UNIVERSITY OF GRONINGEN

Relocation of Facilities in an Integrated Fleet Management Model

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Master Industrial Engineering and Management

August 2018

UNIVERSITY OF GRONINGEN

Abstract

Master Industrial Engineering and Management

Research Project

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This study set out to determine the effects of relocation of facilities on an integrated fleet management model. Considering growing environmental concerns, the transportation industry recognizes the need to green their fleet. One of the main barriers in the adoption of Alternative Fuel Trucks (AFTs) is the lack of an infrastructural facility network for these trucks. To facilitate the transition from diesel trucks to AFTs, the strategic location-allocation problem of AFT facilities that can fuel and maintain AFTs is crucial. Due to the high impact related to these strategic decisions, this research proposes two MIP formulations that extends an integrated fleet management model with the functions to close and move maintenance facilities. The use of the presented models to assist in the decision-making process in logistic problems is particularly useful if demands or targets are decreasing or if it is expected that the location of demands and bans changes.

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Chapter 1

Introduction

In the last years, air pollution has become a great international environmental concern. The goal of the Paris Agreement, ratified by 146 countries and signed by 48 countries, is to keep temperature rise below 2 °C. The concentration of greenhouse gasses (GHGs) in the atmosphere is directly related to the temperature rise. Therefore, one of the key aspects of the Paris Agreement is to reach global peaking of GHGs as soon as possible by the development of sinks and the removal of sources of GHGs [1]. One of these major sources of GHGs is the transportation sector. In Europe, the transportation sector contributes to almost a quarter of all GHGs in the atmosphere. In cities, it is the main air polluter [2].

The dominant transport mode is road transport. In the European Union, road transport contributes to 75% of the total tone-kilometers [3]. It is the biggest polluter in the transportation sector, contributing to more than 70% of the GHG emissions in 2014. Road transport contributes to almost one-fifth of the total carbon dioxide (CO_2) emissions of the European Union. CO_2 is the main greenhouse gas. Heavy duty vehicles (HDVs) are responsible for about one quarter of the road transport's CO_2 emissions although they make up only a small share of the total vehicle fleet [4][5]. HDVs are defined as passenger transport vehicles for over eight persons or freight trucks with a mass of over 3.5 tonnes [6]. Transportation is a rapidly growing sector. Without any action, it is expected that emissions continue to grow 10% from 2010 to 2030 [4].

Hence, the European Commission has set some priority areas for action to meet the Paris Agreement. One of these areas is the deployment of alternative energy for transport and the movement towards zero emissions vehicles. By 2050, the goal is a decrease of 60% of the CO_2 emissions from transport compared to 1990 levels. In 2017, HDVs emissions were 19% above 1990 levels [6][7]. On the 17th May, 2018, the Juncker Commission announced their final set of actions to clean Europe's transport system including their main goal towards their plan called 'Clean Mobility' [8]. In 2025, the regulations state that the average CO_2 emissions from HDVs have to be 15% lower compared to 2019 standards. By 2030, the aspiration is a further reduction of 30%. The 2030 target is aspirational and will be reviewed by 2022 [9]. The EU is assisting transport companies to design trucks in order to fulfill these regulations.

Road transport is a backbone of most economies, it is responsible for a large share of the goods movement. Additionally, freight transport is responsible for the economies within the transport sector, but it is also responsible for all economies depending on the transported goods [10]. Therefore, transport is an important sector, dependent on many stakeholders, concerning high investments and influenced by many levels of decisions. Furthermore, the sector has to adapt to political, social, economical and environmental changes [10]. Therefore, it is very important that the right methods and tools are used in their decision making processes.

Altogether, the greening of transportation fleets has gained attention of stakeholders in the industry. There is an environmental concern leading to competitive and regulative pressures and increasing fossil fuel prices [11]. To a greater extent, managers using fossil fuels are forced to consider alternative fuels such as bio-diesel, hydrogen, electricity, ethanol or natural gas for their HDVs [12]. Over the last few years, more companies are adding Alternative Fuel Vehicles (AFVs) to their fleet. However, in Europe, 98% of all trucks in 2017 is still dependent on diesel [9]. Major growth is required in the adoption of AFVs. Nonetheless, there are several barriers in the adoption of AFVs. A major complication in the overall adoption of AFVs is the lack of infrastructural fuel and maintenance facility networks for these vehicles. A further investigation on facilities in networks is a dominant feature in this field of research. In order to make the choice for AFVs more attractive, the infrastructure of facilities has to be deployed in convenient locations in convenient time frames [13].

The goal of this research is to propose an integrated fleet management model that facilitates this transition to a greener HDV fleet, focusing on the infrastructural fuel and maintenance networks. This research builds upon the work of Ilke Bakir, who proposed an integrated fleet management model that introduced alternative fuel trucks (AFTs) into an existing diesel fleet in long-haul trucking [14]. In Bakir's model, strategic, tactical and operational decisions are included. The presented model incorporates both fleet purchase and retirement decisions, infrastructural decisions; the opening of the required facilities and decisions to assign specific trucks to particular routes. As discussed, the adoption of AFTs is heavily reliant on the infrastructural network and its AFT facilities. Although there are many studies on the use of models in fleet replacement decisions, to date, there has not yet been research that compares differences in the features of different models regarding the facility infrastructure. This research fills in on that knowledge gap. This study proposes two integrated models. Both are an extension to the integrated fleet management model. The first model introduces the feature to close facilities. The second model proposes the feature to move facilities, next to opening and closing facilities. This is the first study to introduce these possibilities in an integrated fleet management model. This has been conducted to provide two ways of providing the network to cope with more robustness. In order to show the benefits of these models, the optimal fleet management decisions are given for different realistic test instances considering the demand, costs and targets in the models. A mixed integer programming (MIP) approach is used to solve the integrated fleet management problem. This modelling approach is used to create better insight in the decisions and to adapt to changes in the network. MIP is particularly useful for its flexibility to add specific characteristics and information to the model.

The remaining part of the chapters proceed as follows: first, a brief overview of the literature on fleet replacement, relocations and mobile facilities is given in chapter 2. Chapter 3 concerns the description of the two MIP formulations used for this research. Chapter 4 gives a computational analysis to analyze the impact of the different models on different problem instances. Chapter 5 gives the conclusions and limitations of this research and describes areas for further research.

Chapter 2

Literature Review

2.1 Literature

Fleet renewal poses a challenging question to logistic service providers. It imposes many challenges; a strategy has to be made to purchase and salvage vehicles within technological evolution and, nowadays, in the face of environmental concerns. Furthermore, cost minimization is still a major aspect in fleet management [15]. A large body of literature in the field of Management Science and Operations Research has investigated fleet replacement models. These models make optimal decisions regarding vehicle purchases, salvages, operations and maintenance [16]. Fleet replacement models belong to the class of replacement models and are divided in practice-oriented and research-oriented categories. Research-oriented models use economical optimization to assist in replacement decisions. For these models, the model's objective function is usually a minimization of the sum of the total fleet costs over a given planning horizon [17]. In order to make decisions in fleet management, mathematical modeling is often used. For example, a MIP formulation for parallel equipment replacement management is given in [18]. [19] uses integer programming (IP) to assist in parallel fleet replacement decisions for a city tour operator in Europe. Parallel replacement refers to the replacements of assets that are economically independent and operate in parallel [19].

Three types of decisions or planning levels are widely recognized: strategic, tactical and operational based decisions [10][20]. Strategic decisions often require high investments and are planned over a long time horizon. They often determine the general policies of the organization. It is recognized that high capital decisions and investments are often involved with strategic decisions, they are very important in defining the infrastructure of the network [21][22]. Tactical decisions address material flow and resource management in the most efficient manner over a medium term horizon [10]. Operational decisions refer to short-term, time-dependent resource allocation [23]. The integrated fleet management model of Bakir simultaneously addresses all three types of decisions [14]. Strategic decisions manage the infrastructural physical network. These determine when and where to open maintenance facilities for AFTs. These strategic location problems have a long term essence [24]. [10] gives an overview of different location and network design models. The tactical decision is a fleet sizing problem; when, which and how many trucks to purchase and salvage. The operational decision determines which trucks to assigns to which routes in the network. All decisions are interrelated with strong financial and organizational implications [3]. Therefore, criteria and constraints are used to determine the optimal fleet management strategy. The integrated fleet management model uses a loaded truck-mile target for the percentage of loaded truck-miles that has to be travelled with AFTs [14]. For these models, choices can be made from a discrete set of alternatives. Therefore, for this type of problems, MIP models can be used. The models consider trade-offs between different combinations of decisions in order to find the optimal combination that satisfies all constraints and minimizes costs [22]. This is beneficial compared to general rules of thumb since these are often oversimplified and not able to adapt to specific situations or circumstances that change in time or happen over time. MIP is particularly able to do that.

Several studies address the importance of maintenance facilities in replacing a fleet [12] [13]. The optimal number and location of alternative fuel stations and maintenance facilities has to be determined in a way that demand is covered and the limited capacity of AFTs is considered. Literature addresses this type of problems as facility location problems. Facility locations are a critical strategic aspect in many firms. [25] provides an overview of the facility location research till 1998. [24] gives a review on the classifications and applications of facility location problems. In general, a facility location problem includes a set of distributed customers which have a demand and a set of available locations for facilities to serve those customer demands. In combination with the restriction of a set of constraints, certain questions can be answered. Possible questions could be: (i) Where to open facilities? (ii) Which demands can be serviced from these facilities to minimize costs [21]? Opening or re-opening facilities often require large investments. Therefore, it is expected that facilities are operable for a long planning horizon [21][26]. During this planning horizon, it is expected that parameters in the system change. Therefore, facility locations have to be chosen not only according to the current state of the system, but also anticipating on changes in the network in such manner that the system remains profitable during its total lifetime [25]. This field of problems are called dynamic facility location problems. Optimization considers the trade-off between planned location sites and their related costs [26]. Two criteria for dynamic facility locations are described by [24]; first the trade-off between expenditures and revenues for the facility location and secondly, the time to open and close a facility. [27] proposes an algorithm that incorporates both mixed-integer and dynamic methods in order to solve a multi-period facility location problem over an entire planning horizon.

