource requests to external carriers. The objective is to minimize the sum of all costs, internal and external. The cost of an external carrier was set to six times the distance between depot and the client. Both the research of Kopfer and Wang (2009) and Bolduc et al. (2007) do not allow refusing a client.

In our case of the pickup and delivery selection problem with a LSP (PDSPLSP), outsourcing requests to a LSP induces a fixed cost for each request. The PDSPLSP checks if it is cheaper to perform the request with an own vehicle or pay the LSP to perform the requests. A third option is to refuse the client. The optimal routes constructed for a carrier in the PDSPLSP are not necessarily the same as the optimal routes for the PDSP. In the PDSPLSP a carrier may decide to perform a request that remains unserved in the PDSP instead of an accepted request, even when this leads to a lower profit, because the profit obtained from outsourcing a request that is accepted in the PDSP may be higher than the profit of outsourcing requests that are unserved in the PDSP. So within the PDSPLSP the total profit of the own routes may be lower, but the profit obtained from the outsourced requests may be sufficiently high enough to overcome this loss. This may lead to a higher total profit.

To represent the PDSPLSP an additional decision variable is introduced:

$$\begin{aligned} Ylsp_i &= \text{binary outsource variables} \\ &= 1 \text{ if an LSP performs request } i \end{aligned}$$

Both Y_i^k and $Ylsp_i$ are connected with each other. $Ylsp_i$ is only allowed to be equal to one if Y_i^k is equal to zero. Only when a request is not performed by a vehicle of the carrier it may be outsourced to an LSP. This may be formulated as:

$$\text{if} \sum_{k=1}^{K} Y_i^k = 0 \text{ ,than } Ylsp_i \leq 1 \qquad \forall i \in P$$

$$\text{if} \sum_{k=1}^{K} Y_i^k = 1 \text{ ,than } Ylsp_i = 0 \qquad \forall i \in P$$

This can be put into one constraint (7.4).

$$\sum_{k=1}^{K} Y_i^k + Ylsp_i \leq 1 \quad \forall i \in P \tag{7.4}$$

The symbol, C_{lsp}, represents the cost generated when outsourcing a request. This allows redefining the objective function to:

$$\max \sum_{k \in K} \Big[\sum_{i \in P} Rev_i \cdot Y_i^k - \sum_{i \in N} \sum_{j \in N} ct \cdot d_{ij} \cdot X_{ij}^k \Big] + \sum_{i \in P} \Big[Rev_i \cdot Ylsp_i - C_{lsp} \cdot Ylsp_i \Big] \tag{7.5}$$

In section 7.4.1 the modifications to the TSA algorithm are presented. A numerical example is given in section 7.4.2.

7.4.1 Modifications to the TSA algorithm

The insertion heuristic of the TSA algorithm is adapted to incorporate profits from outsourcing requests to an LSP. In a first step the potential profit from outsourcing a request is calculated for all requests. This is the difference between the revenue gained and the price paid to the LSP. In a next step requests are added to routes in the same way as in the insertion heuristic of section 6.2. However, this time it is not only checked whether it is profitable to perform a request, but also if it is more profitable than outsourcing a request to an LSP. When a request is inserted into a route of a carrier it cannot be outsourced to an LSP.

The INSERT and SWICH operators are also slightly modified. Every time a request is inserted into a route from the list of unserved requests, it is verified whether the profit is higher than the potential profit obtained when outsourcing the request.

To solve the PDSPLSP, the DELETE operator (of algorithm 5 in section 6.5) is also used as a local search operator in a modified form. A request may be removed from a route when a higher profit can be obtained from outsourcing the request to an LSP. Within the SHUFFLE(S) algorithm, obtaining a higher profit is not an objective and the request is removed regardless of the potential profit to allow extra diversification from the current local optimum.

At the end of the algorithm all requests that remain unserved by the carrier are checked. If the fixed cost to outsource the request is less than the revenue gained from the client, the request is outsourced to an LSP. This new algorithm is further referred to as the TSA-LSP algorithm.

7.4.2 Numerical examples

In this section the reduced instance of class one (as used in section 7.2.2) is solved for the PDSPLSP. Next, the outcome of the PDSP is compared with the outcome of the PDSPLSP for the original instance of class one with 50 requests.

7.4.2.1 PDSPLSP instance of class 1

A fixed outsourcing cost of 50€ for a single request is added to the instance. The optimal solution found with AIMMS is given in table 7.8 and took 92,88 minutes to solve. The maximum total profit gained is 561,47€.

The best found solution of the TSA-LSP algorithm is given in table 7.9 and has a run time of three seconds. The total profit obtained is 561,26€ and has a gap of 0,04% with optimal profit found by AIMMS. Although the difference in total profit is very small the structure of the solution is quite different. Instead of three only two requests are outsourced to an LSP in the solution of the TSA-LSP algorithm. Furthermore one request less is accepted and two out of the five routes are different than in the optimal solution. None of the remaining unserved requests have a revenue higher than 50€. On the other hand several requests that are performed by the carrier have a revenue higher than 50€, this means that the carrier is able to perform the requests at a lower cost than the LSP.

Table 7.8: PDSPLSP: Optimal solution of reduced instance 1

Route 1:	0 - 19 - 44 - 25 - 50 - 0
Route 2:	0 - 14 - 2 - 8 - 27 - 33 - 39 - 0
Route 3:	0 - 5 - 6 - 4 - 29 - 31 - 30 - 15 - 40 - 0
Route 4:	0 - 3 - 18 - 28 - 7 - 32 - 43 - 0
Route 5:	0 - 24 - 17 - 49 - 23 - 42 - 48 - 0
Unserved requests:	1, 9, 10, 11, 20, 21, 22
Performed by the LSP:	12, 13, 16

Table 7.9: PDSPLSP: TSA-LSP algorithm

Route 1:	0 - 19 - 44 - 25 - 50 - 0
Route 2:	0 - 14 - 2 - 8 - 27 - 33 - 39 - 0
Route 3:	0 - 5 - 17 - 4 - 29 - 30 - 23 - 42 - 48 - 0
Route 4:	0 - 3 - 18 - 28 - 7 - 32 - 43 - 0
Route 5:	0 - 24 - 12 - 49 - 37 - 15 - 40 - 0
Unserved requests:	1, 6, 9, 10, 11, 20, 21, 22
Performed by the LSP:	13, 16

7.4.2.2 Comparison between the PDSP and the PDSPLSP

The complete set of 50 requests from the original instance of class one is solved for the PDSP and PDSPLSP. Again a fixed outsource cost of 50€ is used for the LSP. In table 7.10 the best found solution of the PDSP with the TSA algorithm is given. Table 7.11 shows the best found solution of the PDSPLSP with the TSA-LSP algorithm. Within the PDSP a profit was achieved of 1261,59€ the TSA algorithm has a run time of 82 seconds. Solving the instance as a PDSPLSP lead to a total profit of 1323,30€, from which 1242,37€ is generated by the vehicle fleet of the carrier and an additional 80,93€ was gained from outsourcing requests to an LSP. The TSA-LSP algorithm has a run time of 116 seconds. An increase in profit of 4,9% is obtained when outsourcing is allowed.

When comparing both solutions it can be seen that fewer requests are refused

Table 7.10: PDSP: Best found solution of instance 1

Route 1:	0 - 24 - 34 - 74 - 84 - 47 - 97 - 0
Route 2:	0 - 46 - 14 - 96 - 36 - 86 - 64 - 0
Route 3:	0 - 19 - 69 - 2 - 28 - 45 - 32 - 78 - 52 - 95 - 82 - 0
Route 4:	0 - 27 - 6 - 4 - 54 - 56 - 37 - 77 - 87 - 0
Route 5:	0 - 44 - 8 - 94 - 58 - 29 - 79 - 0
Route 6:	0 - 12 - 10 - 62 - 40 - 15 - 90 - 65 - 60 - 0
Route 7:	0 - 39 - 30 - 89 - 26 - 80 - 43 - 76 - 23 - 93 - 73 - 0
Route 8:	0 - 50 - 16 - 66 - 100 - 0
Route 9:	0 - 3 - 18 - 53 - 33 - 83 - 68 - 0
Route 10:	0 - 5 - 35 - 42 - 55 - 7 - 85 - 57 - 92 - 0
Unserved requests:	1, 9, 11, 13, 17, 20, 21, 22, 25, 31, 38, 41, 48, 49

Table 7.11: PDSPLSP: Best found solution of instance 1

Route 1:	0 - 24 - 12 - 74 - 62 - 40 - 15 - 90 - 65 - 0
Route 2:	0 - 46 - 14 - 96 - 36 - 86 - 64 - 0
Route 3:	0 - 19 - 69 - 27 - 6 - 4 - 54 - 56 - 37 - 77 - 87 - 0
Route 4:	0 - 35 - 42 - 7 - 85 - 57 - 92 - 0
Route 5:	0 - 44 - 8 - 94 - 58 - 29 - 79 - 0
Route 6:	0 - 43 - 28 - 78 - 32 - 93 - 82 - 0
Route 7:	0 - 39 - 89 - 49 - 45 - 23 - 95 - 99 - 73 - 0
Route 8:	0 - 50 - 34 - 2 - 84 - 52 - 100 - 0
Route 9:	0 - 3 - 18 - 53 - 33 - 83 - 68 - 0
Route 10:	0 - 5 - 30 - 26 - 80 - 76 - 55 - 0
Unserved requests:	1, 9, 10, 11, 17, 20, 21, 22, 31, 41, 48
Performed by the LSP:	13, 16, 25, 38, 47

in the PDSPLSP, 11 compared to 14 requests in the PDSP. At the same time less requests are performed by the vehicle fleet of the carrier. In the PDSP 36 requests are accepted by the carrier. In the PDSPLSP 34 requests are done by the carrier, the remaining five requests are outsourced to an LSP. The profit made by the carrier with the use of his own vehicle fleet is higher in the case of the PDSP. In the PDSPLSP some requests are outsourced to the LSP leading to a higher total profit, although they also could have been done by the carrier. Only three out of the ten routes constructed by the carrier are the same in both cases (routes 2, 5 and 9). The other seven routes differ largely. This shows that the PDSP and the PDSPLSP, although they show some similarities, are very different planning problems leading to different outcomes. In the examples discussed in this section the price for an LSP to serve a client was fixed and the same for all requests. Future research may look at different methods to calculate the price of an LSP. In Bolduc et al. (2007) the price is based on the distance between the depot and the client. The same principle could by applied in the PDSPLSP by basing the price on the distance between pickup and delivery. This however does not alter the applied TSA-LSP algorithm.

7.5 An alternative revenue model for the carrier

Within the freight transportation framework proposed in chapter 3 the pricing of the transport requests may happen in two ways. Either the price is fixed, resulting in a selection problem for the carrier to determine the profitable requests or the pricing is done accordingly to the cost incurred to execute the request.

