

ROUTING IN TRUCKING SERVICE NETWORK DESIGN PROBLEM WITH
TRANSSHIPMENTS AND DRIVER REGULATIONS

by

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B.S., Industrial Engineering, Boğaziçi University, 2019

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science

Graduate Program in Industrial Engineering
Boğaziçi University

2022

ACKNOWLEDGEMENTS

First of all, I would like to express my special thanks to my supervisor Prof. Ümit Bilge for her endless support, precious comments, patience, and immense knowledge throughout this dissertation. Her encouragement is the main motivation for me to start working in BUFAIM laboratory, where I can call my home. I also started graduate studies with the motivation and confidence she has given to me.

Secondly, I am very grateful to Prof. Dr. Necati Aras for his critical interventions that prevented me from getting lost throughout this work. Besides my supervisors, I also want to thank Assist. Prof. Mustafa Gökçe Baydoğan for his support and motivation throughout the years. Moreover, I am grateful to Assist. Prof. Hande Küçükaydın for being in my thesis committee.

I wish to thank all the former and current members of BUFAIM for their support. I want to thank Gökalp for his endless guidance, and my colleagues Mert, Bahadır and Çiğdem for the great times we spent together in BUFAIM before the pandemic. To Safa, Burak, Ege, Muso, Feyza, and Yasin, you are perfect friends for almost ten years. Last but certainly not least, my deepest gratitude to İdil who is always both inspiration and best friend of mine. Life would be meaningless in the absence of your friendship and love.

I also want to express my gratitude for my family. I would like to thank my father for giving me the perspective whenever I doubt my actions. Life would be much more harder without the patience and help of my mother. Last but not least, I want to thank my uncle Ali Hakan Mih for being the perfect brother for me.

I also thank TÜBİTAK for their financial support during my graduate studies under BİDEB-2210 programme. Moreover, I would like to thank *Ekol Logistics* and *Kolay Gelsin* for providing data for this challenging problem to study in this thesis.

ABSTRACT

ROUTING IN TRUCKING SERVICE NETWORK DESIGN PROBLEM WITH TRANSSHIPMENTS AND DRIVER REGULATIONS

Most of the large transportation companies are currently trying to have the scale to operate their middle-mile or long-distance transportation plans, while using both their resources and outsourced vehicles. The aim is to deliver customer shipments from stocking origins to last-mile delivery transfer stations. Freight transportation planning is done manually in most logistics companies, often leading to poor transportation plans or plans whose quality is hard to assess. Furthermore, since transportation plans are needed almost every day, it is crucial to have a solution procedure that is as efficient as possible. We have tried to model this environment without loss of generality while developing a methodology to solve this problem efficiently. This is an operational problem that falls into the domain of trucking service network design and operation. We offer a mathematical model and a solution methodology for this problem taking consolidation, transshipment, synchronization, and driver regulations into consideration. Our model employs a pre-processing strategy for creating the data representing the transportation environment. Moreover, a matheuristic is presented for considering multiple periods of operation. The proposed models can be used for companies operating both with their own and rental vehicles. Distribution of the vehicles throughout the transportation network is crucial for the companies that operate with their own vehicles, since the aim is to plan over a horizon, rather than a single day. The assumptions and the parameters used in the models are based on data coming from already operating large companies. The benefit of using this mathematical model is to achieve a better transportation plan with a reasonable amount of time.