There is a large volume of published studies describing the role of facility location-allocation problems in the field of emergency response and disaster relief. Location-allocation problems address the problem of locating a new facility to satisfy demand such that the costs are minimized [28]. Disaster relief operations find the optimal manner to respond to emergencies [29]. After personnel, transportation fleets are the second largest overhead costs in humanitarian actions [30]. [31] addresses the importance of the location of shelters (facilities) for evacuation planning in flood and hurricane management. The study uses a computer-based tool to make its tactical and operational decisions, the location of shelters is a variable in the system. [29] uses a multi-commodity, multi-modal network model to determine routes, its deliveries and load plans during emergencies. A description of a stochastic model that plans the storage and distribution of medical supplies that can be used during emergencies is given by [32]. [33] provides a linear programming (LP) model formulation that determines real-time evacuation location, evacuation routes and departure schedules for emergency response in no-notice disasters. No-notice disasters are unexpected, large-incident disasters where immediate evacuation has to take place. A mathematical model that solves a location-allocation problem in disaster aftermath using a master level non-linear problem and a slave problem is described in [34]. The model addresses both locating and routing problems. When sudden changes occur in the aftermath of a disaster, demand changes too. [35] proposes a MIP model that minimizes operational costs and unsatisfied demand to cope with uncertainty in the aftermath of humanitarian operations. One of the most recognized sources of uncertainty in supply chain management and fleet management is demand [20][36]. Mobile facilities help networks to cope with uncertainty. In mobile facility relocation problems, a model searches if facilities have to be relocated, and if a re-assignment of clients has to take place, so that the total facility (re-)location and travel costs are minimized. [37] presents two heuristics for the mobile facility location problem. The mobile facility location problem can be elaborated by adding a maximal capacity to the facilities; leading to a capacitated mobile facility location problem [38]. [39] gives a further generalization of a capacitated facility location problem where facilities are limited by the demand they can serve; a capacitated facility locating/network design problem.

Important benefits of mobile facilities are described in health care applications. Ambulances are a specific example of these mobile facilities. [40] gives a review of the evolution of location and relocation models for ambulances. This article describes the emergence of re-locations. Computers can redesign the ambulance redeployment strategy at any time t. [41] describes an heuristic that determines the optimal set of locations for a set of facilities. These facilities are moved, against costs, in a network with changes in its state. The example of change in state is a change in travel time. The lengths of routes can change for ambulances in crowded cities, for example, due to traffic jams. [42] uses a multi-objective combinatorial optimization for a location-routing problem for mobile facilities in a developing country. The purpose of this mobile facility is the extension of access of these facilities. The mobile facility location problem has also been addressed in a study concerning facilities decisions in Soweto, South Africa [43].

This research combines the integrated fleet management model and the literature on mobile facilities. The model of Bakir inhibits a strategic facility location-allocation problem next to the general fleet replacement model [14]. It determines when and where to open AFT facilities (location) and assigns AFT trucks to routes in the network (allocation). The static opening of facilities is not always able to cope with sudden changes in the network. As literature suggests, mobile facilities let the network cope with uncertainty. Over time, it can be decided if an AFT facility is still required or if a facility has to be relocated and trucks have to be allocated again. The possibility of mobile facilities, as discussed in literature, facilitates this reassignment and relocation. This research will elaborate the integrated fleet management model of Bakir by incorporating a relocating and redeployment strategy. This is accomplished by adding two functions to the model. First, the possibility to close facilities and second the possibility to move facilities from one location to a new location. In this way, the model is able to use the existing facilities to cope with changes in the network. The purpose of the model remains to minimize costs while satisfying all demand in the network.

2.2 Contributions of this Study

In this thesis, the modelling of two mixed integer programming (MIP) formulations is considered. Literature is extended in the way that these models elaborate on the strategic component of the integrated fleet management model, addressing the discussed possibilities of relocation strategies in a facility infrastructure. The novelty of this approach is to elaborate on the strategic planning decisions within an integrated model by modelling these into the MIP formulation. As literature suggests, mobile facilities provide the system to adapt to changes and regulations in the system, contributing to a robust network. In this way, networks are likely to remain profitable over their entire life. In order to incorporate relocations, two new functions are added to the integrated fleet management model. First, the possibility to close AFT facilities and second, the possibility to move AFT facilities. Both functions facilitate this relocation, closing facilitates relocation by closing a facility at an old location and opening a facility at a new location and moving directly facilitates a relocation by moving a facility from an old location to the new location. To show the benefits of these functions, the new models will be investigated on their performance in different scenarios.

The objective of this research is two-fold. First, to develop and present these two new MIP formulations that include the functions of opening, closing and moving facilities, and second, to provide a computational study that demonstrates the benefits of the two new MIP models in assisting in the decision making process for logistic problems and to determine which model has to be used in the decision making process. The benefits will be assessed by comparing the solutions of the different models for different problem instances. The problem instances will replicate different networks and scenarios in the network. The scenarios are related to the demand, the percentage of demand that has to be fulfilled by AFTs and changes in costs of the AFTs and the AFT facilities. Assessment will take place based on cost benefits, the number of decision variables and solution time.

Chapter 3

Model Formulations

In this section two MIP formulations are presented for simultaneously making strategic, tactical and operational decisions in fleet replacement. These decisions are made in the setting of integrating AFTs into an existing Diesel truck (DT) fleet. AFTs require different maintenance and fueling facilities, strategic decisions determine when and where to open these AFT facilities. Tactical decisions manage when, how many, and what truck type to buy and retire. AFT purchases are encouraged by travelled loaded truck-mile targets. These targets set the proportion of loaded truck miles travelled by AFTs to total loaded truck-miles. Operational decisions manage the assignment of trucks to routes in the network. The routes are based on the number and location of terminals in the network. The function of a terminal is two-fold. It is the demand origin and destination point in the network and a possible location to open AFT facilities. Routes connect two or more terminals, trucks are assigned to a specific route to fulfill the demand between the terminals in that route. It is assumed that demand quantities are known in the beginning of the planning horizon. All demand in the network must be satisfied on specific time periods while minimizing costs.

The strategic decision to close down AFT facilities, next to opening them, is integrated in the model formulation in 3.1. This MIP formulation is further referred to as model C. In 3.2, a MIP formulation is given that includes the possibility of moving the facility from one terminal to another, alongside opening and closing the facility. This MIP formulation will be further referred to as model M.

3.1 Model C

Let $G = (N, A)$ be a network, where N is the set of nodes and A is a set of arcs. The nodes represent the terminals and the arcs represent the connections between these terminals. The set of terminals represent the possible locations for AFT facilities. Trucks are assigned to a set of predefined routes R, it is assumed that the truck's range is large enough to travel these routes without immediate refueling or maintenance stops. The fleet must satisfy the demand of truck loads that have to travel between specified origin and destination demand points. Thus, the demand is located on the arcs. The loaded truck-mile target enforces travelling with AFTs in the network. For the motivation of using loaded truck-mile targets rather than truck-mile targets, see [14].

3.1.1 Formulation model C

There are six types of decision variables in model C that concern the three type of decisions. The variables representing decisions regarding maintenance facilities are modelled as binary variables, the other variables are modelled as continuous variables. This is a fair approximation due to the significant number of trucks assigned to the routes in this model. The decision variables are presented below:

- When and where to open and close maintenance facilities to service AFTs:

  y_{jt} 1 if opening facility at $j \in N$ in the beginning of time period $t \in \{1, ..., T\}$, otherwise 0

  $z_{j\tau t}$ 1 if facility at $j \in N$ opened in beginning of period $\tau \in \{1, ..., t\}$ is closed in the beginning of time period $t \in \{1, ..., T\}$, otherwise 0

- The number and time to purchase and salvage alternative fuel trucks (A) and diesel trucks (D):

  p_t^k Number of trucks of type $k \in \{A, D\}$ purchased at beginning of period $t \in \{1, ..., T\}$

  $r_{\tau t}^k$ Number of trucks of type $k \in \{A, D\}$ that were purchased in the beginning of $\tau \in \{1, ..., t\}$ to be salvaged in the beginning of time period $t \in \{1, ..., T\}$

- Assigning both truck types to routes in the network:

  $x_{i\tau t}^k$ Number of trucks of type $k \in \{A, D\}$ that were purchased in the beginning of $\tau \in \{1, ..., t\}$ to be assigned to route $i \in R$ in time period $t \in \{1, ..., T\}$

  l_{at}^k Number of trucks of type $k \in \{A, D\}$ passing through arc $a \in A$ in period $t \in \{1, ..., T\}$

Following are the parameters used in C.

C_{jt} Cost of opening an AFT facility at terminal j at the beginning of period t and operating it till end of planning horizon

$Q_{j\tau t}$	Costs of closing an AFT facility at terminal j opened in the beginning of period τ closed in the beginning of period t
P_t^k	Cost of purchasing a truck of type k at beginning of period t
$R_{\tau t}^k$	Salvage value of retiring a truck of type k purchased at the beginning of period τ at the beginning of period t
$c_{\tau t}^k$	Cost of operating a truck of type k purchased at the beginning of period τ in period t
$p_t^{=D}$	Number of diesel trucks in initial fleet, purchased in period t ($t \leq 0$)
n_i	Number of times route i can be traversed by a truck in one period
τ_a	Travel time on arc a
D_{at}	Demand on arc a in period t in full truck loads
M_{it}	Big-M: maximum number of trucks that will benefit from opening an AFT facility along route i, Big-M is calculated as $M_{it} = \frac{max_{a \in A(i)} D_{at}}{n_i}$, where $A(i)$ are the arcs on route i
b_t	Target proportion of loaded truck-miles to be travelled by AFTs

The model formulation C can be formulated as below. The objective function is given in (1), it gives the sum of the costs of opening, closing down and operating AFT facilities and the costs of purchasing, retiring and operating the trucks. C_{jt} incorporates the costs related to opening the facility, dependent on the terminal location and the operating costs for the facility, paid for till the end of the time horizon. It is important to notice that $Q_{j\tau t}$ includes three components. The first component is a revenue; the salvage value of the AFT facility, the second component is also a revenue; the returned operating costs that have been paid for in C_{jt}. The third component is a cost; the costs related to closing down the facility, dependent on the terminal location. The salvage value and the returned operating costs are substracted from the closing costs, therefore, C_{jt} can be minimized. The end-of-horizon costs are incorporated in $c_{\tau T}^k$. Herein, all costs to operate both truck types till the end of the planning horizon, if $\tau \leq T$, are incorporated. In this way, end of horizon effects are accurately represented. Constraint (2) and (3) are inventory balance equations, where (2) represents the inventory balance of the fleet purchased before or at period 0. (4) connects $x_{i\tau t}^k$ with l_{at}^k and constraint (5) makes sure that all demand on the arcs is satisfied. (6) presents the big-M constraint that assures the presence of an AFT facility on a route if there are AFTs assigned to that route. Since AFTs are new in the network, there are no AFT facilities in the network. These are required to perform fuel and maintenance operations on the AFTs. Furthermore, (7) sets the target constraint of the proportion of loaded truck-miles that has to be travelled by AFTs to total loaded truck-miles. Finally, (8) satisfies that AFT facilities can only be closed at j if they were opened and not closed at j in an earlier time period. (9) and (10) represent the binary constraints.