In chapters 5 and 6 the assumption was made that the price is fixed and that revenue depends on the distance between the pickup and delivery point of the client. A price per kilometre of four euro was asked to the client. Hence it was up to the carrier to select clients based on their revenue keeping in mind his limited resources. In most real life cases transport prices depend on the total number of units that are being transported as well and not solely on the distance travelled. However, this may be easily applied in the presented heuristic of chapter 6. No alterations to the heuristic need to be made in order to take into account unit pricing. The only difference would be the calculation of the proposed revenue in the input data. Therefore instances where transport revenue depends on the number of units transported may be solved with the heuristic as well. In this section the assumption of a fixed revenue per kilometre is relaxed. Now the carrier has the opportunity to set his price according to the costs made to execute the transport requests. The objective is to try to accept as many clients as possible given the limited resources and later determine the price each client has to pay to cover the total cost. The problem at hand is still a selection problem due to the fixed vehicle size and the limited amount of working hours each day, but the objective is no longer to maximize the profit. The carrier will try to serve as many clients as possible during a single day. In a final step the transport price for each client is calculated, based on the minimum price necessary to cover the cost made and a fixed profit margin. From the view point of the carrier it is assumed that there is no cost difference between the routing of an empty truck or a full truck. The cost of a truck is considered to depend solely on the distance travelled. The extra fuel consumption for driving a truck that is loaded is considered to be marginal in the total cost of operating a truck per kilometre.

The objective function of section 5.4 is replaced by function (7.6), all constraints remain the same.

$$\max \sum_{i \in P} \Big[\sum_{k=1}^{K} Y_i^k \Big] \tag{7.6}$$

In literature this type of selection problem, which maximizes the number of accepted clients within a PDP, is not often studied. A variant of this selection problem, where resources are scarce, may be found in Colorni and Righini (2001). They propose a dynamic dial-a-ride problem in which the maximization of the number of customers served is part of the studied objective function. The other two parts of the objective function are to optimize the level of service perceived by the customers, and minimize the total distance traveled by the vehicles. A customer is accepted if certain conditions are satisfied. In order to satisfy the conditions imposed, a negotiation process exists between the carrier and the client. If a client's request is not acceptable, the client may modify it and the negotiation continues until either the request is accepted or the client gives up.

7.5.1 Modifications to the TSA algorithm

The algorithm is split into two phases. First, the selection problem is solved trying to serve as many clients as possible. In a second phase, the selling price of transport requests is set.

The first phase starts with the insertion heuristic. No revenue per request is given in the input data. The objective is to accept as many requests as possible in order to optimize the use of the available vehicles. Therefore, all requests are inserted as long as vehicle capacity is still available and time windows are respected. When a request is inserted, it is placed into the route where it induces the lowest increase in the transport cost. Furthermore the local search operators are altered. The INSERT operator, now only checks whether an insertion is possible and no longer at the incurred cost of inserting a request. The incurred cost is the transport cost for travelling the additional distance to serve the extra client. The SWITCH, SHIFT and EXCHANGE operators remain the same. As there is no revenue, the transport cost before and after the change is compared instead of the profit. The improvement heuristic repeats the loop of local search operators as long as more requests are accepted (instead of an improvement in profit as with the PDSP). Finally, also in the TSA algorithm the assessment criteria are changed to the number of accepted requests instead of the total profit over all routes. The DELETE operator is no longer used within the TSA algorithm, because the algorithm tries to insert as many requests as possible. The assessment criterion looks for an increase in the number of accepted requests, hence removing a request reduces the chance of finding a better solution.

The second phase calculates the total cost for each vehicle, as the total distance travelled times the price per kilometre. After this, the marginal cost of each client is determined. The cost of a route with and without a client is taken and the difference of these costs is the marginal cost of that request. The total cost of a route is divided between the clients of that route, based on the share of their marginal cost. Afterwards a profit margin is added to the cost, this gives the price asked to clients in order to execute their transport request.

7.5.2 Numerical example

As in section 7.2.2, instance one is used to demonstrate the altered TSA algorithm. Solving the instance with AIMMS leads to the conclusion that the maximal number of requests that could be accepted is 18 out of the 25 requests. As the objective function does not differentiate between two different solutions with equally accepted number of requests, all solutions with 18 accepted requests are optimal. When applying the altered TSA algorithm an optimal solution was found in 17 seconds. The constructed routes can be found in table 7.12.

In a second phase the algorithm determines the price which the carrier has to ask from the client. The cost per route is calculated together with the marginal cost of each request. This can be found in table 7.13. In the table only the number of the pickup location is given to refer to a transport request. For each route the sum of the marginal costs and the share of the marginal cost from each request in the total sum are calculated. Based on these shares the total cost of each route is divided over the requests in that route. A profit margin of 4% is assumed and added to the cost (based on the report of FTA (2012)). This leads to the price asked to the client to execute its transport request. The final outcome can be found in table 7.14.

Table 7.12: Optimal solution when maximizing the number of accepted requests

Route 1:	0 - 5 - 21 - 46 - 30 - 7 - 23 - 32 - 48 - 0
Route 2:	0 - 24 - 10 - 49 - 8 - 22 - 33 - 47 - 35 - 0
Route 3:	0 - 19 - 44 - 6 - 4 - 29 - 31 - 9 - 34 - 0
Route 4:	0 - 14 - 2 - 11 - 27 - 36 - 39 - 0
Route 5:	0 - 3 - 18 - 28 - 15 - 40 - 43 - 0
Unserved requests:	1, 12, 13, 16, 17, 20, 25

Table 7.13: Cost of the routes and marginal cost of the requests

(in euro)	Route 1:	Route 2:	Route 3:	Route 4:	Route 5:
Cost per route:	112,31	114,40	74,30	84,45	70,92
Marginal cost:	5: 43,73	24: 12,36	19: 18,51	14: 17,14	3: 12,30
	21: 4,54	10: 8,02	6: 3,89	2: 29,73	18: 1,85
	7: 15,32	8: 40,38	4: 5,36	11: 16,70	15: 23,99
	23: 17,92	22: 15,72	9: 20,21		

Table 7.14: Price per client to execute the transport request

Route 1:	Route 2:	Route 3:	Route 4:	Route 5:
5: 62,61	24: 19,27	19: 29,83	14: 23,71	3: 23,75
21: 6,54	10: 12,49	6: 6,26	2: 41,02	18: 3,62
7: 21,96	8: 62,82	4: 8,65	11: 23,10	15: 46,38
23: 25,70	22: 24,40	9: 32,53		

None of the routes from table 7.12 corresponds to the optimal solution of the PDSP given in table 7.6. The total number of unserved requests went down with three requests. Only four (1, 13, 16 and 20) out of the seven unserved requests from table 7.12 are the same as in the PDSP. This may indicate that it is hard to serve these requests together with other requests from instance 1. Other clients that remain unserved with the PDSP, because their profit was too low, are now accepted. It can be concluded that different routes are constructed when no prefixed revenue is set and the carrier does not have to optimize his profit.

Using only the number of accepted requests as an assessment criteria in the TSA algorithm, limits the algorithm in finding the optimal solution. As only a limited amount of iterations without improvement is allowed and an improvement is only possible by accepting an additional request. With the local search operators currently used this is only possible by applying the INSERT operator. Future research should look at better suited local search operators or a more appropriated metaheuristic. Next, the objective function could be extended, in further research, by including the minimization of the total cost/distance.

7.6 Multi-period pickup and delivery selection problem

Until now the assumption is made that refusing a client has no impact on future profits of a carrier. However, in reality a carrier may be faced with a client who will not consider doing future business when his transport request is refused. In this section a multi-period pickup and delivery selection problem (MPPDSP) is proposed, which may take into account a possible loss of future transport requests. If a transport request of a client is refused today, the client may stay away in the future. So it might be better to accept a small loss today, to gain larger future profits. In this case, when selecting requests, a distinction has to be made between loyal clients and occasional clients. Losing a loyal client may have a higher impact than missing out on an occasional client.

The MPPDSP is studied as a static problem, in which transport requests of three consecutive periods are known in advance. In literature a rolling horizon is often applied to multi-period routing problems (Arda et al., 2012; Berbeglia et al., 2010; Bostel et al., 2008). Applying a rolling horizon to the PDSP is very hard to solve, as selecting a request in period one has an influence on the profit of future periods. Effects on future profits of a carrier are hard to determine over more than two periods. Decisions on selecting requests in two consecutive periods have to be taken into account, to know what the potential loss or profit is in period three. For this reason it is opted not to apply a rolling horizon, but to select requests for three periods in a row. It is arbitrary chosen to opt for a planning horizon of three periods. This planning horizon can either be shorter or longer, but it has to be kept in mind that more periods make the MPPDSP harder to solve. In this case long-term contracts with clients are undertaken where clients are either accepted for three periods or refused for three periods. Not all clients have transport requests for all three periods, some occasional clients only demand transport for one or two of the three planning periods. For all these clients a single decision is made in period one. These decisions will last for three periods after which in period four new decisions have to be made for the new batch of transport requests.

To the author's knowledge the MPPDSP as defined in this section is not yet studied in literature. Even the multi-period VRP is not often studied. In Wen et al. (2010) a dynamic multi-period VRP is studied. The objectives are minimizing the total travel cost and waiting time for customers, while balancing the daily workload. Two main phases are conducted to solve the problem. First a selection is made of which customers to serve in each period, secondly routes are generated. The main differences with the MPPDSP, are that all requests have to be performed and the objective function of the MPPDSP maximizes the profit. Mourgaya and Vanderbeck (2007) investigate a periodic VRP, where visits to clients are planned over a given time horizon to satisfy a certain service level. Again two main phases in the solution method may be recognised. The dates to visit customers are first decided together with the vehicle choice. Later the vehicle routes are optimized. Also Francis et al. (2006) studied the period vehicle routing problem with service choice. Customers may choose the minimum number of times they require service, after which the carrier determines a schedule from a predefined set of visiting days. A carrier may deliver a better service by visiting the client more often than the minimum required. The objective is to minimize the total travel time.

The hardest part of the MPPDSP is to determine the future loss or profit a client will generate, in order to know whether to accept or reject the client. This is also recognised by Schönberger (2005), who state that the lost revenues cannot be adequately incorporated into the calculation of the profitability of a request. The profitability of a request in the future depends on how good the request fits into the constructed routes and whether a profitable route may be constructed together with the other clients. As this depends on future decisions of the carrier, the lost revenues of a request are difficult to assess at the current moment when the decision to accept or reject a client has to be made. Therefore, a simultaneous planning is done for the three periods, instead of studying a dynamic MPPDSP. The assumption is made that a loyal client has the same transport request, a fixed track, in each of the considered planning periods. Other clients might have transport requests in two of the three periods or just a sole transport request in a single period. A selection problem has to be solved for multiple periods at the same time, together with the grouping of requests into vehicles and the construction of vehicle routes.