ÖZET

AKTARMALAR VE SÜRÜŞ DÜZENLEMELERİ İÇEREN ARAÇ SERVİS AĞI TASARLAMA PROBLEMİNDE ROTALAMA

Büyük taşımacılık şirketlerinin çoğu güncel olarak kendilerinin ve dışarıdan temin ettikleri araçları kullanarak orta ve uzun mesafe taşıma planlarını işletebilecek kapasiteye sahip olmaya çalışmaktadır. Amaç, müşteri teslimatlarının toplama başlangıçlarından son noktalarındaki transfer tesislerine taşınmasıdır. Nakliye taşıma planlaması, lojistik şirketlerinin çoğunda elle işleterek yapılmaktadır, bu da sıklıkla kötü taşıma planları ya da kalitenin zor ölçüldüğü planlara yol açmaktadır. Ayrıca, taşıma planını neredeyse her gün için gerektiğinden, olabildiğince verimli bir çözüm prosedürüne sahip olunması çok önemlidir. Bu problem operasyonel seviyede ve araç servis ağı tasarlama problemleri kategorisindedir. Konsolidasyon, aktarma, eşzamanlama, ve sürüş kısıtları içeren problemin çözülmesi için bir matematiksel model ve çözüm metodolojisi öneriyoruz. Modelimiz, taşıma ortamını tanımlayan verinin ön işleme ile hazırlandığı bir yöntemle başvurmaktadır. Ek olarak, birden fazla operasyon dönemini dikkate alan sezgisel bir model gösterilmiştir. Önerilen modeller hem kendi hem de kiralık araçları kullanan şirketler için kullanılabilir. Araçların taşıma ağı üzerindeki dağılımı kendi araçları ile çalışan firmalar için çok önemlidir, çünkü amaç tek bir günü değil bir zaman dilimini planlamaktır. Bu modellerde kullanılan varsayımlar ve parametreler hali hazırda çalışan büyük şirketlerden gelen veriye dayanarak üretilmiştir. Böyle bir matematiksel modeli kullanmanın faydası, makul bir zamanda daha iyi bir taşıma planına ulaşmaktır.

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LIST OF SYMBOLS

A_r^i	Arrival time of a vehicle to node i using r
a_r^i	1 if r consists i except at the last order, 0 otherwise
b_r^i	1 if r consists i except at the first order, 0 otherwise
$B_{rr'}^p$	Transshipment nodes before the origin of p in r (from r to r')
c_r	Fuel and toll costs of route r
c'	Fixed cost of using any route with any vehicle
c'_r	Fixed cost of using r with a specific vehicle
d^p	Aggregated volume of request p
D_r^i	Departure time of a vehicle from node i using r
DR_p	Set of routes ending with the destination node of p
ER_i	Set of routes ending with i
$F_{rr'}^{pi}$	Amount of transshipment of p between r and r' at i
F_r^{pi}	Amount of transshipment of p from other routes to r' at i
G_r^{pi}	Amount of transshipment of p from r to other routes at i
g_r^n	N^{th} node of r
h_r^i	Position in sequence of node i in r
$J_{rr'}^p$	Transshipment nodes after the origin of p in r (from r to r')
$K_{rr'}^p$	Transshipment nodes before the sink of p in r (from r' to r)
L_r^p	Amount of loading of p at its origin by r
N	Set of nodes
N^r	Set of nodes that are included by r
OR_p	Set of routes starting from the origin node of p
P	Set of requests
q_r	Capacity of r with respect to represented vehicle
R	Set of routes
TI^r	Set of routes that have at least one node to transship into r
TO^r	Set of routes that have at least one node to transship from r
U_r^p	Amount of unloading of p at its destination by r

V	Set of vehicles
w_r^p	1 if origin node is earlier than destination of p in r , 0 otherwise
X_r^i	Used capacity of a vehicle at node i using r
Y_r	1 if route r is used, 0 otherwise
$Z_{rr'}^i$	1 if any transshipment occurs between r and r' , 0 otherwise
δ^p	Destination node of request p
λ^p	Loading duration for p per truckload
π_i	Number of vehicles required at node i
σ^i	Earliest start time at i with respect to city logistics
τ_r^i	Driving time to i from previous node using r
Υ_v	Set of routes for vehicle v
ϕ^p	Origin node of request p
ψ^i	Latest delivery time at i with respect to city logistics
ω^p	Unloading duration for p per truckload

LIST OF ACRONYMS/ABBREVIATIONS

ETM	Empty trip management
GDP	Gross domestic product
LHS	Left hand side
LTL	Less-than-truckload
MILP	Mixed-integer linear programming
MIP	Mixed-integer programming
MTL	More-than-truckload
NDP	Network design problem
PDP	Pick-up and delivery problem
PRP	Pollution routing problem
RHS	Right hand side
SND	Service network design
SNDP	Service network design problem
TSNDP	Trucking service network design problem
TSNDP-T	Trucking service network design problem with transshipments
TSNDP-T\S	Trucking service network design problem with transshipments without synchronization

1. INTRODUCTION

Freight transportation is a vital component of the economy in every country. By assuring the effective movement of items, it supports activities related to production, trade, and consumption. In consequence, as pointed out by Crainic and Laporte (1997), freight transportation represents a significant part of the cost of any product, as well as of the national expenditures of a country. Government regulations on drivers, distribution of customer requests throughout a transportation network, and attributes of the vehicles and roads, which change frequently, have significant effects on these costs. Thus, carrier companies need to have the capability of rapidly adjust to changing economic and regulatory conditions in order to stay cost effective and offer reliable, high quality, low cost services to their customers while making profit. All of the transportation planning levels and resources for the transfer operations must work together to achieve these objectives in a smooth and seamless manner.