$$\begin{aligned}\min \sum_{j\in N,t} C_{jt}y_{jt} + \sum_{j\in N,t,\tau\leq t} Q_{j\tau t}z_{j\tau t} + \sum_{k,t} P_t^k p_t^k \\ - \sum_{k,t,\tau\leq t} R_{\tau t}^k r_{\tau t}^k + \sum_{i\in R,k,t,\tau\leq t} c_{\tau t}^k x_{i\tau t}^k \quad (1)\end{aligned}$$

$$\begin{array}{llll}
\text{s.t.} & \sum_{i\in R} x_{i\tau t}^D = p_\tau^{=D} - \sum_{s=\tau}^{t} r_{\tau s}^D & t=1,...,T, \tau\leq 0 & (2)\\
& \sum_{i\in R} x_{i\tau t}^k = p_\tau^k - \sum_{s=\tau}^{t} r_{\tau s}^k & k\in\{A,D\}, t=1,...,T, \tau\leq t & (3)\\
& \sum_{i\in R(a),\tau\leq t} n_i x_{i\tau t}^k \geq l_{at}^k & k\in\{A,D\}, a\in A, t=1,...,T & (4)\\
& l_{at}^A + l_{at}^D = D_{at} & a\in A, t=1,...,T & (5)\\
& x_{i\tau t}^A \leq M_{it}(\sum_{j\in N(i),s\leq t} y_{js} - \sum_{j\in N(i),s\leq\tau} z_{js\tau}) & i\in R, t=1,...,T & (6)\\
& \sum_{a\in A} \tau_a l_{at}^A \geq b_t \sum_{k,a\in A} \tau_a l_{at}^k & t=1,...,T & (7)\\
& y_{js} - \sum_{s=q}^{t-1} z_{jsq} \geq z_{jst} & t=1,...,T, s\leq t & (8)\\
& y_{jt} \in \{0,1\} & j\in N, t=1,...,T & (9)\\
& z_{jt\tau} \in \{0,1\} & j\in N, t=1,...,T, \tau\leq t & (10)\\
& p_t^A, p_t^D \geq 0 & t=1,...,T & (11)\\
& r_{\tau t}^A, r_{\tau t}^D \geq 0 & t=1,...,T, \tau\leq t & (12)\\
& x_{i\tau t}^A, x_{i\tau t}^D \geq 0 & i\in R, t=1,...,T, \tau\leq t & (13)\\
& l_{at}^A, l_{at}^D \geq 0 & a\in A, t=1,...,T & (14)
\end{array}$$

3.1.2 Model C Assumptions

Two types of trucks are considered; Diesel trucks (DTs) and Alternative Fuel Trucks (AFTs). The initial fleet in the model consists of DTs. At *t=0*, there are no AFTs or AFT facilities in the network. Operating costs for trucks include fuel and maintenance costs. These costs increase linearly with the age of the truck, both for DTs and AFTs. At the time of purchase, both truck types immediately turn in a percentage of their original value. From this percentage, there is a straight line depreciation with zero residual value at the end of their useful life. It is assumed that at the end of the model's planning horizon, the trucks are kept, operated indefinitely and replaced at their optimal replacement periods.

In this way, end-of-horizon effects are minimized. The optimal replacement periods are based on the expected life of the truck and a trade-off between the purchase costs, the operating costs and the salvage value.

Facilities provide fueling services and maintenance services. It is assumed that every AFT facility can handle all operations required by AFTs. Hence, there is no quality difference between facilities at different terminals. Facilities open at a terminal at the beginning of a period. Their associated costs depend on the location of this terminal. The operating costs for the facilities are paid till the end of the planning horizon unless the facility is closed earlier. Closing the facility will return the remaining prepaid operating costs. The salvage value of the facility depreciates from its purchase value with straight line depreciation to a residual value at the end of the facility's useful life. Costs related to closing the facility are a percentage of the opening costs. Therefore, these costs depend on the location of the closing terminal.

Demand in this model is randomly generated based on given origin and destination probabilities. To represent real life situations, they are set up as some regions have mostly inbound (inbound-heavy) and some regions have mostly outbound loaded moves (outbound-heavy). There are also regions that have a balanced demand. All costs components in the models in this research are related to time. Therefore, an interest rate has been included to compensate for this time factor.

3.2 Model *M*

This section presents model *M*. This model includes the function of moving AFT facilities from one terminal to another terminal. In model *C*, facilities could be relocated by closing the facility at one terminal location and opening a facility at a new terminal location. Here, the facility remains the same, but is allowed to move from one location to another. Model *M* is an extension of model *C*, opening and closing of facilities is still possible in this model.

3.2.1 Formulation model *M*

- Extra decision variables are added to facilitate moving of the terminals:

$n_{j_1 j_2 \tau t}$ 1 if facility is moved to $j_2 \in N$ from $j_1 \in N$ that was opened in the beginning of $\tau \in \{1, ..., t\}$ in the beginning of time period $t \in \{1, ..., T\}$, otherwise 0

- A parameter is used to represent the costs of moving these facilities:

$N_{j_1 j_2 \tau t}$ Cost of moving a facility from terminal j_1 to terminal j_2 opened in the beginning of period τ in the beginning of period t

Model M is formulated below. (15) gives the new objective function for this model. The costs related to moving the facility are added to (1). Constraint (16) presents the renewed big-M constraint that satisfies that every route that is used by AFTs, has an AFT facility opened on this route or moved to this route. Thereby, this constraint is only satisfied if the facility is opened at or moved to this specific terminal and not moved from or closed at this specific terminal before the time period the route is used by AFTs. (17) assures that facilities can only be moved from a certain location if they have been opened at or moved to that location before and not moved from or closed at that location before. (18) assures that it is only possible to close a facility if it has been opened at or moved to that location before and not closed at or moved from that location before. (19) represents the extra binary constraint.

$$\begin{aligned}\min \sum_{j\in N,t} C_{jt}y_{jt} + \sum_{\substack{j\in N\\ t,\tau\leq t}} Q_{j\tau t}z_{j\tau t} + \sum_{\substack{j_1\in N\\ j_1\neq j_2\\ t,\tau\leq t}} N_{j_1 j_2 \tau t}n_{j_1 j_2 \tau t}&\\ + \sum_{k,t} P_t^k p_t^k - \sum_{k,t,\tau\leq t} R_{\tau t}^k r_{\tau t}^k + \sum_{\substack{i\in R,k\\ t,\tau\leq t}} c_{\tau t}^k x_{i\tau t}^k & \qquad (15)\end{aligned}$$

s.t. $(2), (3), (4), (5), (7), (8), (9), (11), (12), (13), (14)$

$$\begin{aligned}x_{i\tau t}^A \leq M_{it} \sum_{j\in N(i)} \Big(\sum_{s\leq t} y_{js} + \sum_{\substack{j_1\in N\\ j_1\neq j\\ s\leq q\\ q\leq t}} n_{j_1 j s q} - \sum_{\substack{j_2\in N\\ j\neq j_2\\ s\leq q\\ q\leq t}} n_{j j_2 s q} - \sum_{\substack{s\leq q\\ q\leq t}} z_{jsq}\Big)&\\ i\in R, t=1,...,T, \tau\leq t & \qquad (16)\\ n_{j j_2 \tau t} \leq y_{j\tau} + \sum_{q=\tau}^{t-1}\sum_{j_1\in N} n_{j j_1 \tau q} - \sum_{q=\tau}^{t-1}\sum_{j_2\in N} n_{j j_2 \tau q} - \sum_{q=\tau}^{t} z_{j\tau q}&\\ j, j_2\in N, j\neq j_2, t=1,...,T, \tau\leq t & \qquad (17)\\ z_{j\tau t} \leq y_{j\tau} + \sum_{q=\tau}^{t}\sum_{j_1\in N} n_{j j_1 \tau q} - \sum_{q=\tau}^{t}\sum_{j_2\in N} n_{j j_2 \tau q} - \sum_{q=\tau}^{t-1} z_{j\tau q}&\\ j\in N, t=1,...,T, \tau\leq t & \qquad (18)\\ n_{j_1 j_2 \tau t}\in\{0,1\}&\\ j_1, j_2\in N, t=1,...,T, \tau\leq t & \qquad (19)\end{aligned}$$

3.2.2 Model *M* Assumptions

The assumptions for model C hold for model M. $N_{j_1 j_2 \tau t}$ represents all costs related to moving a facility from j_1 to j_2. These moving costs can be separated in three components; the closing down costs at the old location, the building up costs at the new location and the travelling costs related to the travelling distance between the old and new location. The closing down and building up costs are a small percentage of the opening and closing costs respectively. The travelling costs are linearly correlated to the distance between the two facilities. The facility operating costs are incorporated in the costs of opening and closing the facility. They are not included in the moving costs. Facilities are moved at the beginning of a time period. Therefore, AFTs cannot be assigned to routes in a time period, if the facility is moved from that route in that time period.

Chapter 4

Computational Study

This chapter investigates how the different models presented in chapter 3 perform under different scenarios. Optimal fleet management solutions are presented and interpret for different problem instances. These problem instances represent changes in demand, changes in loaded truck-mile targets, changes in prices and changes in regulations concerning AFTs and facilities. For every instance, optimal fleet management strategies are presented for different cost scenarios. A comparison is made between the original model of Bakir, model B; model C and model M [14]. For every instance, the impact of the scenarios on the performance of the models is discussed.

The instances are defined on a network of 10 terminals and 12 time periods. This network is a realistic setting of a real network in smaller scale. The terminals in the network are located in three regions. Table 4.1 shows the distribution of the terminals on the different regions. Furthermore, this table presents the hubs per region. A hub is an effective centre of the activity in a network. In order to represent real life transport operations, hubs act as consolidation centres. All demand between regions is travelling along the hubs. Demand is located on arcs. The demand between different regions is located on the arcs between the hubs. Hence, between regions, there are solely demand arcs between 1, 4 and 6. There are demand arcs between all terminals in the same region.

The initial fleet in the network consists of diesel trucks (DTs). There are no AFTs or AFT facilities in the network at *t=0.* Performances on different problem instances are discussed to emphasize the impact of closing and moving AFT facilities. For every instance, a comparison is given between models *B, C* and *M.* In order to distinguish clear

Region	Terminals	Hub
1	1, 2, 3	1
2	4, 5, 10	4
3	6, 7, 8, 9	6

Table 4.1: Regions in network

results, extreme cost cases are considered. Scenarios are based on the costs of purchasing an AFT, these can be cheaper or more expensive compared to a DT, and the costs of opening an AFT facility, which can be cheap or expensive. For some instances, the costs scenarios are also related to closing and moving cost components.

Computational experiments are run on a machine with a 2,3-GHz dual core Intel Core i5 processor using a Gurobi 7.5.2 solver on a Anaconda 5.2 interface with Python 2.7. The computation time limit for all three models was 100 seconds in all instances except for the problem instance in section 4.2.2.2. In that section, the time limit is set to 500 seconds. Three different problem instances will be discussed; constant demand and a changing target (4.1), changing demand and a constant target (4.2) and limiting regulations on fleet management models (4.3). These instances have been selected to see the effect of target on the models (4.1), to see the effect of demand on the networks (4.2) and the effect of regulations that not change the demand or target (4.3). For every of these instances, different scenarios are presented and the optimal facility management decisions of the models are discussed. The problem instance of constant demand and constant target is not discussed separately. This example will open and operate facilities till the end of the planned horizon for every cost scenario in every model. Models C and M will not give different decisions compared to model B. Hence, this experiment will not contribute to more knowledge on this research and will not be mentioned in this section.