To extend the PDSP of chapter 5 to a MPPDSP the problem formulation needs to be adapted. In Cordeau et al. (1997) a periodic VRP is presented, on which the formulation of the MPPDSP is based. A multigraph $G = (V, A)$ is defined in which the same arc can be travelled several times in the planning horizon. Each arc set of A is determined by a vehicle, k and a day, l. Each day, l is part of the planning horizon $L = 1, ..., d$, with d the total number of days in the planning horizon. To formulate the MPPDSP as a linear problem, the decision variables are extended with index l, for each day of the planning horizon on which they are used. A client is accepted or rejected for the entire planning period, for this reason an extra constraint (7.12) is added. However not all clients have a transport request for each planning period, some clients demand transport for only one or two periods. To incorporate this into the model formulation an extra parameter, E_{il}, is introduced. When a request i exists on day l parameter E_{il} is equal to one, otherwise it is equal to zero. Constraints (7.21) and (7.22) are only required when there is a transport demand for that day. In section 5.4 the variables and constraints that form the base for the formulation of the MPPDSP are defined.

$$\max \sum_{k \in K} \sum_{l \in D} \Big[\sum_{i \in P} Rev_{il} \cdot Y_{il}^k - \sum_{i \in N} \sum_{j \in N} ct \cdot d_{ij} \cdot X_{ijl}^k \Big] \tag{7.7}$$

$$\sum_{\substack{j=1 \\ j \neq i}}^{N} X_{ijl}^k - \sum_{\substack{j=1 \\ j \neq i}}^{N} X_{jil}^k = 0 \qquad \forall i \in N, \forall k \in K, \forall l \in L \tag{7.8}$$

$$\sum_{j \in P} X_{0jl}^k \leq 1 \qquad \forall k \in K, \forall l \in L \tag{7.9}$$

$$\sum_{i \in D} X_{i(2n+1)l}^k \leq 1 \qquad \forall k \in K, \forall l \in L \tag{7.10}$$

$$\sum_{k=1}^{K} Y_{il}^k \leq 1 \qquad \forall i \in P, \forall l \in L \tag{7.11}$$

$$\sum_{k=1}^{K} Y_{il}^k = \sum_{k=1}^{K} Y_{im}^k \qquad \forall i \in P, \forall l, m \in L \wedge l \neq m \tag{7.12}$$

$$L_{il}^k \leq Q_{\max} \qquad \forall i \in N, k \in K, \forall l \in L \quad (7.13)$$

$$L_{0l}^k = 0 \qquad \forall k \in K, \forall l \in L \quad (7.14)$$

$$L_{jl}^k - L_{il}^k - \mid q_{jl} \mid \geq -M \cdot (1 - X_{ijl}^k) \qquad \forall i, j \in N \wedge i \neq j, \ \forall k \in K, \forall l \in L \quad (7.15)$$

$$e_{il} + ot_{il} \cdot \mid q_{il} \mid \leq T_{il}^k \leq l_{il} \qquad \forall i \in N \backslash O, \forall k \in K, \forall l \in L \quad (7.16)$$

$$T_{0l}^k = s_k \qquad \forall k \in K, \forall l \in L \quad (7.17)$$

$$s_k \leq T_{il}^k \leq f_k \qquad \forall i \in N, \forall k \in K, \forall l \in L \quad (7.18)$$

$$T_{il}^k + t_{ij} - T_{jl}^k + ot_{jl} \cdot \mid q_{jl} \mid \leq (1 - X_{ijl}^k) \cdot M \qquad \forall i, j \in N, \forall k \in K, \forall l \in L \quad (7.19)$$

$$T_{il}^k + t_{i(n+i)} - T_{(n+i)l}^k \leq (1 - Y_{il}^k) \cdot M \qquad \forall i \in P, \forall k \in K, \forall l \in L \quad (7.20)$$

$$\sum_{j \in N \backslash O} X_{ijl}^k = Y_{il}^k \cdot E_{il} \qquad \forall i \in P, \forall k \in K, \forall l \in L \quad (7.21)$$

$$\sum_{j \in N \backslash O} X_{j(n+i)l}^k = Y_{il}^k \cdot E_{il} \qquad \forall i \in P, \forall k \in K, \forall l \in L \quad (7.22)$$

$$X_{ijl}^k \in \{0, 1\} \qquad \forall i, j \in N, \forall k \in K, \forall l \in L \quad (7.23)$$

$$Y_{il}^k \in \{0, 1\} \qquad \forall i \in P, \forall k \in K, \forall l \in L \quad (7.24)$$

$$T_{il}^k, L_{il}^k \geq 0 \qquad \forall i \in N, \forall k \in K, \forall l \in L \quad (7.25)$$

7.6.1 Modifications to the TSA algorithm

In this section the TSA algorithm is extended to include the planning period of three days. First the insertion heuristic is adapted. After the construction of routes for day one, which is done as described in section 6.2, the accepted requests are inserted in routes for day two and three. When the request exists in days two or three it is inserted into the routes of that day. First, a profitable insertion is tried, when this is not possible the request is inserted regardless of the potential loss. The insertion heuristic results in an initial solution for which day one has only profitable routes and day two and three may contain routes which are not profitable. This is to ensure that a request which is accepted, is also performed on all three days. The local search operators and the metaheuristic attempt to increase the overall profit of the three days. Here it is no longer necessary that day one has only profitable routes. When accepting a transport request it can be that this request may only be served at a profit for one or two days and that a loss is generated on the other days. As long as there is an overall profit the client is accepted.

The local search operators EXCHANGE and SHIFT remain unchanged and are applied between routes within the same day. The INSERT operator is extended to include multiple days. A separate INSERT operator is made for each day. In the INSERT operator of, for example, day one a possible profitable insertion of an unserved request that exists for that period is considered. If the operator succeeds to insert a new request, this request is also inserted for the other days given that the request exists for those days. In case of a successful insertion into routes of day one, the insertion into routes of day two or three no longer needs to be profitable. At the end of the INSERT operator it is checked whether the total profit of the entire planning period is increased. If this is not the case the request is again removed and the search continues. Hence for each INSERT operator it is necessary that the insertion in the routes of the considered period is profitable, that the overall profit of the planning period increases and that a feasible insertion is possible on all days. In the SWITCH operator first the request with the lowest marginal profit is removed from the route considered on a certain day. Secondly, this request is also removed from the planning for the other two days. The SWITCH operator has the same principle as the INSERT operator to insert a request from the list of unserved requests.

The TSA algorithm remains unchanged for the MPPDSP. Only the DELETE operator is modified. When a request is removed, it is deleted from the routes of all planning days. To check if a solution found is better than the previous solution, the overall profit of the planning period is compared.

The modified TSA algorithm for the MPPDSP will be referred to as MP-TSA algorithm.

7.6.2 Numerical example

Due to the inclusion of multiple periods, the complexity of the PDSP is strongly increased. Extra constraints are added and an extra index is included for each of the variables. This makes the MPPDSP very hard to solve. If we still want to be able to solve an instance to optimality with AIMMS we have to further reduce the instance considered in section 7.2.2. For each day in the planning period 19 transport requests are received from 19 different clients. From these 19 requests seven are common for all days, six are available for two out of three days and six requests are clients who have only a transport demand for one day. The instance used in this section can be found in tables F.1 and F.2 of appendix F.

The optimal solution found with AIMMS is given in table 7.15. An overall profit over the entire planning period of 1151,10€ is obtained. This solution was found in 1114,47 seconds. It may be noticed that transport requests of loyal clients (request for three days) are not always combined in the same route. As some requests of other clients are not available on all days, this allows creating different combinations of routes for each day. So a separate planning is done for each day. This causes extra complexity in the MPPDSP, as not only a selection of requests has to be made, but it has to be taken into account that different routing possibilities exist for each day.

The best found solution generated with the MP-TSA algorithm has a profit of 1060,42€ and is given in table 7.16. The MP-TSA algorithm only took 13 seconds to find the solution. A gap exists in the overall profit of 7,9% with the optimal solution. Given the increased complexity of the MPPDSP compared to the PDSP, the MP-TSA algorithm still produces solutions with an acceptable quality. Future research may consider alternative methods to solve the MPPDSP. Moreover the run time of the algorithm has to be kept in mind. For this small example the MP-TSA algorithm already took longer to solve than the TSA-algorithm for the PDSP. This may be overcome by generating a two-phase algorithm, in which the selection of requests is separated from the construction of routes. Selection rules may be formulated in a first phase, which for example give different weights to loyal clients and to occasional clients. Due to the division between selecting clients and constructing routes, the run time could possibly be reduced This, however, needs still be further investigated. Furthermore, methods to determine the future lost revenues of a request should be considered. Being able to incorporate the future revenues of a client would allow to improve the selection of requests.

Table 7.15: MPPDSP: Optimal solution with AIMMS

Day 1:	
Route 1:	0 - 5 - 6 - 4 - 38 - 40 - 39 - 7 - 20 - 41 - 54 - 0
Route 2:	0 - 21 - 9 - 55 - 43 - 12 - 46 - 0
Route 3:	0 - 11 - 2 - 36 - 45 - 0
Day 2:	
Route 1:	0 - 5 - 15 - 6 - 4 - 38 - 40 - 39 - 49 - 0
Route 2:	0 - 24 - 28 - 58 - 2 - 62 - 36 - 7 - 41 - 23 - 57 - 0
Route 3:	0 - 16 - 50 - 9 - 43 - 27 - 61 - 0
Day 3:	
Route 1:	0 - 33 - 2 - 31 - 36 - 7 - 65 - 41 - 67 - 0
Route 2:	0 - 16 - 50 - 11 - 34 - 68 - 45 - 0
Route 3:	0 - 5 - 15 - 6 - 4 - 38 - 40 - 39 - 12 - 46 - 49 - 0
Unserved requests:	1, 3, 8, 10, 13, 14, 17, 18, 19, 22, 25, 26, 29, 30, 32

Table 7.16: MPPDSP: Best solution with MP-TSA algorithm

Day 1:	
Route 1:	0 - 2 - 19 - 36 - 53 - 0
Route 2:	0 - 5 - 11 - 4 - 38 - 39 - 45 - 0
Route 3:	0 - 21 - 9 - 55 - 43 - 7 - 20 - 41 - 54 - 0
Day 2:	
Route 1:	0 - 15 - 9 - 43 - 27 - 61 - 49 - 0
Route 2:	0 - 16 - 24 - 50 - 28 - 58 - 2 - 62 - 36 - 7 - 41 - 23 - 57 - 0
Route 3:	0 - 5 - 14 - 4 - 38 - 26 - 39 - 48 - 60 - 0
Day 3:	
Route 1:	0 - 30 - 64 - 14 - 4 - 38 - 48 - 0
Route 2:	0 - 16 - 50 - 11 - 2 - 31 - 36 - 7 - 65 - 41 - 45 - 0
Route 3:	0 - 5 - 15 - 34 - 39 - 68 - 49 - 0
Unserved requests:	1, 3, 6, 8, 10, 12, 13, 17, 18, 22, 25, 29, 32, 33

7.7 Integrating alternative problem settings in the freight transportation framework

In this chapter alternative problem settings are formulated based on problems carriers may encounter. In this section a reflection is made whether these problem settings could be integrated in the freight transportation framework of chapters 3 and 4. It would give a more realistic image of reality and adds more details to the model as decisions of carriers are better represented. When incorporating these alternative problem settings a trade-off has to be made between the benefit of the extra detail and information and the cost of longer run times in the model.