Trucking operations refer to freight transportation industry by means of road trucks. Products are carried from first-mile suppliers to the last-mile customers as can be seen from Figure 1.1. Middle distance freight transportation is a type of logistics and cargo activity that involves trucks and their corresponding batch deliveries between distribution centers located in different regions.

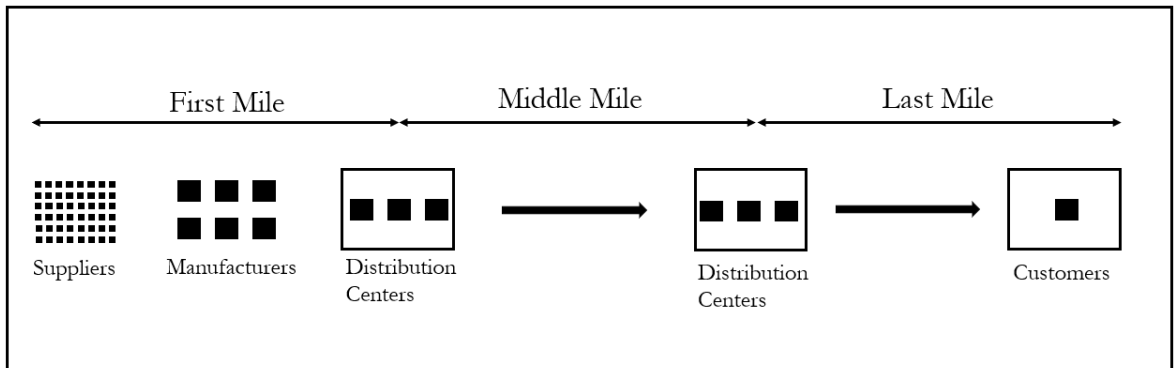


Figure 1.1. Classification of transportation steps.

Trucking services can be provided by both large-scale companies that own thousands of vehicles and also by relatively small firms operating with a few vehicles. In many sectors the individual customer requests are usually small in volume compared to standard truck capacities. Logistics firms that serve such customers make use of flexibilities such as allowing vehicles to be dispatched before they are fully loaded and consolidating loads of different customers in the same vehicle. This mode of operation is called less-than-truckload (LTL).

In general, the problem is a major operational problem of logistic firms which aims optimal utilization and assignment of resources, while considering transshipments between the vehicles at intermediate transfer stations that is required due to better utilization of vehicle capacities, and driving regulations. The problem is a variant of the less-than-truckload service network design and vehicle routing problems in the literature, and is a hard problem by nature.

The freight transportation is a complex system that consists of drivers, vehicles and transfer facilities. There are inter-dependent and complex relationships between all of these components creating many tradeoffs and management decisions to be made that affect the effectiveness of the system. The companies often use a given route set defined over a network of cities and roads for carrying out their logistics activities over a planning horizon. Routing of daily freight through over this network needs to meet the short term demand obeying both company targets and customer specifications. The customers should be ensured a timely and reliable service level while assigning the truck drivers to feasible routes in terms of the driving regulations.

Freight transportation planning is done manually in most of the logistics companies, often leading to poor transportation plans or plans whose quality is hard to assess. All of the company policies regarding different planning levels and operational units must work together to achieve these tasks in a smooth, seamless and optimized manner. These planning activities can be classified as defined by Crainic (2000) into three levels:

- *Strategic*: Long term decisions of designing the physical logistics network and defining the service policies.
- *Tactical*: Medium term decisions that focuses on designing the network by building or improving the infrastructure, choices of transportation services, assigning resources to particular logistics tasks, designing the allowable routes for a given network.
- *Operational*: Short term decisions about assignment of vehicles and crews to the tasks and to the routes, the maintenance of the resources, the matching and dispatching rules of the routes and corresponding vehicles, and planning the transportation schedules for a given period of concern.