4.1 Constant Demand, Changing Target

The first problem instance discussed is the relatively simple case of constant demand and a changing target. Constant demand refers to a scenario where demand quantities do not change over the total planned horizon. This does not mean that demand on all arcs is the same, this demand alters. However, demand on one arc remains constant over time. The loaded truck-mile target does change over time. Two different changing targets are considered to show the impact of this target. The first problem instance is a decreasing target (4.1.1) and the second instance concerns a parabolic target (4.1.2).

4.1.1 Constant Demand, Decreasing Target

In this problem instance, the loaded truck-mile target gradually decreases from 80% to 0% over the planning horizon. As governments or company's boards change, policies are prone to change too. In these changing environments, decisions made by previous leaders

(a) Expensive AFT, Cheap Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	1, 4, 6	1, 4, 6	-	1, 4, 6	-	-
7	-	-	1	-	1	-
10	-	-	4, 6	-	4, 6	-

(b) Expensive AFT, Expensive Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	1, 4, 6	1, 4, 6	-	1, 4, 6	-	-
7	-	-	1	-	1	-
10	-	-	4, 6	-	4, 6	-

(c) Facility Cost and Computation Time

	(a)			*(b)*		
	B	**C**	**M**	**B**	**C**	**M**
% Facility Cost Reduction[1]	-	30.96	30.96	-	75.63	75.63
% Total Cost Reduction[1]	-	0.03	0.03	-	0.47	0.47
Computation Time (s)[2][3]	0.59	8.84	Limit	0.58	7.70	Limit
% Optimality Gap[4]	-	-	0.031	-	-	0.030

Table 4.2: Constant demand, decreasing target

may be withdrawn [44] [45]. A high loaded truck-mile target represents a decision that can be resigned.

If AFTs are more expensive compared to DTs, the target enforces the purchase of AFTs. If AFTs are purchased, the big-M constraint forces the model to open AFT facilities. If the target decreases, less and less AFTs are forced to be in the system. However, a decreasing number of AFTs will not close facilities immediately. Facilities are located on routes used by AFTs. The facility is allowed to close if there is no single AFT using the routes that pass the facility.

In the case of cheap AFTs, the target will not enforce the decision to purchase AFTs. In contrary, for those cases, trucks that are purchased in the network are AFTs and their facilities are built immediately at *t=1*. Therefore, for this problem instance, the discussion on the impact of different models is limited to the cases with expensive AFTs.

As table 4.2 shows, there is a difference in the results for model *B* and models *C* and *M*. If AFTs are expensive, the target forces the network to purchase AFTs. As the target decreases, AFTs are retired and DTs are purchased. The purchases and retirements of trucks in these scenarios can be found in Appendix A.1. Over time, less facilities are required to satisfy the big-M constraint, as can be seen at *t=7*, where the facility at

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[1] Compared to the use of model *B*

[2] Time until optimal solution is found, optimal solution is an optimality gap with a tolerance of 1.00e-4

[3] Time limit is 100 seconds

[4] Optimality gap if the time limit is reached

terminal 1 is closed. It can be seen that at period $t = 10$, the target reached 0 and all AFTs were retired. As a consequence, AFT facilities are no longer required in the network and are closed. Here, a difference is seen between model B and models C and M. B has to keep all facilities open even if they are not in use. Models C and M provide the network with the opportunity to close these facilities and receive their salvage value and returned operational costs. This leads to a cost reduction of costs related to facilities of approximately 31% for cheap facilities and 75% for expensive facilities. As expected, the cost reduction on the total costs is more significant for expensive facilities (0.47%) compared to cheap facilities (0.03%). The total costs and facility costs for all problem instances in this computational study can be found in Appendix B. These costs indicate that a cost reduction of 0.47% is significant in the order of magnitude of a complete fleet management model. The costs of cheap facilities are set very low for this scenario. Therefore, these costs have little impact on the total costs. Model M presents no extra costs benefits compared to model C, facilities are not moved. As expected, if the need for AFTs is going down, in the end, the facilities will close. Still, a basic amount of facilities is always required to satisfy the smallest target. The last facilities will be closed, if the target is zero and all AFTs are retired.

Closing is associated with costs and revenues. The closing costs consist of three components. First, the costs related to closing down the facility. Second, the salvage value of the facility and third, the returned operating costs. If AFT facilities are not required in the network, closing is beneficial, as long as the returned operating costs plus the salvage value of the facility is higher than the costs related to closing down the facility.

Overall, these results indicate that for this problem instance, model C fulfills to assist in the decision-making process. The costs benefits for models C and M are equal. However, the computation time for model M is more than ten times as large, which makes the choice for model C beneficial. Facilities close if they are not enforces to be in the network to satisfy constraints, as long as the revenue components related to closing the facility are higher than the cost component related to closing the facility.

4.1.2 Constant Demand, Parabolic Target

Two different scenarios are considered for this problem instance of a constant demand and a parabolic loaded truck-mile target. The first scenario (I) is a target starting at 0% going up till 80%. After reaching this peak, the target decreases back to 0%. The results for this scenario are presented in table 4.3. The second scenario (II) starts with a high target of 80% that decreases to 0% and increases back till 80%. The results for this scenario

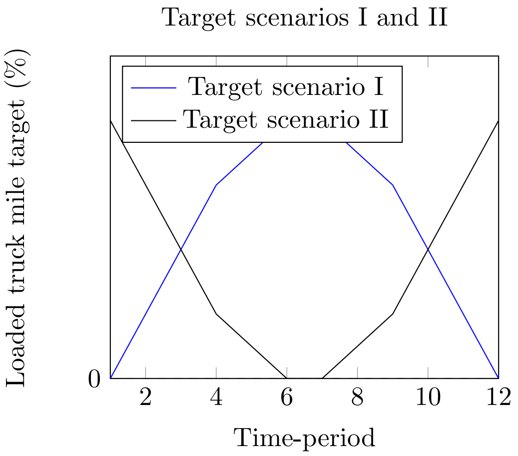

FIGURE 4.1: Target scenarios I and II

are set out in table 4.4. The pattern of both targets is represented in figure 4.1. These scenarios have been studied to represent the changes of targets in real life situations. As discussed in section 4.1.1, a target can change due to changes in governments or boards and their policies. Thereby, a target may be adapted to seasonal changes. For example, during the yearly Chinese smog season, Beijing has said to limit the number of polluting cars driving in the city [46]. This represents an increasing loaded AFT-mile target. After the smog season, policy makers decrease this target again. For these scenarios, both the influences of an increasing and a decreasing target are shown. For this reason will the problem instance of constant demand and an increasing target not be discussed separately. For this instance, all three models will solely open facilities for this instance.

The problem instance of constant demand and a parabolic target is discussed for the cases of expensive AFTs. It is apparent from the tables that the loaded truck-mile target has a strong influence on the facility decisions. Table 4.3, representing the scenario of the target that first increases and later decreases, indicates that if the target increases, facilities have to be bought to satisfy the high target. At *t=7*, when the target decreases, the situation is similar to the situation described in section 4.1.1. If facilities are no longer required, they will close. Hence, it is evident that the revenues of the salvage value and the returned operating costs are higher than the closing costs. Due to the high target, three facilities are bought. Later, these are closed in models C and M. For expensive facilities, this leads to high facility costs reductions of 72.7% and total cost reductions of 0.39%. For cheap facilities, the cost reductions are lower, 18.7% for the facility costs and 0.03% for the total costs.

Table 4.4 shows different implications. Although the target reaches zero at *t=6*, facilities are not closed. This difference can be explained by the purchases and retirements of

(a) Expensive AFT, Cheap Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	4	1	-	1	-	-
4	1, 6	4, 6	-	4, 6	-	-
10	-	-	6	-	6	-
11	-	-	4	-	4	-
12	-	-	1	-	1	-

(b) Expensive AFT, Expensive Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	4	1	-	1	-	-
4	1, 6	4, 6	-	4, 6	-	-
10	-	-	6	-	6	-
11	-	-	4	-	4	-
12	-	-	1	-	1	-

(c) Facility Cost and Computation Time

	(a)			*(b)*		
	B	**C**	**M**	**B**	**C**	**M**
% Facility Cost Reduction	-	18.69	18.69	-	72.72	72.72
% Total Cost Reduction	-	0.03	0.03	-	0.39	0.39
Computation Time (s)	0.79	47.42	Limit	0.60	21.08	Limit
% Gap	-	-	0.041	-	-	0.119

Table 4.3: Constant demand, parabolic target scenario I

trucks in this scenario. The purchases and retirements of trucks for both target scenarios are presented in Appendix A.2. Purchases and retirements in scenario I are gradual according to the increasing and decreasing target. For scenario II, the target is 80% at *t=0*. Therefore, the system immediately purchases almost exclusively AFTs. These trucks are expensive and have an optimal replacement period larger than the planned horizon. Beside, the operation costs for AFTs are equal to the operation costs of DTs. The system plans its fleet decisions over the total time horizon. For these purposes, the system will not retire its AFTs if those are required in the network some periods later. It is cheaper to operate trucks and facilities for the time periods the target does not force them to be in the system, than to retire AFTs, close facilities, buy DTs and eventually open AFTs and facilities again some periods later.

In the event that operating AFTs becomes more expensive than retiring AFTs and buying DTs, it is seen by experiment that the system will retire AFTs and there will be no AFTs in the system at *t=6* and *t=7*. Still, facilities are not closed. This result is explained by the fact that the system plans that these facilities will be needed some time periods later. As a consequence, facilities will only be closed if the costs of closing and re-opening is lower than the operating costs for the two time periods.

(a) Expensive AFT, Cheap Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	1, 4, 6	1, 4, 6	-	1, 4, 6	-	-

(b) Expensive AFT, Expensive Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	1, 4, 6	1, 4, 6	-	1, 4, 6	-	-

(c) Facility Cost and Computation Time

	(a)			*(b)*		
	B	**C**	**M**	**B**	**C**	**M**
% Facility Cost Reduction	-	0	0	-	0	0
% Total Cost Reduction	-	0	0	-	0	0
Computation Time (s)	0.38	9.21	Limit	0.56	16.86	Limit
% Gap	-	-	0.0176	-	-	0.0026

Table 4.4: Constant demand, parabolic target scenario II

In conclusion, the parabolic target suggests the use of model *C*. The function to move facilities is not used in this problem instance. Model *C* has a longer computation time than model *B*, model *C* takes on average 30 times as long to find the optimal solution. However, the use of model *C* can lead to significant cost reductions which compensate for that fact (up to 73% facility cost reduction for expensive facilities). Facilities are closed when the target decreases and is not planned to increase again. However, facilities are not closed if the target increases again. This difference is important to notice. A parabolic target due to seasonal changes is likely to occur every year. In those cases, it is cheaper to keep the trucks in the system as long as the operating costs are lower compared to the difference between the salvage value of AFTs and their new purchase price. As long as there are AFTs used in the network, facilities will be required too. Thus, it is important to plan according to the predicted changes in the network. If there is an ongoing parabolic target and a large network, the use of model *B* is sufficient. This will save computation time and it is expected that facilities are kept open between the parabolic targets.