The PDSPCR in particular forms an interesting opportunity for the Logistic module. Carriers are often confronted with loyal clients, whom they cannot refuse or clients with long-term contracts. The integration of the PDSPCR in the framework may form some difficulties as decisions are formed on several time frames. The compulsory requests are accepted as tactical engagement in long-term planning. These decisions have to be modelled separately from the day-to-day planning of other transport requests.

Adding a fixed vehicle cost to the model does not require a lot of alterations. Only the algorithm used by the carrier is changed. A different decision criterion is applied and the carrier has to check if the revenue he obtains is high enough to cover the fixed vehicle cost. Other interactions in the framework remain the same. It has to be studied whether the actual decisions of a carrier is better represented with or without fixed vehicle costs.

The PDSPLSP on the other hand is harder to integrate in the current freight transportation framework. As carriers rely on each other to act as an LSP, to whom they may outsource certain requests. A carrier may receive orders directly from clients together with outsourced orders from other carriers in the model. At the same time the carrier himself may outsource transport orders to other carriers. This requires carriers to cooperate with each other and complicates the modelling of these interactions. Future research should look at horizontal cooperation and analyses onto the freight transportation model have to be performed to see if this extra modelling effort leads to better results.

Within the freight transportation model the option exists to iterate the price negotiation process between carriers and firms. This allows firms to let carriers compete with one another to set the best transport price for their transport request. The revenue model presented in section 7.5 facilitates this negotiation process, as individual transport prices are set for each client based on his transport request. When a firm has received the current transport price of a carrier he has to recalculate the optimal transport chain based on this new information, afterwards a new transport request is sent to his preferred carriers. This iteration continues until an agreement is reached.

Adding multiple periods to the decision making of the freight transportation framework allows fewer runs of the model. Within the MPPDSP selection decisions are made for a longer period in time, while the planning and routing of the vehicles are performed for each period. This means that the model has fewer runs because not all firms are sending out a transport request in each simulation period. However, the MPPDSP is more complex than the PDSP and requires a longer run time.

7.8 Conclusions and further research

Five alternative problem settings of the PDSP of chapters 5 and 6 are presented in this chapter. For each of them the implications on the TSA algorithm are investigated and shown with the help of a numerical example. These problem settings give interesting opportunities of incorporating real life situations of carriers in the freight transportation framework of chapter 3. Assumptions made in the PDSP are altered, which make some of these new problems harder to solve. Overall it may be concluded that solving these alternative problem settings with altered versions of the TSA algorithm lead to good results. Future research should further look at heuristics to solve the problems at hand and thoroughly test the new algorithms.

The altered version of the TSA algorithm for the PDSPCR in section 7.2 lead to good initial results. An alternative method for creating the initial solution, in case of a large share of compulsory requests, should be further studied. Here, allowing infeasible solutions might facilitate the process of finding good solutions with the heuristic. The aspects of the PDSPCR looks promising for integrating in the freight transportation framework proposed in this thesis. It will allow simulating long-term contracts. Future experiments with the PDSPCR could look at the requirements for this integration.

A PDSP with fixed vehicle cost in presented in section 7.3. The TSA* algorithm as presented may lead to diverse solutions, depending on the moment when the profitability of the routes is checked. From the different runs made with the TSA* algorithm, it can be concluded that the algorithm does not produce consistent solutions. Although the optimal solution was found in the numerical example made. Future research may introduce an additional local search operator, which tries to remove a route and insert the requests in other existing routes. This will make the algorithm less depended on finding a near optimal solution before considering the fixed vehicle cost. Taking this cost and the profitability of the routes into account throughout the entire algorithm may lead to better solutions and a more robust algorithm. Also routes with a low profit may be removed to increase the overall profit.

For the PDSPLSP of section 7.4 the altered version of the TSA algorithm give a good initial result. Still further research should test the algorithm on larger instances and may look at different methods to calculate the price of an LSP. To be able to integrate this model into the freight transportation framework, research on horizontal cooperation between carriers needs to be conducted.

In section 7.5 a selection problem without fixed revenue from clients is introduced. The objective is to serve as many clients as possible given the limited resources. The price of the transport service is calculated based on the actual induced cost. At the moment the only object is to serve as many clients as possible, however no differentiation is made between two solutions with the same amount of clients. Future research should try to create a bi-objective formulation, in which in first instance the number of accepted requests is maximized and secondly the total cost for the carrier is minimized. This would furthermore require the development of a new, better suited, algorithm to handle the bi-objective criteria.

Section 7.6 elaborates on the MPPDSP. To the author's knowledge this problem has not been studied before. The MPPDSP is especially hard to solve as multiple decisions have to be taken for a period over time. The impact of these decisions on the profitability of routes is hard to asses on the moment of the decision taking. A two-phase heuristic may form the objective of future research. This allows separating the selection of requests from the routing of requests with different vehicles. Also methods to assess the profitability or loss a request may generate in the future need to be looked into.

Chapter 8

Final conclusions and further research

The purpose of this thesis was to develop a new freight transportation framework in which the focus lies on the logistic decisions taken by the involved actors. Two main topics can be recognized in this thesis. The first part of this thesis deals with understanding how current freight transportation models work and what their shortcomings are (chapter 2). Based on this analysis a new conceptual freight transportation framework is proposed to fill in the research gaps (chapters 3 and 4). Secondly, the operational decisions of a carrier are formulated as a pickup and delivery selection problem and solved by a heuristic algorithm (chapters 5 and 6). This problem is extended into several alternative problem settings in chapter 7. This final chapter summarizes the main conclusions and indicates opportunities for future research (figure 8.1).

8.1 Final conclusions

Transportation models are often used by governments to have a better understanding of transport habits and to assess their policy decisions concerning, for example, infrastructure or subsidies to encourage durable transport modes. Early transportation models mainly focus on passenger transport and are built on an aggregated level. Due to the usage of aggregated data, they are missing out on behavioural aspects of individuals. Furthermore, these models may be biased due to aggregation errors. From the 1990's activity-based models are receiving a growing attention. These mod-

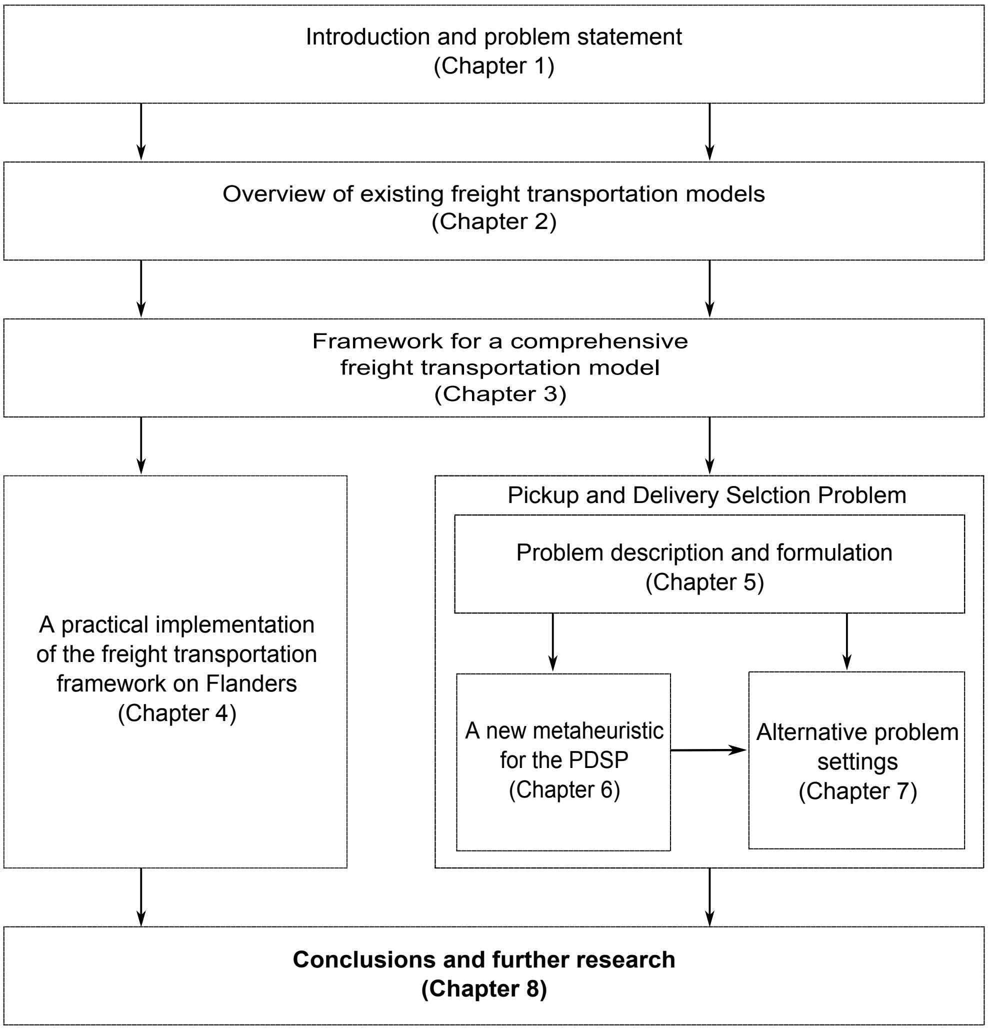

Figure 8.1: Outline of the thesis - Chapter 8

els are based on the awareness that travel behaviour is derived from the activities an individual performs.

Although early transportation models focus on passenger transport, a growing need for incorporating freight transport arises to have a complete picture of the transport within an area. Freight transport is mainly conducted via roads and hence interferes with passenger transport. This lead to the introduction of freight transportation models. Freight transportation models follow more or less the same path as passenger transportation models, starting from a basic aggregated four-step model, to more complex activity-based models during recent years. Still some difficulties remain to accurately represent the complex mechanism of freight transport. Several decision making actors need to be included and logistic decisions have to be modelled to represent freight flows at a disaggregated level. This will help to translate economic activities into vehicle movements. Only in the last decade freight transportation models tries to represent the logistical elements of the different actors involved.

To overcome the shortcomings of the state-of-the-practice four-step models, a new conceptual freight transportation framework is proposed in this thesis. A micro-simulated activity-based framework is created. This framework is able to model the characteristics of the different actors, to simulate the interactions between logistic players and represent trends in supply chain management and logistics. In this way, the framework gives guidance for a new state-of-the-art freight transportation model. Three types of actors are defined on a microscopic level, firms who are sending and receiving the goods, forwarders who are responsible for managing the entire transport chain and carriers who execute the transport. Interactions between actors are conducted via contracts. Contract formation may be achieved in several iterations, in which transport prices are adjusted and the details of the transport contract are worked out. Transport chains are built in a separate module and form the basis of the way goods are transported. This allows the incorporation of multiple transport modes.