In this study, we focus on the operational level decisions of the freight transportation systems. Firstly, we propose a mathematical model to design the daily transportation plan regarding the selection of routes and the assignment of requests to the vehicles using these routes, while obeying the driver regulations, due dates and capacity restrictions. This model can directly be used by the companies operating with a fleet that is fully out-sourced by rental vehicles. Secondly, a matheuristic for planning multiple periods of operations is presented where this proposed strategy can also be used for a fleet consisting of either company-owned or rental vehicles. Since the final positions of the vehicles at the end of a planning period is crucial for the company-owned vehicles, proposed matheuristic aims to adjust the number of vehicles for a particular node at a desired level. Furthermore, the usage of the proposed model as a decision support tool on the tactical level of planning is discussed. The following sections show the motivation of the work and more detail on the structure of the dissertation.

1.1. Motivation

Trucking service network design is a complex problem that involves many design and planning decisions, thus there are a large number of problems that could be labelled as service network design problems such as vehicle routing, crew planning, load and

unload planning, dispatching problems and flow planning. LTL shipments for large companies often require a consolidation plan which is a hard problem to solve manually. Consolidation of requests can be more advantageous, if the vehicles are allowed to transfer some requests to other vehicles at intermediate nodes which have temporary storage area. The transfer of requests between two vehicles is called transshipment in the context of this dissertation.

Figure 1.2 shows a simple instance consisting four nodes, five requests, and six vehicles where the benefit of performing transshipment is demonstrated.

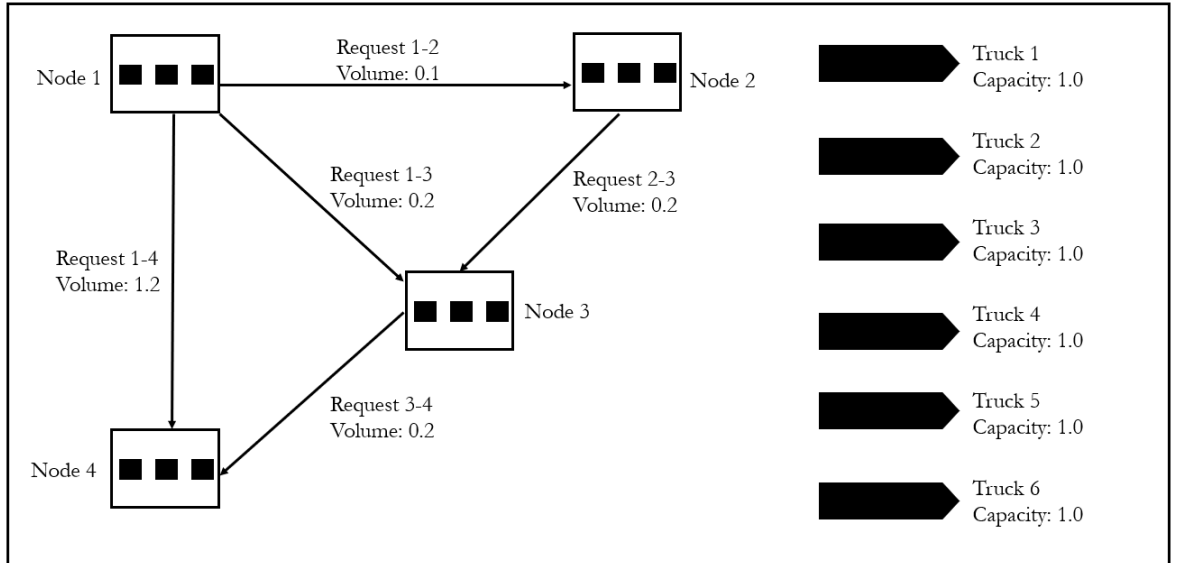


Figure 1.2. Example network.

In the figure, Request $i-j$ refers to a load obtained by aggregating the demand that is originated from node i and destined to node j . For the sake of simplicity, assume that all arcs between the vertices can be travelled without violating the travel duration and the due date constraints. Furthermore, assume that all vehicles in the system have a capacity of one for the sake of simplicity. When these three strategies are used for solving the transportation of the example network, first strategy needs six vehicles, whereas the second and third use three vehicles. Although the number of vehicles is equal in second and third strategies, allowing the system to transship requests at intermediate nodes can reduce the cost of transportation. Consider three different strategies: first, transporting every request from its origin to destination node

directly by a distinct vehicle, i.e., no consolidation. Second, allowing the route set to have some combinations that include more than two nodes, therefore implicitly allowing consolidation of the requests while loading the requests to the vehicles. Third, the vehicles are able to transship some requests at intermediate nodes, assuming the transfer stations located in the nodes have unlimited inventory capacity.