4.2 Changing Demand, Constant Target

To see the effects of demand on model outcomes, in this problem setting, contrary to the previous section, the loaded truck-mile target is constant and the demand is changing. All the problem instances in this section use a constant loaded AFT-mile target of 40%. This indicates that 40% of the total loaded truck-miles has to be travelled by AFTs. Two types of demand changes are distinguished; a change in the amount of demand (4.2.1) and

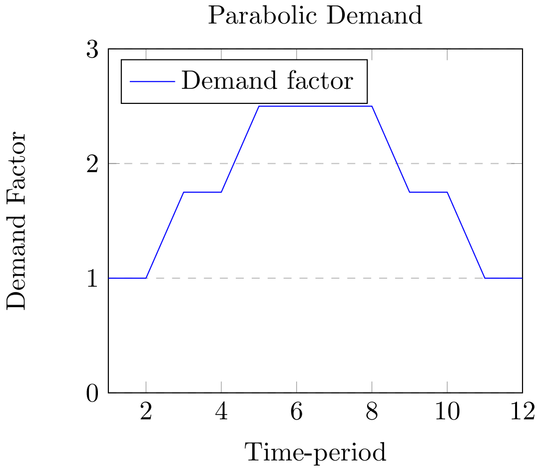

Figure 4.2: Demand factor over time

a change in inbound-heavy and outbound-heavy demand regions (4.2.2). For this second problem instance, two different scenarios will be discussed.

4.2.1 Parabolic Demand, Constant Target

In this class of problem instances a total varying demand is considered. As time passes, demand quantities raise till 250% of the original demand and after this peak at *t=6* till *t=8*, the total demand decreases back to its original value. Figure 4.2 shows this parabolic demand over the planned time horizon. It is important to notice that the total demand of the complete network is increasing and decreasing. Hence, the different demand quantities on every arc are increasing and decreasing with the same percentage. This could represent products that have a seasonal demand, for example Christmas goods or ice cream. In a specific period of the year there is an increased demand for these specific goods [47]. The loaded truck-mile target remains constant at 40% over the total planned horizon. Inbound heavy regions, outbound heavy regions and balanced regions remain the same over the total planned horizon.

It can be expected that extra facilities have to be bought to cope with the increased demand. However, the results in table 4.5 show that there were no extra facilities opened. The explanation for this is that purchases of extra trucks cope this increased demand. The purchases and retirements of trucks for this problem instance are represented in Appendix A.3. The types of trucks will use the same routes their truck type has been using before the demand increased. New AFTs will use the same routes AFTs were using and new DTs will use the same routes DTs were using. In this way, there is no need to open extra facilities, since facilities are not capacitated. If the total demand increases, the proportion of AFTs related to DTs does not change. In the case of expensive AFTs, the purchases

(a) Expensive AFT, Cheap facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	1, 4, 6	1, 4, 6	-	1, 4, 6	-	-

(b) Expensive AFT, Expensive Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	4, 6	4, 6	-	4, 6	-	-

(c) Cheap AFT, Expensive facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	1, 2, 4, 6, 10	1, 2, 4, 6, 10	-	1, 2, 4, 6, 10	-	-

(d) Cheap AFT, Cheap Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	1, 2, 4, 6, 10	1, 2, 4, 6, 10	-	1, 2, 4, 6, 10	-	-

(e) Facility Cost and Solving Time a,b

	(a)			*(b)*		
	B	**C**	**M**	**B**	**C**	**M**
% Facility Cost Reduction	-	0	0	-	0	0
% Total Cost Reduction	-	0	0	-	0	0
Solving Time (s)	0.37	1.55	29.7	1.23	26.71	Limit
% Gap	-	-	-	-	-	0.0376

(f) Facility Cost and Solving Time c,d

	(c)			*(d)*		
	B	**C**	**M**	**B**	**C**	**M**
% Facility Cost Reduction	-	0	0	-	0	0
% Total Cost Reduction	-	0	0	-	0	0
Solving Time (s)	0.76	22.66	Limit	0.53	5.21	Limit
% Gap	-	-	0.1833	-	-	0.0248

Table 4.5: Parabolic demand, constant target

and retirements of AFTs and DTs are in proportion to the loaded truck mile target. At *t=0*, all required facilities were built to fulfill future demand.

In the event that AFTs are cheap, purchases solely consist of AFTs that are travelling all routes in the system. In consequence, there are more facilities in the system when AFTs are cheap. This is related to the fact that all demand in the system is fulfilled by AFTs. All used routes in the system require an AFT facility along them.

In summary, the results of this section show that if the ratio between the number of AFTs and the number of DTs in the system remains the same, no change in facility management is required. In this case, model *B* will be sufficient to determine the optimal fleet management strategy. The use of models *C* and *M* does not lead to any costs reductions and both models have considerably longer computation times due to the increased number of decision variables.

4.2.2 Change in Demand Regions, Constant Target

This problem instance represents a swap in inbound-heavy and outbound-heavy demand regions. This can happen in multiple situations. For example, due to the transfer of a factory or a population shift in the network [48]. For this problem instance, two different scenario's are considered. The first scenario concerns a single swap in demand regions (4.2.2.1) and the second scenario represents a double swap in demand regions (4.2.2.2). Total demand stays about the same in both scenarios.

4.2.2.1 Single Swap in Demand Regions, Constant Target

The single swap instance is discussed first. At $t=7$, the demand from one region swaps from heavy to zero and the demand from another region swaps from zero to heavy. Heavy demand is a doubling of the normal demand. The demand of the third region is constant. Over time, localization of demand on the arcs changes, total demand stays about the same. This demand pattern poses challenges for the localization of facilities. In model B, it is seen that the location of the facility had to be thought over carefully and was chosen on a central location [14].

Table 4.6 presents the optimal facility location decisions for a single swap at $t=7$. In the event that AFTs are expensive (4.6ab), the minimal number of AFTs and facilities (2) is bought to satisfy the target. In the previous sections, the moving function of model M has not yet been used. However, in tables 4.6ef, the costs benefits of closing and moving are clearly shown. Model B has to open an extra facility to be able to satisfy the demand of the new demand region after the swap. Model C immediately closes the facility at terminal 6 when the new facility at terminal 1 is opened. It can be seen that when a facility is not needed anymore, model C will close this facility, leading to a facility cost benefit between 17.76 and 25.95 %. Therefore, as long as closing down a facility will return value, model C will close down this facility if there are no AFTs passing the routes along this facility anymore.

Model M shows that if moving is possible, the model moves the facility from the old location (6) to the new location (1) instead of closing one facility at the old location and opening a new facility at the new location. This happens as long as the costs relating to moving the facility are lower than the difference between opening a new facility and the returned revenue obtained from closing an old facility.

In the event that AFTs are cheaper (4.6cd), the same facilities are required compared to expensive AFTs. At $t=7$, the facility at terminal 4 is kept open in the first region and the

(a) Expensive AFT, Cheap Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	4, 6	4, 6	-	4, 6	-	-
7	1	1	6	-	-	(6,1)

(b) Expensive AFT, Expensive Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	4, 6	4, 6	-	4, 6	-	-
7	1	1	6	-	-	(6,1)

(c) Cheap AFT, Expensive Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	4, 6	4, 6	-	4, 6	-	-
7	1	1	6	-	-	(6,1)

(d) Cheap AFT, Cheap Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	4, 6	4, 6	-	4, 6	-	-
7	1	1	6	-	-	(6,1)

(e) Facility Cost and Computation Time a,b

	(a)			*(b)*		
	B	**C**	**M**	**B**	**C**	**M**
% Facility Cost Reduction	-	17.76	18.50	-	25.95	27.54
% Total Cost Reduction	-	0.002	0.002	-	0.022	0.024
Computation Time (s)	0.27	1.1	29.7	0.87	74.12	Limit
% Optimality Gap	-	-	-	-	-	0.038

(f) Facility Cost and Computation Time c,d

	(c)			*(d)*		
	B	**C**	**M**	**B**	**C**	**M**
% Facility Cost Reduction	-	25.95	27.54	-	17.76	18.50
% Total Cost Reduction	-	0.258	0.279	-	0.018	0.019
Computation Time (s)	0.76	22.66	Limit	0.53	5.21	Limit
% Optimality Gap	-	-	0.183	-	-	0.025

Table 4.6: Single swap demand regions, constant target

facility at terminal 6 is moved to terminal 1. This can be explained by the fact that the facility at terminal 4 is the facility at the hub of the constant demand region (region 2), this demand remains the same thus the facility is still required. Terminal 6 is the hub of the demand heavy region (region 3) in the periods up to t=*7* and terminal 1 is the hub of the demand heavy region (region 1) after t=*7*. By covering these terminals, all positive demand arcs in the system are covered.

The moving costs are dependent on two cost factors. The first cost factor (I) influences the costs of closing down the facility at the old location and building up the facility at the new location after the transfer. These fixed costs are a small percentage of the original closing and opening costs for that location. The other cost factor (II) is influencing the costs related to the travelling distance. These are variable travelling costs directly related to the distance between the old terminal and the new terminal location.

The results in this section suggest that if the location of the demand's inbound- and outbound-heavy regions changes, it can be beneficial to move the facility. Model M facilitates this choice, contributing to an extra facility cost reductions of more than 1%. Total cost reductions are more significant for expensive facilities. Moving is beneficial if the costs are lower compared to opening an extra facility (model B) and lower than opening a new facility and closing an old facility. The next section (4.2.2.2), therefore, moves on to discuss further on the effects of the different cost factors discussed in this section.

4.2.2.2 Double Demand Swap Demand Regions, Constant Target

To further show the impact of the different moving costs factors described in the previous section, this second problem instance is presented. This instance represents a double swap in inbound and outbound-heavy demand regions. It can be compared to the previous section. Although, for this problem instance, the demand's inbound and outbound heavy regions swap twice. At *t=5*, the demand from one region swaps from heavy to zero and at *t=9*, it swaps back. This swap is reversed for the second region and for the third region the demand remains constant over the total planned horizon.

To optimally show the impact of the different moving cost factors, the price of an AFT is set cheaper than a DT. In this way, all purchased trucks in the network are AFTs and the impact of the demand region swaps can clearly be seen. Hence, the loaded truck-mile target does not influence the fleet management decisions. The different scenario's discussed for this instance are cheap and expensive facilities and standard moving costs, a cheap opening and closing multiplier (factor I) or a cheap travel multiplier (factor II). This experiment was designed to show the impact of these different cost factors.

There are two matters standing out in the optimal fleet management decisions of this section. The results in tables 4.7 and 4.8 reveal that for the standard moving costs (4.7a, 4.8a), closing the old facility and opening a new facility is cheaper. These results can be explained by the cost difference between the revenues of closing down the old facility and the costs of opening a new facility. These are lower than the moving costs in this scenario. The moving costs are higher compared to the results in table 4.6cd. In this scenario, the facility has to move twice, to the new location and back, which leads to a doubling of the moving costs.