A small scale example of the Logistic module of this framework is executed. This revealed that the initial shipment size used to determine the transfer points within the transport chain may have a large impact on the total logistic cost. This has an influence on the eventually chosen transport chain during the contract formation and on the chains considered for consolidation. Consolidation decisions at terminals are part of the task of a forwarder, because he is responsible for several clients and manages larger freight flows. Two different consolidation types are considered in the framework, either using a connected hub system or constructing a corridor. From the sensitivity analysis it became clear that the transport prices of the different transport modes influence the optimal transport chain. Besides, the price for loading or unloading a truck takes up a large share of the total transport cost in intermodal transport. Hence, special attention has to be paid to gathering accurate data on a disaggregated level.

The second part of this thesis highlights the decisions of a carrier. The operational planning decisions of a carrier consist of accepting transport requests of clients and constructing daily vehicle routes. Several clients may have less-than-truckload requests to be transported between two specified locations, these clients are consolidated into vehicle tours by the carrier. However, a carrier has only a limited capacity within his own vehicle fleet. Therefore he can only serve a selection of clients. Transport requests of clients are only accepted if they contribute to a higher total profit. A paired pickup and delivery selection problem is not often investigated in literature. This thesis tries to fill this gap. Furthermore, it is the first time operational decisions of a carrier are simulated in this way within a freight transportation model.

Two new local search operators, INSERT and SWITCH, are created to be able to handle the selection of transport requests. Together with the local search operators, SHIFT and EXCHANGE, an improvement heuristic is developed. Next, a tabu-embedded simulated annealing algorithm is proposed to solve the selection and routing problem. The TSA algorithm is able to further improve solutions found by the improvement heuristic. Numerical experiments on a benchmark data set created based on a full factorial design show that the algorithm is robust with respect to variations in problem characteristics. Although the TSA algorithm is not developed to solve PDP instances, tests on benchmark data of Li and Lim (2001) give good results. This indicates that the algorithm is able to construct short routes for the selected requests.

Finally, alternative problem settings of the PDSP are considered. Different assumptions made in PDSP are relaxed. It is studied how these problem settings may be solved by using altered versions of the TSA algorithm. Numerical examples are solved for each of these problem settings and it is discussed how the algorithm may be adapted. Results are compared with the optimal solution found by optimization software AIMMS. Good initial results are obtained for most of these problems settings, which indicate the versatility of the TSA algorithm. First, a PDSP with compulsory requests is created which have to be performed by the carrier and may not be refused. The adapted TSA algorithm gives good initial results for this problem setting. A second alternative introduces a fixed vehicle cost when a route is assigned to a vehicle. The different solutions found show a great versatility and it may be concluded that the TSA algorithm in its current form is not suited to solve this problem. The option to outsource clients to an LSP is studied in a third problem setting. The constructed routes for a carrier differ largely from the routes of PDSP, indicated that the PDSPLSP is a very different planning problem. In the fourth alternative, an alternative revenue model for the carrier is proposed. Here revenue is not predefined, but determined based on the actual travel cost. The objective is to accept as many clients as possible. Using only the number of accepted requests as an assessment criteria in the TSA algorithm, limits the algorithm in finding the optimal solution. Lastly, a multi-period PDSP is considered. The MPPDSP is especially hard to solve as multiple decisions have to be taken for a period over time. The impact of these decisions on the profitability of routes is hard to asses on the moment of the decision taking. Therefore, a static problem is studied and selecting decisions are made for a fixed period of time. The MPPDSP has a higher complexity than the PDSP and the computing time to solve the problem increases.

8.2 Future research

Using activity-based models to simulate freight transport is a rather young research domain. Although research attention for activity-based modelling techniques has increased in the last years, several opportunities for further research may be identified.

In this thesis only the Logistic module of the proposed freight transportation framework is explored. Still further work needs to be done before the module may be integrated within an operational freight transportation model. Within the Logistic module, an interesting research direction would be to examine the 'Transport chain generation' module in more detail. Differences in the use of transport chains between the different actors may be investigated. Furthermore, the total logistic costs involved and more specifically the difference in transport costs between the agents should be more synchronized with real life data. Case study results of Flanders demonstrate that average shipment size used in the 'Transport chain generation' module has a large impact on the results. More insight in the cost structure of carriers and forwarders may lead to a more realistic representation of the transport chain formation and may improve the module. Instead of using a separate cost for the (un)loading of the truck and the vessel or train within intermodal transport, the implementation of transhipment costs should be considered. At the same time, cost sharing mechanisms in rail and IWW transport within transport chains using intermodal transport may be investigated. Next to data and cost issues found in the module an important research opportunity lies in the behavioural aspects of the actors. As the model works on a microscopic level the representation of actors is of crucial importance. Still it is hard to represent different firms by a uniform model strategy. Behavioural experiments needs to be conducted to have a better insight and to see whether the model is sufficiently capable to capture the handlings of the different actors involved. The consolidation options of a forwarder presented in the framework are an interesting concept for further research. The consolidation of different commodity categories have to be investigated as legal and practical limitations may arise. In this thesis only two options are discussed, other consolidation options need to be further explored.

Different consolidation strategies are not often found in freight transportation models. Finally, the need exists to gather detailed data to be able to model on a microscopic level and implement the proposed framework. A market study and interviews with the different agents involved should be conducted.

Before the conceptual freight transportation framework of chapter 3 may be implemented, the earlier discussed shortcomings within the Logistic module need to be addressed in a first step. This will allow the model to overcome one of the drawbacks in recent freight transportation models, that is simulating the decisions of different actors with respect to a multimodal freight network. Next to the Logistic module, future research opportunities exist in the modelling of the other three modules (Generation module, Market module and Network assignment) within the framework to get a fully operational activity-based freight transportation model. Taking economic data on a microscopic level as an input for the model requires further research. In literature transport demand is mostly modelled on an aggregated level, after which disaggregation steps are required. Data may get lost due to aggregation. To overcome this problem the Generation and Market module should simulate demand on a microscopic level. Detailed data on the goods produced and consumed forms the starting point to model freight transport, as freight flows are mainly derived from economic activities. Hence in a second step towards the implementation of the framework these modules should be further developed. Particularly the micro-simulation of the Generation and Market module haven't received much attention in literature as mostly aggregated government provided data is used to model freight transport.

Regarding the operational planning of carrier decisions a detailed representation is worked out in this thesis. Still, future work may be defined. In first instance the scalability of the heuristic needs to be investigated. Because the algorithm should be implemented in an operational freight transportation model the run time has to be kept in mind. At the moment the local search operators are applied on all vehicles each time the improvement heuristic is run. As the improvement heuristic is called at several stages within the algorithm scalability may become an issue when enlarging the model. To overcome this problem future research might, for example, consider techniques to identify promising movements within the local search operators. Furthermore, allowing infeasible solutions may be considered. Relaxing the requirement of having feasible solutions at all times may give the algorithm the possibility to explore a larger solution area and might facilitate the finding of a good end solution. When these previous issues are solved further research should look at the integration of the PDSP into the freight transportation framework. Interactions between the different actors need to be modelled taking into account the working of the algorithm.

However the PDSP may also stand alone and be a research subject within the domain of operational research. This allows investigating several extensions to the problem. Only a single vehicle type is assumed in this thesis, while multiple types are used in practice. Furthermore, different types of goods are transported which are not always allowed to be consolidated. Future research could test how the algorithm may be adapted and how consolidation limitations within vehicle routes may be integrated. For some commodity types it may be infeasible to be transported together or certain vehicle types cannot be used, like for example refrigerated goods. In a later stage these extensions might be considered for integration within the proposed freight transportation framework. To allow carriers to use the model in practice, a dynamic version of the PDSP may be studied in the future. This does not require all requests to be known in advanced, but new requests and changes in existing requests might happen during the planning period. Therefore, the algorithm should be adapted to allow constructed routes to be changed and rerouted during the planning period.

Finally, a number of extensions can be made to the problem description of the carrier. These extensions are first introduced in chapter 7 and the TSA algorithm is adapted to solve numerical examples. Still future research may look at solving certain problems encountered in chapter 7. In the first problem alternative compulsory requests are introduced. The development of a PDSP with compulsory requests looks promising and further research is required to integrate the aspects into the freight transportation model at hand. This will allow simulating long-term contracts with clients. An alternative method for creating the initial solution, in case of a large share of compulsory requests, should be further studied. Here, allowing infeasible solutions might facilitate the process of finding good solutions with the heuristic. For the PDSP with fixed vehicle cost, further research may introduce an additional local search operator, which tries to lower the number of vehicles used during the search. This will make the algorithm less depended on finding a near optimal solution before considering the fixed vehicle cost. Taking the transport cost and the profitability of the routes into account throughout the entire algorithm may lead to better solutions and a more robust algorithm. Future research concerning the PDSPLSP could investigate different methods to calculate the price of an LSP. The pricing of an LSP may happen in a practical way based on real life examples, allowing price variations based on the transport request of the client. To be able to integrate this model into the freight transportation framework, research on horizontal cooperation between carriers needs to be conducted. In a fourth extension there is no fixed revenue per kilometre. The objective is to maximize the number of clients served. At the moment no differentiation is made between two solutions with the same amount of served clients. Future research could look at introducing a bi-objective approach. First the number of accepted requests is maximized and secondly the total cost for the carrier is minimized. This would furthermore require the development of a new algorithm to handle the bi-objective criteria. The last extension studied is the multi-period PDSP. In the future, research could be conducted to form a two-phase heuristic. This may allow separating the periodical selection of requests from the daily routing of the requests with multiple vehicles. Also methods to assess the profitability or loss a request may generate in the future need to be looked into.

Appendix A

List of transport chain options in Flanders

Table A.1: Transport chain options

Category	Transport chains
Road	Light road
	Light road - heavy road
	Light road - heavy road - light road
	Heavy road - Heavy road (consolidated) - Heavy road
	Heavy road
	Heavy road - light road
Direct rail	One direct link
Road - Rail	Light road - rail - light road
	Heavy road - rail
	Heavy road - rail - heavy road
	Rail - heavy road
Road - Inland waterways	
	Light road - IWW - light road
	Heavy road - IWW
	Heavy road - IWW - heavy road
	IWW - Heavy road
Direct sea	One direct link for import/export
Road - Sea	Light road - sea
	Heavy road - sea
	Sea - light road
	Sea - heavy road
Sea - Inland waterways	Sea - IWW
	IWW - sea
Sea - Road - Rail	Sea - rail - heavy road
	Heavy road - rail - sea
Sea - Inland waterways - road	
	Sea - IWW - heavy road
	Heavy road - IWW - Sea
Road - Air	Heavy road - Air (Export)
	Light road - Air (Export)
	Air (Import) - heavy road
	Air (Import) - light road

Appendix B

Constructed links for the sensitivity analysis

In tables B.1 and B.2 the 53 constructed links between the selected zones for commodity category 1 are shown. For the factorial design the distance and yearly demand are divided between their high and low values. For the distance, a distance of less than 50 kilometre is considered low and a distance between 90 and 180 kilometre is considered high. The yearly demand is considered low for links with less than 500 tons and high for links between 1300 and 3000 tons. This means that each category exist of ± 12 links. Two links are selected for each factorial point, this is shown in the tables.