Table 1.1 shows the results of these three strategies in detail. In our simple example, allowing the transshipment between vehicles has resulted in different assignment of vehicles to the routes, thus leading to a lower total cost of transportation. As can be seen from Table 1.1, third vehicle has selected a different route in third strategy which has a lower cost of operating than the alternative in the second strategy. Note that, the columns of the table refer to the strategy name, used vehicles and their corresponding assigned routes, the requests that are loaded to these vehicles and their loaded volume, the used capacity of the vehicle after the loading/unloading operations at a particular node, i.e., capacity on the departure, and the total cost of operations.

As a consequence, given the distances between nodes and the cost of routing between each pair of nodes, the total cost is 16910.50, 10542.00, and 8644.50, respectively for each strategy. Transshipment of the requests between the vehicles lead to lower the total operational cost.

Table 1.1. The summary of the three strategies including vehicle and request movements.

Strategy	Vehicle ID	Route	Requests	Transported Volume	Used Capacity	Cost of Route	Total Cost
1	1	1-2	(1-2)	0.1	0.1 - 0.0	1930.50	16910.50
	2	1-3	(1-3)	0.2	0.2 - 0.0	3141.25	
	3	1-4	(1-4)	1.0	1.0 - 0.0	4570.50	
	4	1-4	(1-4)	0.2	0.2 - 0.0	4570.50	
	5	2-3	(2-3)	0.2	0.2 - 0.0	1245.75	
	6	3-4	(3-4)	0.2	0.2 - 0.0	1452.00	
2	1	1-4	(1-4) ¹	1.0	1.0 - 0.0	4570.50	10542.00
	2	1-2-3	(1-2), (1-3), (2-3)	0.1, 0.2, 0.2	0.3 - 0.2 - 0.0	1376.25	
	3	1-3-4	(1-4) ² , (3-4)	0.2, 0.2	0.2 - 0.4 - 0.0	4595.25	
3	1	1-4	(1-4) ¹	1.0	1.0 - 0.0	4570.50	8644.50
	2	1-2-3	(1-2), (1-3), (1-4) ² , (2-3)	0.1, 0.2, 0.2, 0.2	0.5 - 0.2 - 0.0	1376.25	
	3	2-3-4	(1-4) ² , (3-4)	0.2, 0.2	0.2 - 0.4 - 0.0	2697.75	

Although there is a vast literature for the long-distance vehicle routing and scheduling including transshipments (see e.g., Golden *et al.* 2008; Savelsbergh and van Woensel 2016), trucking service network design problems that handle driver regulations, route selection, dispatching schedule and possible transshipments between the vehicles at the same time are not covered in the literature.

The fundamental innovation in this dissertation is modeling such a complex environment under the aforementioned critical requirements of various aspects of transportation industry. The proposed mathematical modeling strategy eliminates driver regulation constraints by means of a pre-processing phase, while loading, unloading, transshipment, due date control and scheduling are handled by corresponding decision variables and constraints. The proposed model is a novel contribution to the operations in fields such as e-commerce companies and cargo activities for large retailers. The model can be applied in the vast majority of applications of the aforementioned domains in different countries with minimal adjustment, since the government regulations are not included in the constraints of the mathematical formulations.

Although most of the work in the literature covers only limited aspects of the whole problem and makes assumptions about some of the components of the transportation environment, this thesis tries to handle nearly all of the aspects of a transportation system. The proposed work models the loading, unloading, and transshipment of the requests to the vehicles, handles several driving regulations, e.g., for one-day, two-days, one-week and two-weeks driving hour limits, adjusts the synchronization and scheduling of the vehicles in continuous time, prevents due date violations of the requests that should be transported, and obeys the capacity restrictions of the existing vehicles in a given period. With these original and innovative modeling features that cover the aforementioned components of a physical transportation environment are the contribution of this dissertation.

1.2. Organization

The rest of the thesis begins with a literature review. Chapter 2 presents an overview of the related literature in the service network design problems, vehicle routing problem variants and liner shipping service design problems.

Chapter 3 is dedicated to the proposed models and approaches about the trucking service network design problems. The problem is defined at first, then a pre-processing strategy for creating the input of the model is introduced. The mathematical model using the input created by a unique pre-processing strategy is presented. Moreover, a matheuristic for modeling multiple consecutive periods of operations while considering the vehicle balancing is given. Alternatives for a suitable objective function for the proposed models is also discussed.

Chapter 4 presents experimental results on a set of test problems. After testing the performance of the exact solution procedure, experiments for testing the operational strategies are conducted. An application of the proposed model to an existing company is also shown in Section 4.3.4. Lastly, Chapter 5 provides conclusions and future research directions.