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[5] Time limit in this instance (4.2.2.2) is changed to 500 seconds

(a) Cheap Facility, Standard Moving Costs

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	4, 6	4, 6	-	4, 6	-	-
5	1	1	6	1	6	-
9	-	6	1	6	1	-

(b) Cheap Facility, Cheap opening and closing multiplier, Factor I

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	4, 6	4, 6	-	4, 6	-	-
5	1	1	6	1	6	-
9	-	6	1	6	1	-

(c) Cheap Facility, Cheap Travel Multiplier, Factor II

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	4, 6	4, 6	-	4, 6	-	-
5	1	1	6	-	-	(6,1)
9	-	6	1	-	-	(1,6)

(d) Facility Cost and Computation Times a,b

	(a)			*(b)*		
	B	**C**	**M**	**B**	**C**	**M**
% Facility Cost Reduction	-	19.93	19.93	-	19.93	19.93
% Total Cost Reduction	-	0.019	0.019	-	0.019	0.019
Computation Time (s)[5]	2.94	314.82	Limit	2.94	314.82	Limit
% Gap	-	-	0.013	-	-	0.016

(e) Facility Cost and Computation Times c

	(c)		
	B	**C**	**M**
% Facility Cost Reduction	-	19.93	25.57
% Total Cost Reduction	-	0.019	0.024
Computation Time (s)	2.94	314.82	Limit
% Gap	-	-	0.013

Table 4.7: Double swap demand regions, cheap facilities, constant target

In the case of cheap facilities, facilities in model M do not move if factor I is cheap (table 4.7b) but moves if factor II is cheap (table 4.7c). In the case of expensive facilities, the facility moves if factor I is cheap (table 4.8b) and does not move when factor II is cheap (table 4.8c). This can be explained by the fact that the opening and closing multiplier (I) has limited effect on a cheap facility since it is a percentage of the cheap opening and closing costs of this facility. In contrary, this factor is significant if it is a percentage of the expensive opening and closing costs of an expensive facility. The travel distance costs factor (II) contributes to a high percentage of the total moving costs when facilities are cheap since the opening and closing costs components of facilities is relatively low. It is a smaller percentage in the case of an expensive facility where the opening and closing costs component of a new facility is relatively expensive. Interestingly, there is also an other difference between the solutions for the cheap and expensive facilities. For expensive *(a) Expensive Facility, Standard Moving Costs*

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	4, 6	4, 6	-	4, 6	-	-
5	1	1	-	1	-	-
9	-	-	1	-	1	-

(b) Expensive Facility, Cheap opening and closing multiplier, factor I

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	4, 6	4, 6	-	4, 6	-	-
5	1	1	-	-	-	(6,1)
9	-	-	1	-	-	(1,6)

(c) Expensive Facility, Cheap Travel Multiplier, factor II

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	4, 6	4, 6	-	4, 6	-	-
5	1	1	-	1	-	-
9	-	-	1	-	1	-

(d) Facility Cost and Computation Times a,b

	(a)			*(b)*		
	B	**C**	**M**	**B**	**C**	**M**
% Facility Cost Reduction	-	24.93	24.93	-	24.93	31.22
% Total Cost Reduction	-	0.22	0.22	-	0.22	0.275
Computation Time (s)	1.26	139.31	Limit	1.26	139.31	Limit
% Gap	-	-	0.134	-	-	0.117

(e) Facility Cost and Computation Times c

	(c)		
	B	**C**	**M**
% Facility Cost Reduction	-	24.93	24.93
% Total Cost Reduction	-	0.22	0.22
Computation Time (s)	1.26	139.31	Limit
% Gap	-	-	0.1554

Table 4.8: Double swap demand regions, expensive facilities, constant target

facilities (table 4.8), the facility at terminal 6 is kept open from time period 5 to 9. For cheap facilities (table 4.7), this facility is closed at *t=5* and opened again at *t=9*. This result is explained by the fact that, for expensive facilities, the costs to close and re-open a facility are higher compared to the operating costs for those four time periods. In the case of cheap facilities, this is the contrary; it is cheaper to close and re-open facilities than to pay the operating costs of *t=5* to *t=9*.

Taken together, these results give a clear indication of the advantages of the use of model *M*. This model takes both the closing and the moving costs into consideration, and is thereby capable of making the right considerations and decisions for the network, taken into account the effects of the costs related to these functions. Despite the fact that model *M* has at least a more than 4 times longer computational time compared to model *C*, the possible cost benefit of model M of approximately 6% extra facility cost reduction propagates for the use of this model. However, the use of model M is solely recommended if facilities are not cheap and have a significant impact on the total costs. In this scenario, model C is sufficient for the scenario of cheap facilities while model M can be used in the scenarios of expensive facilities.

4.3 Regulations on Fleet Management

These problem instances represent changes in the environment of the network. Different limitations are added in addition to the original constraints of the models. The first problem instance describes a scenario where it is prohibited to build facilities at the regions' hubs (4.3.1). The optimal fleet management decisions for this problem instance are given for cheap and expensive AFTs and cheap and expensive facilities. The second problem instance considers the case of temporal bans on diesel trucks at specific terminal locations (4.3.2). The scenarios considering expensive AFTs and cheap and expensive facilities are discussed.

4.3.1 Facilities Prohibited at Hubs

This instance considers a scenario where it is not allowed to build AFT facilities at the region's hubs. As seen in previous sections of this chapter, almost all facilities in different instances are built at the hub's terminal. Hubs are heavy junctions, there could be a possibility that it is not allowed to build a facility at this location due to high costs or limited space. The hubs for this network are described in table 4.1. Two different scenario's are considered to see the influence on the fleet management decisions. The first scenario is the scenario of constant demand and a constant target (4.3.1.1) and the second scenario considers a single swap in demand regions and a constant target (4.3.1.2). For both scenarios, loaded truck mile targets are constant at 40%.

4.3.1.1 Facilities Prohibited at Hubs, Constant Demand, Constant Target

Table 4.9 presents the optimal fleet management decisions for the first scenario, the simplest test instance of constant demand and a constant loaded truck-mile target. The demand is constant over time and differs per arc. The results in table 4.9 show the impact of the prohibition. If routes pass multiple regions, they always pass one of the hubs. In the case of expensive AFTs (4.9ab), two facilities have to be opened in every region to satisfy the target. Facilities are opened at terminals 2 and 3 in region 1, at terminals

(a) Expensive AFT, Cheap Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	2, 3, 5, 8, 9, 10	2, 3, 5, 8, 9, 10	-	2, 3, 5, 8, 9, 10	-	-

(b) Expensive AFT, Expensive Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	2, 3, 5, 8, 9, 10	2, 3, 5, 8, 9, 10	-	2, 3, 5, 8, 9, 10	-	-

(c) Cheap AFT, Expensive Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	2, 3, 5, 7, 8, 9, 10	2, 3, 5, 7, 8, 9, 10	-	2, 3, 5, 7, 8, 9, 10	-	-

(d) Cheap AFT, Cheap Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	2, 3, 5, 7, 8, 9, 10	2, 3, 5, 7, 8, 9, 10	-	2, 3, 5, 7, 8, 9, 10	-	-

(e) Facility Cost and Computation Time a,b

	(a)			*(b)*		
	B	**C**	**M**	**B**	**C**	**M**
% Facility Cost Reduction	-	0	0	-	0	0
% Total Cost Reduction	-	0	0	-	0	0
Computation Time (s)	0.32	3.27	Limit	0.56	2.35	Limit
% Optimality Gap	-	-	0.042	-	-	0.042

(f) Facility Cost and Computation Time c,d

	(c)			*(d)*		
	B	**C**	**M**	**B**	**C**	**M**
% Facility Cost Reduction	-	0	0	-	0	0
% Total Cost Reduction	-	0	0	-	0	0
Computation Time (s)	2.26	89.72	Limit	0.56	3.14	Limit
% Optimality Gap	-	-	0.462	-	-	0.037

Table 4.9: No facility at hubs, constant demand, constant target

5 and 10 in region 2 and at terminals 8 and 9 in region 3. In the case that AFTs are cheaper compared to DTs, facilities are opened at every terminal except for the hubs. This can be seen in 4.9c and 4.9d. This can be explained by the fact that almost all trucks in the network are AFTs. The purchases and retirements of trucks in the network are represented in Appendix A.6. Facilities have to be opened on every route AFTs pass.

The results suggest that for this problem instance with a constant demand and a constant target, opening facilities is the only function used. Models C and M do not provide any costs benefits. Therefore, for this problem instance, the use of model B would be beneficial considering the increase in decision variables and computation time for models C and M.

4.3.1.2 Facilities Prohibited at Hubs, Single Swap in Demand Regions, Constant Target

The second scenario is the scenario of a single demand swap and a constant loaded truck-mile target, as seen in section 4.2.2. There, it was seen that after the swap, the facilities were moved to the hub of the new demand heavy location. For this scenario, it is not allowed to move the facility to a hub. To satisfy the constraints, in table 4.10, it is seen that facilities are required at multiple terminal locations. This can be explained by the presence of a hub in all demand routes. Therefore, by opening a facility at a hub, all terminals in the region are covered. In this scenario, multiple facilities are used to satisfy the same demands. For the standard moving cost factors, it is shown that for expensive facilities, moving is cost beneficial, leading to a 24 to 35 % facility cost reduction and a 0.006 to 0.448% total cost reduction. For cheap facilities, closing is beneficial, leading to a facility cost reduction of 15 to 23 %. This indicates that the closing and reopening costs for cheap facilities are lower than the moving costs to move a facility. Referring back to section 4.2.2.2, this suggests that the moving multiplier leads to too high moving costs for this instance (factor II).

Overall, the results of this section suggest that prohibiting facilities to open at hub terminals does change the strategic decisions of where to open a facility. However, it does not influence the strategic decisions made by models *B, C* and *M*, as seen in the previous sections. If demand and target are constant, facilities will not be closed or moved and the use of model *B* to assist in the decision making process is sufficient. If the location of the demand changes, models *C* and *M* will use their functions to close and move facilities. All decisions remain based on achieving the lowest possible costs while satisfying all constraints. Model *C* is sufficient for cheap facilities, since the extra computation time does not outweigh the small extra total cost reductions. Model *M* can be used in the case of expensive facilities. Here, the extra computation time does lead to an extra facility and total cost reduction.