Table B.1: Constructed links in NST/R category 1

From zone	To zone	Distance (km)	Q (ton)	Factorial design
Courtray	**Genk**	**171,43**	**2898,67**	**Distance: +, Q: +**
Genk	Courtray	171,37	934,35	
Bruges	St.-Truiden	161,56	1597,83	
Antwerp	Courtray	105,88	663,51	
Courtray	**Antwerp**	**105,68**	**2530,16**	**Distance: +, Q: +**
Bruges	Mechelen	105,28	507,59	
Bruges	Antwerp (1)	98,44	948,91	
Bruges	**Antwerp (2)**	**98,44**	**316,3**	**Distance: +, Q: -**
Antwerp	**Bruges (1)**	**98,39**	**235,47**	**Distance: +, Q: -**
Antwerp	Bruges (2)	98,39	941,9	
Courtray	Zaventem	95,44	621,64	
Antwerp	Genk	92,56	916,52	
Genk	Antwerp	92,3	1266,61	
Antwerp	St.-Truiden	88,06	1492,12	
St.-Truiden	Antwerp	87,77	704,63	
Gent	Leuven	81,47	1106,28	
Genk	Mechelen	81,46	792,66	
Zaventem	Genk	76,27	1157,11	
Genk	Zaventem	76,22	189,4	
Aalst	Brugge	75,9	1630,19	
Gent	Zaventem (1)	65,15	251,55	
Gent	Zaventem (2)	65,15	503,1	
Zaventem	Gent	65,06	1207	
Antwerp	Gent (1)	64,58	317,84	
Antwerp	Gent (2)	64,58	529,73	
Antwerp	Gent (3)	64,58	635,68	
Antwerp	Gent (4)	64,58	847,58	

Table B.2: Constructed links in NST/R category 1 (cont.)

From zone	**To zone**	**Distance (km)**	**Q (ton)**	**Factorial design**
Gent	Antwerp (1)	64,45	344,23	
Gent	Antwerp (2)	64,45	1032,69	
Gent	Antwerp (3)	64,45	1549,04	
Antwerp	Aalst	53,55	1274,4	
Antwerp	Leuven (1)	53,47	389,9	
Antwerp	Leuven (2)	53,47	974,74	
Aalst	Antwerp	53,28	437,9	
Leuven	Antwerp (1)	53,18	1372,08	
Leuven	Antwerp (2)	53,18	1568,1	
Courtray	Brugge	52,9	2872,29	
Antwerpen	Zaventem	50,49	164,76	
Zaventem	Antwerp (1)	50,28	150,02	
Zaventem	Antwerp (2)	50,28	600,07	
Gent	**Bruges** (1)	**46,39**	**1433,03**	**Distance: -, Q: +**
Gent	Bruges (2)	46,39	716,51	
Brugge	Gent	46,39	1050,61	
Mechelen	Aalst	36,47	795,14	
Gent	**Aalst**	**32,16**	**1648,97**	**Distance: -, Q: +**
Mechelen	Antwerp (1)	29,74	734,63	
Mechelen	**Antwerp (2)**	**29,74**	**367,31**	**Distance: -, Q: -**
Mechelen	Antwerp (3)	29,74	1101,64	
Antwerp	Mechelen (1)	29,66	531,34	
Antwerp	Mechelen (2)	29,66	850,14	
St.-Truiden	Genk	29,53	791,25	
Mechelen	**Zaventem**	**21,45**	**403,83**	**Distance: -, Q: -**
Zaventem	Mechelen	21,16	704,05	

Appendix C

Detailed results: Improvement and TSA algorithm

Table C.1: Detailed results for the new benchmark data

Class	**Local Search**		**Time**	**TSA algorithm**		**Time**	**Gap**	
	Profit	**Unserved requests**		**Profit**	**Unserved requests**		**Profit**	**Unserved requests**
1	1193,79	28%	2 sec	1261,59	28%	82 sec	5,68%	0%
2	2127,43	51%	6 sec	2604,42	44%	630 sec	22,42%	-7%
3	1248,25	32%	1 sec	1389,58	28%	88 sec	11,32%	-4%
4	1638,38	46%	13 sec	2114,65	44%	406 sec	29,07%	-2%
5	1222,96	28%	2 sec	1327,36	28%	123 sec	8,54%	0%
6	1820,62	51%	6 sec	2195,16	47%	256 sec	20,57%	-4%
7	1749,68	10%	3 sec	1810,48	6%	125 sec	3,47%	-4%
8	2326,04	44%	14 sec	2726,24	42%	873 sec	17,21%	-2%
9	1829,01	42%	1 sec	1859,25	38%	23 sec	1,65%	-4%
10	2536,37	66%	3 sec	3420,16	58%	298 sec	34,84%	-8%
11	2105,17	38%	1 sec	2261,98	36%	64 sec	7,45%	-2%
12	3543,35	56%	7 sec	4411,36	51%	370 sec	24,50%	-5%
13	2320,37	38%	1 sec	2497,16	36%	55 sec	7,62%	-2%
14	2640,28	65%	2 sec	3384,78	63%	163 sec	28,20%	-2%
15	2458,48	26%	1 sec	2851,82	24%	67 sec	16,00%	-2%
16	4501,15	49%	17 sec	5020,67	48%	413 sec	11,54%	-1%
17	1252,00	20%	1 sec	1300,42	20%	76 sec	3,87%	0%
18	2575,10	37%	12 sec	2911,95	34%	682 sec	13,08%	-3%
19	1529,70	8%	5 sec	1579,81	6%	76 sec	3,28%	-2%
20	2881,09	35%	24 sec	3166,91	33%	1009 sec	9,92%	-2%
21	1235,37	14%	2 sec	1349,73	14%	112 sec	9,26%	0%
22	2310,65	35%	13 sec	2511,11	32%	378 sec	8,68%	-3%
23	1491,83	6%	4 sec	1567,79	2%	162 sec	5,09%	-4%
24	2918,04	24%	22 sec	3242,13	19%	578 sec	11,11%	-5%
25	2112,80	28%	1 sec	2248,66	22%	22 sec	6,43%	-6%
26	4022,18	42%	6 sec	4385,77	44%	198 sec	9,04%	2%
27	2825,17	16%	2 sec	3000,11	16%	43 sec	6,19%	0%
28	5270,68	37%	11 sec	5520,16	35%	465 sec	4,73%	-2%
29	2339,39	24%	1 sec	2481,58	24%	64 sec	6,08%	0%
30	3280,07	54%	5 sec	3657,89	51%	188 sec	11,52%	-3%
31	3291,75	14%	2 sec	3480,74	10%	78 sec	5,74%	-4%
32	5657,87	32%	15 sec	6342,53	31%	594 sec	12,10%	-1%

Appendix D

Detailed results: PDSP without time windows

Table D.1: Detailed results for the PDSP without time windows

Class	Local Search		Time	TSA algorithm		Time	Gap	
	Profit	**Unserved requests**		**Profit**	**Unserved requests**		**Profit**	**Unserved requests**
1	1212,58	26%	2 sec	1329,48	22%	51 sec	9,64%	-4%
2	2458,67	44%	13 sec	2765,19	42%	984 sec	12,47%	-2%
3	1506,77	22%	4 sec	1516,4	22%	57 sec	0,64%	0%
4	2022,01	39%	12 sec	2415,19	32%	892 sec	19,45%	-7%
5	1364,62	16%	4 sec	1478,36	12%	158 sec	8,33%	-4%
6	2120,96	45%	11 sec	2571,74	41%	269 sec	21,25%	-4%
7	1847,26	6%	6 sec	1972,92	6%	456 sec	6,80%	0%
8	2742,8	32%	21 sec	3305,99	29%	1213 sec	20,53%	-3%
9	2035,48	36%	3 sec	2102,62	36%	37 sec	3,30%	0%
10	3141,00	55%	5 sec	3850,56	50%	292 sec	22,59%	-5%
11	2335,83	32%	2 sec	2498,38	26%	71 sec	6,96%	-6%
12	4573,89	49%	8 sec	5085,05	46%	573 sec	11,18%	-3%
13	2521,04	32%	2 sec	2920,93	26%	91 sec	15,86%	-6%
14	3327,74	58%	6 sec	3853,11	57%	282 sec	15,79%	-1%
15	3168,20	8%	9 sec	3222,00	6%	77 sec	1,70%	-2%
16	4925,06	46%	7 sec	5948,31	40%	598 sec	20,78%	-6%
17	1246,55	18%	1 sec	1368,11	16%	81 sec	9,75%	-2%
18	2765,48	30%	13 sec	3074,23	24%	648 sec	11,16%	-6%
19	1570,05	6%	5 sec	1642,29	2%	217 sec	4,60%	-4%
20	3116,11	28%	32 sec	3416,04	23%	1703 sec	9,63%	-5%
21	1357,82	16%	2 sec	1453,72	12%	126 sec	7,06%	-4%
22	2599,36	24%	22 sec	2799,47	22%	564 sec	7,70%	-2%
23	1617,11	6%	10 sec	1659,22	0%	216 sec	2,60%	-6%
24	3471,16	16%	34 sec	3664,06	9%	1646 sec	5,56%	-7%
25	2261,69	20%	1 sec	2407,92	18%	70 sec	6,47%	-2%
26	4494,32	41%	13 sec	4932,81	39%	226 sec	9,76%	-2%
27	2881,36	20%	2 sec	3031,56	10%	93 sec	5,21%	-10%
28	5466,51	27%	15 sec	6101,19	25%	624 sec	11,61%	-2%
29	2496,34	18%	2 sec	2623,98	18%	133 sec	5,11%	0%
30	3938,99	43%	8 sec	4531,00	41%	482 sec	15,03%	-2%
31	3713,90	6%	6 sec	3742,65	8%	80 sec	0,77%	2%
32	6661,22	24%	21 sec	7114,22	22%	1069 sec	6,80%	-2%

Appendix E

Input requests of instance 1

In table E.1 the input requests of instance one are given. Requests given in *italic* are compulsory requests of the PDSPCR. The location of the depot is shown in the first line. The first column shows the node number. The following two columns gives the X- and Y-coordinate. The coordinates of each node is expressed in kilometers. Column four and five show the time window on each node in minutes. The sixth column gives the operation time for (un)loading each unit. The amount that needs to be transported is given in column seven. The revenue generated by each requests is shown in column eight. In the last column, the corresponding delivery (pickup) node is given. Distance, time and revenue are all given with three decimal digits.