2. LITERATURE REVIEW

This chapter presents a brief literature review about the relevant topics with this dissertation. In Section 2.1, a definition and a classification of service network design problems are given. Section 2.2 provides different problem type applications and discusses the corresponding solution methodologies for transportation planning. At the end of this chapter, Section 2.4 outlines liner shipping service network design problems which have important similarities with the freight transportation.

2.1. Definition and Classification of Service Network Design

Freight transportation problems are usually discussed under the heading “service network design (SND)”. Also, there are many instances in the literature that are classified as types of rich vehicle routing problems. Routing and scheduling problems mainly cover the planning activities performed by logistics companies. In this context, scheduling usually refers to railway activities and their corresponding dispatching decisions, whereas the term routing is usually used for trucking and its operating policies. Toth and Vigo (1998) present one of the earliest surveys of optimization models and solution techniques for routing and scheduling in freight transportation.

Crainic and Rousseau (1986) introduce the application of the term network optimization to freight transportation planning. They present a framework for modeling tactical and strategic planning operations which include consolidation and transfer operations at the intermediate terminals. Although their model uses fixed frequencies for the services, their work is crucial for separating operational aspects of service network design problems from the tactical and strategical level of planning. The three levels of transportation planning are clearly defined in Crainic (2000); strategical, tactical, and operational.

Modeling the physical environment including the vehicles and the node network is crucial for defining a service network design problem correctly. Since the customer

requests should be transported from their origin nodes to their destination nodes with a certain level of service standards, Irnich (2002) mentions that it is important to state problem characteristics by modeling the physical structure.

Wieberneit (2008) presents an important review on service network design approaches for freight transportation. Furthermore, Bakir *et al.* (2021) is a recent review that summarizes latest mathematical models and solution approaches on motor carrier service network design problems, including the load and flow planning of the requests on the vehicles. SND problems are divided into three categories and many examples related with all levels of planning are given.

Route generation is a strategical level of decision for a transportation system and it directly affects the complexity of an operational level model. Barnhart *et al.* (2002) propose an algorithm as a pre-processing strategy in their study to generate the possible route alternatives for a planning period. They use Dantzig-Wolfe Decomposition for the generation of the route pool. Jansen *et al.* (2004) present a heuristic method for generating possible routes for a given node network.

Freight transportation including driver regulations, due date, vehicle capacities and route selection can be classified as an operational problem. Another aspect of the operational level planning is also pointed out by Macharis and Bontekoning (2004), the need of positioning empty vehicles in order to prevent the imbalances throughout the network. To correct the differences coming from discrepancies between the demand and supply of the requests at nodes of the network, vehicles must be repositioned with respect to a model decision. Crainic (1999) proposes that the empty vehicle management problem itself is complicated and there are large number of possible movements in addition to the uncertainty in the future demand of requests. Since empty vehicle movements are usually not profitable for the companies, vehicles are expected to load some requests in all trips.

Uncertain demand structure causes transportation systems to be infeasible in an operational period due to imbalance of vehicles at the transfer stations. Lium *et al.*

(2009) propose a stochastic programming approach to service network design formulations by introducing scenario elements to the model. However, they assumed periodic schedules for both the number of vehicles required and the periodic customer requests. While stochastic service network design is another important aspect to trucking systems, (see as Hoff *et al.*, 2010; Bai *et al.*, 2014, among others), in this study this line of work will not be pursued any further.

2.2. Operational Level Service Network Design Problems and Solution Techniques

Operational level freight transportation planning should minimize the total transportation cost of delivering all requests from the origin to the destination node without violating the constraints defined by the physical environment. The total cost in the operational level planning mainly comprises of the variable cost of routing including fuel and tolls and the fixed cost of using the vehicles. The cost of operating an intermediate transfer station is not included in the operational level, since the design and set-up of node network is a tactical level decision.

Hence, the summation of costs associated with selected route and fleet decisions is the total operational variable cost in the planning horizon, and it is usually minimized by means of a mixed-integer mathematical model. Since transportation constitutes a significant fraction of the total cost of a product, there are numerous studies in this regard. For example, Jarrah *et al.* (2009) propose a large-scale, LTL service network design formulation for long-haul freight transportation planning. Integer programming is used to model the routing problem that aims to minimize overall transportation costs. Such problems are known to be NP-hard (Balakrishnan *et al.*, 1989).