4.3.2 Temporal Diesel Bans, Constant Demand, No Target

This instance is different compared to all other instances. For this problem instance, there is no target involved to enforce the purchase of AFTs. Many governments do not have specific targets to enforce the use of AFTs. However, some ban DTs or other polluting trucks in certain regions or cities [49][50][51]. There are also cities that have temporal bans on DTs or other polluting vehicles in cities to temporary lower the air pollution [52][53]. Two different scenario's are considered to show the influence of these temporal

(a) Expensive AFT, Cheap Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	5, 7, 8, 9, 10	5, 7, 8, 9, 10	-	5, 7, 8, 9, 10	-	-
7	2, 3	2, 3	7, 8, 9	2, 3	7, 8, 9	-

(b) Expensive AFT, Expensive Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	5, 7, 8, 9, 10	5, 7, 8, 9, 10	-	5, 7, 8, 9, 10	-	-
7	2, 3	2, 3	7, 8, 9	-	8	(9,2), (7,3)

(c) Cheap AFT, Expensive Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	5, 7, 8, 9, 10	5, 7, 8, 9, 10	-	5, 7, 8, 9, 10	-	-
7	2, 3	2, 3	8, 9	-	-	(9,2) (8,3)

(d) Cheap AFT, Cheap Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
1	5, 7, 8, 9, 10	5, 7, 8, 9, 10	-	5, 7, 8, 9, 10	-	-
7	2, 3	2, 3	8, 9	2, 3	7, 8	-

(e) Facility Cost and Computation Time a,b

	(a)			*(b)*		
	B	**C**	**M**	**B**	**C**	**M**
% Facility Cost Reduction	-	22.83	22.83	-	32.93	35.01
% Total Cost Reduction	-	0.004	0.004	-	0.005	0.006
Computation Time (s)	0.38	0.88	15.39	0.48	12.18	Limit
% Optimality Gap	-	-	-	-	-	0.027

(f) Facility Cost and Computation Time c,d

	(c)			*(d)*		
	B	**C**	**M**	**B**	**C**	**M**
% Facility Cost Reduction	-	21.96	24.02	-	15.22	15.22
% Total Cost Reduction	-	0.416	0.448	-	0.003	0.003
Computation Time (s)	2.26	Limit	Limit	0.56	3.14	Limit
% Optimality Gap	-	0.039	0.344	-	-	0.037

Table 4.10: No facility at hubs, swap demand regions, constant target

bans on the different models. The first scenario is a scenario considering two temporal bans for the same terminal location in different time periods. The second scenario represents two temporal bans on two different terminal locations. The optimal fleet management decisions are discussed for the scenarios of expensive AFTs and cheap and expensive facilities.

4.3.2.1 Two Temporal Diesel Bans on the Same Terminal, Constant Demand, No Target

This scenario bans DTs from all routes passing terminal 5 from time period 4 to 6 and period 8 to 10. Thus, the diesel ban appears twice on the same terminal in different time

(a) Expensive AFT, Cheap Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
4	5	5	-	5	-	-
10	-	-	5	-	5	-

(b) Expensive AFT, Expensive Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
4	5	5	-	5	-	-
10	-	-	5	-	5	-

(c) Facility Cost and Computation Time

	(a)			*(b)*		
	B	**C**	**M**	**B**	**C**	**M**
% Facility Cost Reduction	-	30.41	30.41	-	82.79	82.79
% Total Cost Reduction	-	0.006	0.006	-	0.148	0.148
Computation Time (s)	0.30	2.29	40.43	0.61	1.51	37.39
% Gap	-	-		-	-	

Table 4.11: Two temporal diesel bans on terminal 5, constant demand, no target

(a) Expensive AFT, Cheap Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
4	6	6	-	6	-	-
8	5	5	6	-	-	(6,5)
10	-	-	5	-	5	-

(b) Expensive AFT, Expensive Facility

Period	**B** Open	**C** Open	**C** Close	**M** Open	**M** Close	**M** Move
4	6	6	-	6	-	-
8	5	5	6	-	-	(6,5)
10	-	-	5	-	5	-

(c) Facility Cost and Computation Time

	(a)			*(b)*		
	B	**C**	**M**	**B**	**C**	**M**
% Facility Cost Reduction	-	50.31	50.93	-	76.72	79.29
% Total Cost Reduction	-	0.016	0.001	-	0.316	0.326
Computation Time (s)	0.60	1.66	Limit	0.65	9.07	Limit
% Gap	-	-	0.015	-	-	0.059

Table 4.12: Two temporal diesel bans on terminals 9 and 5, constant demand, no target

periods. The results for this scenario are presented in table 4.11.

The observed results in table 4.11 present the optimal fleet management strategies for two bans on the same terminal location to satisfy demand at this terminal. At $t=4$, DTs are banned from all routes passing along terminal 5. At this point in time, AFTs have to be bought. The purchases and retirements of the trucks for this section are presented in Appendix A.8. The big-M constraint ensures the opening of an AFT facility at that time period. If the ban is no longer in use, and there is no future sight on a new ban on this location, models C and M close the AFT facilities. Interestingly, facilities are not closed in between the two bans. This can simply be explained by the fact that the AFTs in the system will not be retired as was shown in section A.2. Therefore, facilities are still forced to be in the network.

Overall, facilities will close if there are no longer AFTs using the routes along them. However, if it is likely that a temporal ban is planned on a more frequent base, the results suggest that logistic policy makers must keep these facilities open until they can be used for the next ban. The location of the ban or the demand does not change for this instance. A change in facility location is not required and model C is sufficient to assist in the decision making for this instance. If there are no further bans planned, this can lead to a approximate 30-82 % facility cost reduction, depending on the costs of the facility.

4.3.2.2 Two Temporal Diesel Bans on Different Terminals, Constant Demand, No Target

The benefit of model M can be seen in the solutions of the optimal fleet management strategies if bans come into force at different locations. To represent this scenario, there is a ban of DTs at terminal 9 from time period 4 to 6 and subsequently, there is a DT ban at terminal 5 from time period 8 to 10.

Table 4.12 highlights the fact that facilities have to be opened at both diesel ban locations to satisfy all demand. Facilities are opened at terminal 6 and terminal 5. The fact that the facility is opened at terminal 6 and not at terminal 9 can be explained by the fact that terminal 6 is the hub of region 3, where terminal 9 is located in. Since a hub is a consolidation centre, all demand routes that pass terminal 9 pass terminal 6 too.

There is no diesel ban from *t=6* to *t=8*. Therefore, there is no constraint that forces a facility to be at a specific location in the network. The models will choose the cheapest option in all cases. It is more beneficial to change the location of the terminal as late as possible. From *t=6* to *t=8*, there is no ban forcing AFTs to be in the network. However, AFTs are kept in the system and moved to the new banned routes at *t=8*. Hence, as AFTs are in the system, AFT facilities are required to be in the system.

To conclude this section, bans in a system force the same use of facility models compared to targets. The temporal bans in section 4.3.2.1 can be compared to a parabolic target (section 4.1.1). For this reason, the use of model C is sufficient. A change in the location of demand (section 4.2.2 and 4.10) or the relocation of a ban forces the system to open facilities at different locations. The use of model M proves to lead to costs benefits. However, these costs difference are not significant, less than 0.01 total cost reduction for expensive facilities. The computation times for model M are more than 10 times as large compared to model C. For this reason, if a larger model leads to an increase in decision variables and computation times, model C can also be used.

Chapter 5

Conclusions, Limitations and Further Work

This study set out to demonstrate the functions of closing and moving facilities in an integrated fleet management model and to investigate how these new functions perform in the models. It is the first study comparing different decisions regarding the facility infrastructure in an integrated fleet management model. Two MIP models were developed, model C, capable of opening and closing, and model M, where facilities can open, close and move. The study was designed to determine when the use of a specific model is favoured to assist in the decision-making process of logistic problems.

Road transport is a major component of most economies. However, HDVs are also major air polluters. Considering the growing environmental concerns, the transportation sector recognizes the need to green their fleet. One of the main barriers in the adoption of AFTs is the lack of an infrastructural network for AFT facilities. Therefore, to facilitate the transition from DTs to AFTs, the strategic decision of location-allocation of facilities is crucial. Due to the high impact related to these strategic decisions, this research elaborated further on the functions regarding AFT facilities in order to make the total integrated model more robust to cope with changes in the network. Literature suggests that networks become more robust if they are able to cope with uncertainty. By implementing the possibility to close and move facilities in the integrated fleet management model, next to the existing possibility to open facilities, the aim was to make these networks more profitable over their planned horizon. Two elaborated integrated fleet management models were developed to accommodate opening and closing (model C) and opening, closing and moving (model M). This contribution has been new in this field of dynamic fleet management models. It contributes to a deeper understanding on the influence of facilities in the overall transition of fleets.

Different test instances were used to investigate the behaviour of the different models. The study has shown that different problem instances can use a different model to assist in the decision-making process of logistic problems. It is demonstrated that for many instances, the newly developed models are more complete in their decisions and therefore, beneficial.

The original model of Bakir (model B) is solely capable of opening facilities. The optimal fleet management results show that this is sufficient if demand or targets remain constant or increase. However, for all other instances, models C and M are considered favorable ascribed by the computational study. The problem instances in sections 4.1, 4.2, and 4.3 use the possibility to close and move facilities. There is a reduction of costs compared to model B, and the use of these models will lead to more cost beneficial results for its user.

The availability of the option to open, close and move AFT facilities provides measurable benefits to logistic service providers. Since model M is capable to represent all of these functions, including all the functions inhibited by models B and C, it is argued that logistic policy makers use this model to assist in their decision making processes. For the problem instances used in this research, the moving of facilities is cost beneficial in the case of a change in demand regions (4.2.2) and within a changed region of temporal diesel bans (4.3.2.2). Although the percentage total cost reductions do not exceed 0.5%, this is still a large cost reduction regarding the high values related to fleet management (see Appendix B).

For the small test instance of 10 terminals and 12 time periods that was used in this study, the use of model M as decision making tool is always beneficial. This model finds the optimal solution considering all possible options and is able to solve most problem instances in time (100 s) with a small optimally gap ($\leq$0.1%). However, most real life fleets do not have this small size. Hence, solving the model will take considerably longer. For example, if the number of time periods is doubled, the number of decision variables for model B more than triples. These differences are even larger for models C and M. The sizes of the models differ considerably. For the small test instance that was used in this research, approximately 40% of the decision variables is eliminated by using model C instead of model M. This difference is so significant due to the fact that model M uses decisions variables $n_{j_1 j_2 \tau t}$. The computation times are on average more than 40 times as large if the optimal solution has to be found for both models. The difference in the number of decision variables between models B and C is smaller. Using model B will decrease the number of decision variables by approximately 5% compared to model C. The computation times of model C are on average 10 to 20 times longer compared to model B.

If larger instances are used, a decision has to be made regarding the use of which integrated model. It is demonstrated that for the cases of increasing or constant demands or targets, the use of model B is sufficient. For these scenarios, facilities are solely opened and the model has the smallest number of decision variables and thus the shortest computation time. For decreasing demands or targets in one location or if the moving costs between all location pairs are equal leading to a simplified version of model M, model C is appropriate. This model is capable of closing and has considerably shorter computation times compared to model M due to the lack of decision variables $n_{j_1 j_2 \tau t}$. Model M has to be used if the location of demands, targets or bans change. However, due to the large computation times and a minimal impact, in the case of cheap facilities, model C can also be used. In real life, it is expected that facilities are more likely to be expensive than cheap. Therefore, facility cost reductions do have an influence on the total cost reductions. Model M should be used in those cases.