Table E.1: Requests instance 1: depot and pickup nodes

Node i	X (km)	Y (km)	e_i (min)	l_i (min)	ot_i (min)	q_i	Rev_i (€)	d_{i+n} $\backslash p_{j-n}$
0	0,466	11,322	0	480,000	0	0	0	0
1	*10,785*	*18,741*	*208,916*	*309,732*	*3*	*28*	*20,184*	*26*
2	*8,260*	*8,686*	*173,995*	*200,643*	*1*	*11*	*87,188*	*27*
3	*9,252*	*5,150*	*57,137*	*135,370*	*2*	*28*	*50,304*	*28*
4	*15,294*	*8,402*	*201,517*	*233,839*	*2*	*10*	*34,532*	*29*
5	*23,857*	*21,991*	*41,873*	*60,138*	*2*	*9*	*107,240*	*30*
6	13,628	10,751	146,763	183,349	3	11	33,168	31
7	12,155	9,060	347,296	365,119	2	3	45,924	32
8	6,150	9,490	232,980	271,534	3	10	55,600	33
9	13,221	3,900	318,517	389,430	3	20	16,020	34
10	24,344	8,071	162,105	208,646	2	13	25,232	35
11	9,371	24,110	213,373	258,837	3	14	21,776	36
12	8,678	6,488	103,336	158,849	1	27	86,332	37
13	12,263	2,291	189,866	290,058	3	27	50,180	38
14	1,879	3,382	145,172	194,035	2	13	37,408	39
15	6,655	17,591	358,416	376,573	3	6	42,436	40
16	13,053	8,296	158,965	217,017	2	23	63,716	41
17	18,322	18,006	136,591	190,540	2	20	44,976	42
18	12,772	2,381	116,398	123,170	3	1	57,276	43
19	13,347	5,619	23,700	53,652	2	11	39,548	44
20	21,115	5,435	103,049	189,920	2	29	16,720	45
21	12,194	3,270	89,539	155,088	2	24	14,836	46
22	17,651	6,026	252,838	311,639	2	16	26,784	47
23	16,875	1,477	340,677	388,078	2	9	82,528	48
24	0,249	17,756	58,736	85,630	1	10	94,496	49
25	6,204	14,363	120,595	177,070	2	26	56,696	50

Table E.2: Requests instance 1: delivery nodes

Node i	X	Y	e_i	l_i	ot_i	q_i	Rev_i	d_{i+n}
	(km)	(km)	(min)	(min)	(min)		(€)	$\backslash p_{j-n}$
26	*14,469*	*15,292*	*319,048*	*432,505*	*3*	*-28*	*20,184*	*1*
27	*24,531*	*23,191*	*302,071*	*354,576*	*3*	*-11*	*87,188*	*2*
28	*21,775*	*6,307*	*239,521*	*344,812*	*3*	*-28*	*50,304*	*3*
29	*8,051*	*3,703*	*264,196*	*299,559*	*1*	*-10*	*34,532*	*4*
30	*3,316*	*4,761*	*315,247*	*347,439*	*2*	*-9*	*107,240*	*5*
31	7,112	5,622	279,156	313,700	3	-11	33,168	6
32	13,632	20,446	382,451	407,494	1	-3	45,924	7
33	14,180	20,836	336,327	382,005	3	-10	55,600	8
34	15,904	0,926	396,895	442,884	1	-20	16,020	9
35	20,462	13,044	407,678	450,270	2	-13	25,232	10
36	6,668	19,384	361,681	399,311	2	-14	21,776	11
37	22,769	22,837	202,124	285,721	3	-27	86,332	12
38	23,828	7,153	326,884	420,460	3	-27	50,180	13
39	9,087	9,342	402,204	456,839	3	-13	37,408	14
40	16,561	13,791	411,407	430,972	1	-6	42,436	15
41	6,031	22,594	285,671	379,827	3	-23	63,716	16
42	12,094	8,644	349,727	418,857	2	-20	44,976	17
43	1,330	10,990	430,300	453,607	2	-1	57,276	18
44	6,079	12,322	107,250	134,723	1	-11	39,548	19
45	24,620	7,714	224,258	311,171	2	-29	16,720	20
46	8,900	4,976	235,229	310,909	3	-24	14,836	21
47	20,882	11,892	390,380	416,786	1	-16	26,784	22
48	2,490	16,268	435,281	463,553	2	-9	82,528	23
49	23,340	12,765	183,045	209,200	1	-10	94,496	24
50	4,528	0,288	333,211	421,450	3	-26	56,696	25

Appendix F

Input requests of the MPPDSP instance

In table F.1 the input requests of the MPPDSP instance are given. The location of the depot is shown in the first line. The first column shows the node number. The following two columns gives the X- and Y-coordinate. The coordinates of each node is expressed in kilometers. Column four and five show the time window on each node in minutes. The sixth column gives the operation time for (un)loading each unit. The amount that needs to be transported is given in column seven. In columns eight to ten, the revenue generated by each requests is shown for day one to day three respectively. When the revenue is equal to zero, the client does not demand transport for that day. One client may have multiple transport requests spread over the planning period, but each transport requests consist of the same pickup and delivery node and volume to be transported.

Table F.1: Requests MPPDSP instance: depot and pickup nodes

Node i	X (km)	Y (km)	e_i (min)	l_i (min)	ot_i (min)	q_i	Rev_i1 (€)	Rev_i2 (€)	Rev_i3 (€)
0	0,466	11,322	0	480,000	0	0	0	0	0
1	10,785	18,741	208,916	309,732	3	28	20,184	20,184	20,184
2	8,260	8,686	173,995	200,643	1	11	87,188	87,188	87,188
3	9,252	5,150	57,137	135,370	2	28	50,304	50,304	50,304
4	15,294	8,402	201,517	233,839	2	10	34,532	34,532	34,532
5	23,857	21,991	41,873	60,138	2	9	107,240	107,240	107,240
6	13,628	10,751	146,763	183,349	3	11	33,168	33,168	33,168
7	12,155	9,060	347,296	365,119	2	3	45,924	45,924	45,924
8	9,371	24,110	213,373	258,837	3	14	21,776	21,776	0
9	8,678	6,488	103,336	158,849	1	27	86,332	86,332	0
10	12,263	2,291	189,866	290,058	3	27	50,180	50,180	0
11	1,879	3,382	145,172	194,035	2	13	37,408	0	37,408
12	6,655	17,591	358,416	376,573	3	6	42,436	0	42,436
13	13,053	8,296	158,965	217,017	2	23	63,716	0	63,716
14	18,322	18,006	136,591	190,540	2	20	0	44,976	44,976
15	12,772	2,381	116,398	123,170	3	1	0	57,276	57,276
16	13,347	5,619	23,700	53,652	2	11	0	39,548	39,548
17	21,115	5,435	103,049	189,920	2	29	16,720	0	0
18	12,194	3,270	89,539	155,088	2	24	14,836	0	0
19	17,651	6,026	252,838	311,639	2	16	26,784	0	0
20	16,875	1,477	340,677	388,078	2	9	82,528	0	0
21	0,249	17,756	58,736	85,630	1	10	94,496	0	0
22	6,204	14,363	120,595	177,070	2	26	56,696	0	0
23	13,802	24,687	37,8716	403,831	3	4	0	87,332	0
24	22,641	12,780	89,105	95,069	3	1	0	44,968	0
25	15,295	4,898	325,288	405,449	3	22	0	9,028	0
26	24,547	3,665	283,853	307,203	3	2	0	40,344	0
27	21,171	6,835	328,915	344,338	1	10	0	57,628	0
28	19,873	12,298	144,811	176,174	2	11	0	30,412	0
29	5,787	1,659	237,757	320,040	3	27	0	0	67,732
30	10,871	15,727	17,386	44,092	2	13	0	0	19,096
31	17,239	24,009	287,400	305,847	2	6	0	0	11,032
32	18,491	4,521	48,630	134,834	3	28	0	0	12,708
33	10,437	1,878	106,435	133,417	1	21	0	0	78,260
34	2,497	4,440	177,534	200,072	1	16	0	0	79,992

Table F.2: Requests MPPDSP instance: delivery nodes

Node i	X (km)	Y (km)	e_i (min)	l_i (min)	ot_i (min)	q_i	Rev_i1 (€)	Rev_i2 (€)	Rev_i3 (€)
35	14,469	15,292	319,048	432,505	3	-28	20,184	20,184	20,184
36	24,531	23,191	302,071	354,576	3	-11	87,188	87,188	87,188
37	21,775	6,307	239,521	344,812	3	-28	50,304	50,304	50,304
38	8,051	3,703	264,196	299,559	1	-10	34,532	34,532	34,532
39	3,316	4,761	315,247	347,439	2	-9	107,240	107,240	107,240
40	7,112	5,622	279,156	313,700	3	-11	33,168	33,168	33,168
41	13,632	20,446	382,451	407,494	1	-3	45,924	45,924	45,924
42	6,668	19,384	361,681	399,311	2	-14	21,776	21,776	0
43	22,769	22,837	202,124	285,721	3	-27	86,332	86,332	0
44	23,828	7,153	326,884	420,460	3	-27	50,180	50,180	0
45	9,087	9,342	402,204	456,839	3	-13	37,408	0	37,408
46	16,561	13,791	411,407	430,972	1	-6	42,436	0	42,436
47	6,031	22,594	285,671	379,827	3	-23	63,716	0	63,716
48	12,094	8,644	349,727	418,857	2	-20	0	44,976	44,976
49	1,330	10,990	430,300	453,607	2	-1	0	57,276	57,276
50	6,079	12,322	107,250	134,723	1	-11	0	39,548	39,548
51	24,620	7,714	224,258	311,171	2	-29	16,720	0	0
52	8,900	4,976	235,229	310,909	3	-24	14,836	0	0
53	20,882	11,892	390,380	416,786	1	-16	26,784	0	0
54	2,490	16,268	435,281	463,553	2	-9	82,528	0	0
55	23,340	12,765	183,045	209,200	1	-10	94,496	0	0
56	4,528	0,288	333,211	421,450	3	-26	56,696	0	0
57	8,570	3,490	432,806	467,626	2	-4	0	87,332	0
58	11,508	11,214	158,205	178,704	2	-1	0	44,968	0
59	17,549	5,019	411,928	458,412	2	-22	0	9,028	0
60	14,868	0,827	412,389	441,374	3	-2	0	40,344	0
61	7,199	3,318	391,267	401,829	1	-10	0	57,628	0
62	15,253	18,337	244,333	261,575	1	-11	0	30,412	0
63	19,966	10,916	340,347	450,235	3	-27	0	0	67,732
64	15,118	13,546	99,592	122,855	1	-13	0	0	19,096
65	17,893	21,329	371,915	408,402	2	-6	0	0	11,032
66	16,032	2,509	332,106	366,611	1	-28	0	0	12,708
67	14,269	21,065	409,495	432,675	1	-21	0	0	78,260
68	22,016	8,795	372,867	412,415	2	-16	0	0	79,992

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Samenvatting

In het hedendaagse leven is transport niet weg te denken. Goederenvervoer is een deel geworden van het alledaagse leven. Het is nodig om goederen te transporteren binnen de productieketen en om de eindproducten tot bij de klant te brengen. Zeker binnen een globaliserende context en een groeiende consumptie-economie is transport van cruciaal belang. Het vrij verkeer van goederen binnen Europa zorgt ervoor dat bedrijven hun activiteiten uitbreiden over de landsgrenzen heen. De snel groeiende wereldeconomie samen met de veranderingen van economische praktijken (zoals het concentreren van productie omwille van schaalvoordelen, het delokaliseren van bedrijven en het invoeren van 'just-in-time' leveringen) kunnen een verklaring zijn voor de snelle groei van het goederenvervoer binnen de Europese Unie. Door deze toenemende goederenstromen ontstaat een grotere verkeersintensiteit en kan een onevenwicht tussen de verschillende transportmodi worden waargenomen. Het wegtransport is nog steeds verantwoordelijk voor het merendeel van het goederenvervoer. Dit gaat ten nadele van meer duurzame transportmodi en het interfereert met het personenvervoer op de weg. Hierdoor zien beleidsmakers zich genoodzaakt om meer duurzame transportmodi zoals transport via spoor en binnenvaart te promoten. Dit gebeurt deels onder druk van de Europese Unie en deels om de eigen wegen te ontlasten. Al deze trends zorgen ervoor dat bedrijven zich dynamischer moeten opstellen en dat de logistieke activiteiten tussen bedrijven toenemen. Beleidsmakers en private beslissingsnemers moeten deze trends mee opnemen tijdens het nemen van beslissingen en een betere voorspelling van goederenstromen is hiervoor noodzakelijk. Hiertoe maken beleidsmakers gebruik van goederentransportmodellen om de goederenstromen in kaart te brengen. Deze modellen laten toe om de invloed van beleidsbeslissingen op het goederenvervoer na te gaan, zoals het invoeren van wegentaks, het subsidiëren van binnenvaart of grote infrastructuurwerken. Het is dus noodzakelijk om modellen te hebben die de huidige trends accuraat kunnen weergeven.