Wolfiger and Gonzalez (2021) use additional binary variables to represent transshipments between vehicles at intermediary nodes that are shared by both vehicles' routes. Their arc-based mixed-integer programming formulation is solved by a branch-and-cut algorithm. In addition to a binary variable that checks the existence of transshipment between any vehicle v and v' , a continuous decision variable represents the

amount of transshipment between the specified vehicles. Although the problem covered by the authors is a pick-up and delivery problem, their approach for modeling transshipments is useful in our context.

Leung *et al.* (1990) decomposes a rich vehicle routing problem instance, which is very similar to service network design transportation problem, into two sub-problems. The sub-problems including resource management and request dispatching are solved by means of a matheuristic methodology. In Barcos *et al.* (2010), time-constrained vehicle operators are scheduled in a manner such that they return their base nodes (i.e., their home town) in a regular frequency.

Lastly, Greening *et al.* (2021) is a recent study on middle-mile consolidation network design with fixed origin-destination pairs. There are three different models proposed including two mixed integer programming models and one integer programming-based local search heuristic. Although the problem studied is very similar to the transportation environment that this dissertation focuses on, that model does not include a time aspect for scheduling and synchronization of vehicles, which and leaves as a future research topic.

2.3. Modeling Time for Scheduling and Synchronization

Scheduling problem of the drivers of the LTL trucking environment are more complicated than the train dispatches, since the trucking industry usually does not use pre-scheduled routes as in the airline industry. Erera *et al.* (2008) present a dynamic driver management study including real-life constraints for the requests to deliver in an operational period. Drivers should rest after a certain level of continuous driving, therefore the time-constrained trucking operators bring an additional complexity on top of the problem of dispatching requests to the vehicles. Authors propose a greedy search throughout a pool of feasible driver route alternatives with respect to time.

Most of the models in the literature regarding the service network design problems use the methodology of discretizing the time. Determining a time interval instead

of exact synchronization of the vehicles prevents modeling time in a continuous manner, which reduces complexity of the proposed models. Ford and Fulkerson (1958) firstly propose a formulation that uses time intervals for resources in order to solve time-expanded network. Crainic *et al.* (2016) also use discretization of time for solving a problem that requires resource management at each transfer station node while selecting appropriate routes with respect to continuous-time modeling of a freight consolidation carrier environment.

On the other hand, Boland *et al.* (2017) provide a study that does not explicitly model time with variables and parameters that represent continuous-time, but develops a partially time-expanded network which can be applied to continuous-time SND problems. The study proposes a dynamic algorithm that creates a lower bound by a mixed-integer-programming model, then updates the time-expanded network by discovering new time points in the time-expanded network.

Moreira *et al.* (2016) provide a matheuristic for synchronizing resources while considering multiple transshipment locations, for a Portuguese logistics operator company. The constraint structure of the problem is very complex, due to the combination of driver and delivery restrictions, and transshipments.

2.4. Liner Shipping Service Network Design Problems

The service design of carriers is also a problem in liner shipping industry. A carrier company seeks to plan service routes for its ships efficiently, by using the existing facilities and vehicles, while the aim is to transport the given set of demands to a set of ports. Ports are equivalent to the nodes for trucking SND and the problems regarding capacity, routing, and profitability is very similar to the existing challenges in the trucking industry. Thus, liner shipping service network design models are also investigated in the context of this thesis.

Reinhardt and Pisinger (2012) provide a mathematical model for liner shipping network design problem, for which an exact solution procedure is sought. Their branch-

and-cut algorithm can solve the model to optimality for only small instances with up to ten ports and twelve origin-destination pair of customer demands. They explicitly model time with certain parameters and decision variables regarding the arrival time of vessels to the ports.

Akyüz and Lee (2016) develop a decision tool for finding the necessary routes for cargo vessels by including time-related constraints. They propose a mixed integer linear programming model for service type assignment and container routing problem. The crucial point of this study is that repositioning of empty containers is taken into account with transit time restrictions, in a similar way to empty truck balancing for the transfer stations. A similar work is conducted by Plum *et al.* (2014), where instances up to twenty-five ports can be solved to optimality.

The mathematical model presented by Guericke and Tierney (2015) introduce the trade-off between saving fuel cost and vessel speed while not violating the due date for the cargo. Although the model is aimed for the strategic and tactical levels of planning, their model presents an alternative way of handling time-expanded network. The proposed model can be solved optimally in a reasonable amount of time with three different instance settings which have different complexity levels.