The results of this study indicate the importance of the chosen costs in the model. Chapter 4 indicates that the decisions to close and move a facility are sensitive to the associated costs for these actions. Sensitivity analysis of the closing and moving costs have shown different implications in different scenarios. Therefore, for the users of the model, the costs have to be chosen as realistic as possible and have to be thought over carefully. A limitation of this model could be the modelling preference that all operating costs till the end of the planned horizon are paid when a facility is opened. In that way, the costs for operating facilities till the end of the planned horizon are paid upfront. It is modelled that they are returned if the facility is closed. The limitation may be that this return is an incentive to close the facility. However, this is solely a problem if the closing costs are higher than the salvage value of the facility. This is a modelling preference and other modeling options exist. For example, to model the operating costs of the facilities as separate decision variables, similar to the operating costs of the trucks in the model. Another cost limitation are the cost component factors used in the moving costs. The percentage of closing at one facility is equal to the percentage of building at the new facility. If these costs distinguish to a large extent, the model has to be adapted to distinguish these components.

Another limitation of this work is the fact that an unlimited number of AFTs can be served by an AFT facility. In chapter 4, it is seen that there is an unlimited amount of trucks that can be assigned to specific routes, thereby using the same facility. In real life, this is unrealistic as facilities have a maximal number of trucks that can be served in a specific time period. A further study could assess this research gap by integrating capacitated facilities in the network [39]. The current study is also limited by the lack of information on the distance trucks can travel until they need to visit a facility. It was assumed that trucks can travel all routes in the network once, without the need to visit a facility. However, there are long and short routes. A maximum distance will further extend the optimal use of trucks and facilities in the models.

Further research might continue to explore how integrated fleet management models become more robust in real life situations. These situations might be networks that have some routes that cannot be travelled during some hours, for example peak hours in a system. An other option might be to distinguish the fueling facilities for AFTs and the maintenance facilities for AFTs. For these different type of facilities, it is expected that there is a distinction in costs in opening and operating, their expected intensity of use by AFTs and their expected life. In this way, the maintenance and fuel costs of the AFT trucks can be distinguished, different decisions variables related to their opening can be obtained.

The focus of this research particularly was on the transition from a diesel fleet to a fleet of AFTs. However, the model could be extended to a general transition model that transits any fleet to another. Possible further research could explore these other types of transitions and make specific requirements for those transitions that can be added to the general transition model. A further study could assess the mobility of facilities. Model M describes one possibility to enlarge the mobility of facilities. Another option may be to have total mobile facilities that travel to the trucks. This will require a totally different model since there should be a constant indication of where trucks are in the network and when trucks need fuel or maintenance.

Appendix A

Fleet Purchases and Retirements

Time Period	Purchases		Retirements	
	Diesel	AFT	Diesel	AFT
1	-	1938.59	1943.2	-
3	218.79	-	218.79	-
4	806.87	-	-	806.87
7	565.86	-	-	565.86
10	565.86	-	-	565.86

Table A.1: Purchases and retirements, expensive AFTs, constant demand, decreasing target

(a) Target scenario I

Time Period	Purchases		Retirements	
	Diesel	AFT	Diesel	AFT
1	142.74	1249.77	1395.88	-
2	-	205.11	205.11	-
5	-	347.20	347.20	-
6	-	417.61	417.76	-
8	417.61	-	-	417.76
9	347.20	-	-	347.20
10	484.96	-	-	484.96
11	484.96	-	-	484.96
12	484.96	-	-	484.96

(b) Target scenario II

Time Period	Purchases		Retirements	
	Diesel	AFT	Diesel	AFT
1	-	2317.84	2321.96	-
3	68.04	-	68.04	-

Table A.2: Purchases and retirements, expensive AFTs, constant demand, parabolic target *(a) Expensive AFT*

Time Period	Purchases		Retirements	
	Diesel	AFT	Diesel	AFT
1	741.49	877.13	1624	-
3	1574.54	657.81	-	-
5	6823.41	2850.72	-	-
9	-	-	6823.41	2850.72
3	-	-	1574.54	657.81

(b) Cheap AFT

Time Period	Purchases		Retirements	
	Diesel	AFT	Diesel	AFT
1	-	2976.62	2982	-
3	-	2232.35	-	-
5	-	9674.13	-	-
9	-	-	-	9674.13
3	-	-	-	2232.35

Table A.3: Purchases and retirements, expensive AFTs, parabolic demand, constant target

(a) Expensive AFT

Time Period	Purchases		Retirements	
	Diesel	AFT	Diesel	AFT
1	940.79	922.43	1867	-
3	557.93	-	557.93	-
7	-	7.33	313.07	-

(b) Cheap AFT

Time Period	Purchases		Retirements	
	Diesel	AFT	Diesel	AFT
1	-	3578.22	3582	-
7	-	-	-	305.74

Table A.4: Purchases and retirements, single swap demand regions, constant target

Time Period	Purchases		Retirements	
	Diesel	AFT	Diesel	AFT
1	-	3490.05	3493	-
5	-	-	183.20	-
9	-	183.20	-	305.74

Table A.5: Purchases and retirements, cheap AFTs, double swap demand regions, constant target *(a) Expensive AFT*

Time Period	Purchases		Retirements	
	Diesel	AFT	Diesel	AFT
1	562.85	1134.05	1701	-
3	931	-	-	931
12	307.67	-	-	50.53

(b) Cheap AFT

Time Period	Purchases		Retirements	
	Diesel	AFT	Diesel	AFT
1	595.07	1690.84	2290	-
12	-	3204.34	1257.07	-

Table A.6: Purchases and retirements, facilities prohibited at hubs, constant demand, constant target

(a) Expensive AFT

Time Period	Purchases		Retirements	
	Diesel	AFT	Diesel	AFT
1	562.85	1134.05	1701	-
3	931	-	-	931
12	307.67	-	-	50.53

(b) Cheap AFT

Time Period	Purchases		Retirements	
	Diesel	AFT	Diesel	AFT
1	564.5	1307.41	1833	-
3	992.0	-	992	-
7	91.28	-	-	99.78

Table A.7: Purchases and retirements, facilities prohibited at hubs, single swap demand regions, constant target

Time Period	Purchases		Retirements	
	Diesel	AFT	Diesel	AFT
1	1565.38	-	1570	-
3	445.93	-	445.93	-
4	-	329.07	329.07	-
10	329.07-	-	-	329.07

Table A.8: Purchases and retirements, expensive AFTs, two temporal diesel bans, same terminal, constant demand, no target

Time Period	Purchases		Retirements	
	Diesel	AFT	Diesel	AFT
1	1622.88	-	1622	-
3	609.43	-	609.43	-
4	-	236.85	165.57	-
6	40.60	-	-	111.88
10	124.97	-	-	124.97

Table A.9: Purchases and retirements, expensive AFTs, two temporal diesel bans, different terminals, constant demand, no target

Appendix B

Total Costs in Computational Study

This Appendix describes the facility costs (FC) and total costs (TC) of the different test instances described in section 4. Expensive is described as E and cheap as C.

	FC *B*	TC *B*	FC *C*	TC *C*	FC *M*	TC *M*
E AFT, C Facility	4303	6704491	2971	6702566	2971	6702566
E AFT, E Facility	37352	6737539	9104	6706232	9104	6706232

Table B.1: Costs, expensive AFTs, constant demand, decreasing target

	FC *B*	TC *B*	FC *C*	TC *C*	FC *M*	TC *M*
E AFT, C Facility	3643	6927305	2962	6926597	2962	6926597
E AFT, E Facility	36175	6959966	9879	6932992	9879	6932992

Table B.2: Costs, expensive AFTs, constant demand, parabolic target I

	FC *B*	TC *B*	FC *C*	TC *C*	FC *M*	TC *M*
E AFT, C Facility	4603	124874985	4603	124874985	4603	124874985
E AFT, E Facility	37134	124904947	37134	124904947	37134	124904947

Table B.3: Costs, expensive AFTs, constant demand, parabolic target II

	FC *B*	TC *B*	FC *C*	TC *C*	FC *M*	TC *M*
E AFT, C Facility	4599	52745565	4599	52745565	4599	52745565
E AFT, E Facility	24650	52765616	24650	52765616	24650	52765616
C AFT, E Facility	37193	8904301	37193	8904301	37193	8904301
C AFT, C Facility	4560	8871707	4560	8871707	4560	8871707

Table B.4: Costs, parabolic demand, constant target

	FC *B*	TC *B*	FC *C*	TC *C*	FC *M*	TC *M*
E AFT, C Facility	3644	42824892	3000	42824218	2970	42824218
E AFT, E Facility	36107	428557355	26738	42847985	26165	42847414
C AFT, E Facility	36337	3651371	26921	3641955	26166	3641201
C AFT, C Facility	3644	3618679	3000	3618015	2970	3618005

Table B.5: Costs, single swap demand regions, constant target

	FC B	TC B	FC C	TC C	FC M	TC M
Standard	3864	4162841	3094	4162070	3094	4162070
Factor I	3864	4162841	3094	4162070	3094	4162070
Factor II	3864	4162841	3094	4162070	2876	4161853

Table B.6: Costs, cheap AFTs, cheap facilities, double swap demand regions, constant target

	FC B	TC B	FC C	TC C	FC M	TC M
Standard	36969	4195946	27752	4186730	27752	4186730
Factor I	36969	4195946	27752	4186730	25426	4184403
Factor II	36969	4195946	27752	4186730	27752	4186730

Table B.7: Costs, cheap AFTs, expensive facilities, double swap demand regions, constant target

	FC B	TC B	FC C	TC C	FC M	TC M
E AFT, C Facility	7173	54461046	7173	54461046	7173	54461046
E AFT, E Facility	62221	54516094	62221	5451609	62221	5451609
C AFT, E Facility	62221	4964015	62221	4964015	62221	4964015
C AFT, C Facility	7173	4908968	7173	4908968	7173	4908968

Table B.8: Costs, facilities prohibited at hub, constant demand, constant target

	FC B	TC B	FC C	TC C	FC M	TC M
E AFT, C Facility	8724	55429973	6732	55427981	6732	55427981
E AFT, E Facility	85807	55507055	57560	55478808	55773	55477021
C AFT, E Facility	85807	5351845	66976	5329579	65240	5327842
C AFT, C Facility	8725	5271329	7397	5269567	7152	5269759

Table B.9: Costs, facilities prohibited at hub, single swap demand regions, constant target

	FC B	TC B	FC C	TC C	FC M	TC M
E AFT, C Facility	1105	6150988	769	6150653	769	6150653
E AFT, E Facility	11949	6161833	2057	6152740	2057	6152740

Table B.10: Costs, expensive AFTs, two temporal diesel bans, same terminal, constant demand, no target

	FC B	TC B	FC C	TC C	FC M	TC M
E AFT, C Facility	1771	5825499	880	5824611	869	5824927
E AFT, E Facility	24048	5847776	5599	5829325	4980	5828707

Table B.11: Costs, expensive AFTs, two temporal diesel bans, different terminals, constant demand, no target

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