In dit doctoraat wordt gekeken hoe de huidige economische trends en de beslissingen van de verschillende actoren mee opgenomen kunnen worden in een goederentransportmodel. De bijdrage van dit doctoraat is dan ook tweeledig. Enerzijds het ontwikkelen van een nieuw conceptueel goederentransportmodel waarbij de aandacht vooral gaat naar de logistieke elementen en de interacties tussen de verschillende actoren binnen het goederenvervoer. Dit gebeurd binnen een multimodaal netwerk. Binnen de wetenschappelijke literatuur is het gecombineerd simuleren van actoren en de multimodale vervoerskeuze slechts zelden onderzocht. Anderzijds volgt een diepgaande analyse van de beslissingen van vervoerders, aangezien deze een belangrijke rol spelen binnen de logistieke module van het goederentransportmodel. Dit tweede aspect heeft betrekking op het operationele beslissingsniveau van de vervoerder.

In het eerste gedeelte van dit doctoraat wordt een nieuw conceptueel goederentransportmodel ontwikkeld. De nadruk ligt hierbij vooral op het incorporeren van logistieke beslissingen en het simuleren van de actoren die een invloed hebben op de besluitvorming binnen het goederenvervoer. Het doel is om de tekortkomingen van de huidige 'state-of-the-practice' modellen te ondervangen en beter in staat te zijn om de huidige trends te voorspellen en in kaart te brengen. Het model wordt ontwikkeld op een gedesaggregeerd niveau waarbij de focus ligt op de activiteiten van bedrijven en de hieruit afgeleide verplaatsingen en niet meer op de transportverplaatsingen op zich. Dit model is in staat om de karakteristieken van de verschillende actoren mee op te nemen, de interacties tussen hen te simuleren en de logistieke trends binnen bedrijven weer te geven. Een belangrijk aspect in de ontwikkeling van een activiteitengebaseerd model voor goederenvervoer zijn de actoren die betrokken zijn in het beslissingsproces. Drie verschillende types van actoren worden gedefinieerd op microscopisch niveau. Zo zijn er de bedrijven die de goederen verzenden en ontvangen, expediteurs die verantwoordelijk zijn voor de organisatie en management van de volledige transportketen, en tenslotte de vervoerders die het uiteindelijke transport uitvoeren. Al deze actoren zullen trachten hun eigen economische processen te optimaliseren. Interacties tussen deze actoren worden weergegeven met behulp van contracten. Deze contractonderhandelingen komen tot stand na verscheidene iteraties waarbij de transportprijs en de details van het contract worden vastgelegd. Binnen een aparte module in het model worden transportketens gebouwd die de basis vormen van de manier waarop goederen kunnen worden vervoerd. Het voorgestelde goederentransportmodel zit nog in een conceptuele fase en is nog niet geïmplementeerd. Een voorbeeld van de logistieke module van dit conceptueel goederentransportmodel werd uitgewerkt binnen dit doctoraat. Hieruit blijkt dat de initiële verzendingsgrootte die gekozen wordt om de omslagpunten te bepalen binnen de verschillende transportketens een grote invloed heeft op de totale logistieke kost. Dit heeft op zijn beurt een invloed op de gekozen transportketen tijdens de contractonderhandelingen en op de transportketens die in aanmerking komen voor consolidatie. Het al dan niet consolideren van goederen binnen terminals vormt een deel van het takenpakket van de expediteur. Aangezien hij verantwoordelijk is voor meerdere klanten en grotere goederenstromen beheert is hij hiervoor ideaal geplaatst. Binnen het model bestaan twee verschillende types van consolidatie: ofwel door gebruik te maken van een ‘connected hub’ systeem, ofwel door het creëren van zogenaamde ‘corridors’.

Het tweede deel van dit doctoraat focust op de beslissingen van vervoerders. Deze vervullen een belangrijke rol binnen het vooropgestelde goederentransportmodel. Hun beslissingen accuraat kunnen simuleren zal het model toelaten betere voorspellingen te maken. Een vervoerder wordt dagelijks geconfronteerd met meerdere transportaanvragen van klanten. Deze aanvragen bestaan uit een oorsprong en een bestemming die elk onderheven zijn aan specifieke tijdsvensters. Tevens beslaan deze aanvragen niet de volledige capaciteit van een vrachtwagen en kunnen meerdere klanten worden gecombineerd in routes. De vervoerder is echter niet gehouden aan het aanvaarden van alle klanten. Gezien de vervoerder een gelimiteerd aantal voertuigen ter beschikking heeft en het aantal werkuren per dag beperkt zijn, is hij niet in staat alle aanvragen uit te voeren. Elke transportaanvraag die hij uitvoert, levert de vervoerder een vooraf bepaalde omzet op. De beslissingen van de vervoerder zijn dus tweeledig. Enerzijds dient hij een selectie te maken van welke klanten hij wil aanvaarden en anderzijds dient hij deze klanten te combineren in optimale routes om zo zijn winst te kunnen maximaliseren. Hierbij dient rekening te worden gehouden met de tijdsvensters, de capaciteit van de voertuigen en de volgorde van ophalen en leveren van goederen aan de klant. Aangezien voor problemen van realistische grootte het exact oplossen van dit probleem niet meer haalbaar is, wordt een metaheuristiek ontwikkeld. Deze metaheuristiek maakt gebruikt van een combinatie tussen ‘tabu search’ en ‘simulated annealing’. Aangezien het beschreven probleem nog maar zelden is onderzocht binnen de wetenschappelijke literatuur, worden twee nieuwe lokale zoekoperatoren ontwikkeld die worden aangewend binnen de heuristiek. Twee sets van artificiële probleeminstanties worden gebruikt om de vooropgestelde heuristiek te testen. Numerische experimenten tonen aan dat de heuristiek goede resultaten levert. Niet alleen is deze manier van modelleren van operationele beslissingen van vervoerders een nieuwe techniek binnen goederentransportmodellen, ook binnen het onderzoeksdomein van operationeel onderzoek levert dit doctoraat nieuwe technieken voor het oplossen van dit selectieprobleem met winstmaximalisatie. Ten slotte worden verschillende probleemvarianten onderzocht, aangezien deze de probleemsituaties van een vervoerder in het dagelijks leven realistischer kunnen weergeven. Voor elk van deze uitbreidingen is de ontwikkelde heuristiek aangepast en numerieke voorbeelden zijn uitgewerkt. Tevens wordt onderzocht hoe deze uitbreidingen kunnen geïmplementeerd worden binnen het goederentransportmodel. Een eerste uitbreiding omvat het toevoegen van verplichte transportaanvragen. Deze komen van klanten die de vervoerder niet kan weigeren omwille van langdurige contracten of om de goodwill van de klant niet te verliezen. Vervolgens is gekeken naar het toevoegen van een vaste voertuigkost per ingelegde route. Dit kan leiden tot het inleggen van minder routes en bijgevolg ook tot het aanvaarden van minder transportaanvragen. Dit gebeurt wanneer de verkregen winst in een route niet voldoende hoog is om de additionele vaste voertuigkost te dekken. Een derde uitbreiding omvat de mogelijkheid om bepaalde aanvragen van klanten uit te besteden aan een derde partij. Dit gebeurt tegen een vooraf bepaalde kost. Uit het voorbeeld blijkt dat dit het planningsprobleem van een vervoerder grondig verandert. Niet alleen dient hij nu te beslissen welke klanten hij al dan niet aanvaardt, tevens dient gekeken te worden naar welke klanten worden uitbesteed en welke zelf door eigen voertuigen word uitgevoerd. De assumptie dat een vaste prijs per kilometer wordt gehanteerd door de vervoerder wordt herbekeken in een vierde uitbreiding. Hier wordt de transportprijs niet op voorhand bepaald, maar komt deze tot stand na het vormen van de routes. Het optimalisatieprobleem van de vervoerder bestaat nu uit het maximaliseren van het totaal aantal aanvaarde klanten in plaats van de verkregen winst. Als de routes zijn gevormd wordt de transportprijs bepaald op basis van de werkelijke transportkost en het winstpercentage van de vervoerder. Om af te sluiten wordt het probleem bekeken over meerdere periodes heen. Hier dient de vervoerder niet enkel een selectie te doen voor één periode maar voor meerdere periodes tegelijkertijd. De constructie van de routes gebeurt echter nog steeds voor iedere periode afzonderlijk. Dit verhoogt de complexiteit van het probleem aanzienlijk.

Publications and conference participation

Journal publications

Maes, T., Caris A., Ramaekers, K., Janssens, G. K., 2013. Modelling carrier decisions in activity-based freight transportation: a selective pickup and delivery problem with time windows. European Journal on Transportation and Logistics. Submitted, 1st review.

Publications in conference proceedings

Maes, T., Ramaekers, K., Caris A., Bellemans, T., Janssens, G. K., 2010. Creating an innovative activity-based freight transportation framework. In: The European Simulation and Modelling Conference (ESM 2010). Diepenbeek, Belgium, October 25-27, pp. 352–357.

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Other conference participation (abstract)

Maes, T., Ramaekers, K., Caris A., Bellemans, T., Janssens, G. K., 2010. Incorporating logistics decisions in activity-based freight modeling. ORBEL - 24th Annual Conference of the Belgian Operations Research Society. Liege, Belgium, January 28-29.

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Maes, T., Ramaekers, K., Caris A., Janssens, G. K., Bellemans, T., 2011. Modelling logistic decisions of firms and carriers. ORBEL - 25th Annual Conference of the Belgian Operations Research Society. Ghent, Belgium, February 10-11.

Maes, T., Caris A., Ramaekers, K., Janssens, G. K., Bellemans, T., 2012. Pickup and delivery selection problem. ORBEL - 26th Annual Conference of the Belgian Operations Research Society. Brussels, Belgium, February 2-3.

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