Table 2.1. Overview of studies on the literature.

	Problem Type	Route Selection	Transshipment	Time	Synchronization	Driving Regulations	Empty Vehicle Positioning
Jarrah <i>et al.</i> (2009)	SNDP	Tree Based	Included	—	Time Intervals	Included	— Allowed
Barcos <i>et al.</i> (2010)	LTL Routing	—	Limited Nodes	Variable	Time Intervals	Included	Allowed
Plum <i>et al.</i> (2014)	Liner Shipping NDP	—	Included	—	Continuous	—	—
Reinhardt and Pisinger (2012)	Liner Shipping NDP	Arc Selection	Included	Variable	Continuous	Included	—
Akyüz and Lee (2016)	Container Routing	Both Fixed and Selected	Included	Variable	Time Intervals	Included	Allowed
Wolfinger and Gonzalez (2021)	PDP	Arc Selection	Included	Variable	Continuous	Included	—
Greening <i>et al.</i> (2021)	SNDP	Route Pool	Included	Average	Continuous	—	—
This study	TSNDP	Route Pool	Included	Variable	Continuous	Included	Pre-processing Allowed

Table 2.1 organizes the reviewed operational level studies from different areas by their year of publication and provides a comparison with our study, which is in the last row, in terms of various features regarding middle-mile logistics. Almost all of the studies include transshipment of the requests at the intermediate nodes, however variable, i.e. volume dependent, transshipment time is not considered in some studies since this requires modeling continuous time. Instead, average transshipment times are used at the transfer stations for the sake of simplicity. Synchronization of the vehicles and driver regulations are not mentioned in the arc-based models, since those models aim to find the flow on the arcs rather than vehicle dispatching. Similarly, empty trip management is rarely considered in some of the studies. Furthermore, none of the aforementioned papers considers the fleet type, where in this study we propose a methodology that will work with both company-owned and outsourced rental vehicles.

To summarize, existing research focuses on restricted aspects of the overall problem and makes assumptions about the remaining challenges. For instance, driver regulations create additional complexity to SND problems, thus most of the models in the literature cover limited aspects of the problems related to driver management scheme. The pre-processing strategy proposed by this dissertation allows considering many driver-related constraints without changing the structure of the mathematical model. Furthermore, planning multiple periods of operations requires considering weekly and monthly driving regulations. There are studies that try to handle multi-period driver restrictions, however the pre-processing in this thesis can carry the driving information from previous to next planning periods in a very short processing time as compared to the examples in the literature. The total number and characteristics of the possible route alternatives also create complexity to the SND problems. However, the proposed models in this dissertation can practically solve real-life problems as operational planning level models that include route selection and assignment to the vehicles and the corresponding drivers, synchronization and scheduling of the vehicles in a time-expanded network and in the meantime, can be solved daily.

3. PROPOSED MODELS

In the following we introduce the notation, present a node-based model for the *TSNDP-T* (Trucking Service Network Design Problem with Transshipments) that can be solved optimally in a reasonable amount of time. Since optimizing only single operational period may be greedy or myopic in terms of considering minimizing the total cost of multiple planning periods, we also present one extension for the *TSNDP-T* for adjusting the distribution of the vehicles at the end of planning periods as a matheuristic.

3.1. Problem Definition

The problem addressed in this study is the daily middle-mile delivery operation of a logistics company that gives service to e-commerce companies. Every day, a plan should be prepared in the small hours of the day, so that customer orders collected in distribution centers until then will be loaded on trucks to be taken to the distribution center of another city, so that they can be taken to the specific customers by smaller vehicles later during the day. Let N be the set of nodes of the physical middle-mile transportation network. The facilities where customer orders coming from respective suppliers accumulate and get loaded on vehicles in order to be delivered to their destinations, the facilities where these orders are unloaded for last-mile delivery, and facilities where loads en route can be transshipped from one vehicle to another are the nodes of this network. The roads, i.e., the links that connect the nodes are unique with known lengths.

The aim is to transport the customer orders from their origin to their destination such that they will be ready in time for last-mile transportation operation at the destination node. While the total number of individual customer orders on the network is very high, all orders originating from the same origin and destined to the same destination can be aggregated from the perspective of middle-mile transportation. The aggregated orders create a single request $p \in P$, representing the total volume that

should be transported from an origin node to a destination node. To sum up, it can be said that a request p has three features, an origin node, a destination node, and a total volume that is calculated by aggregating the volumes of individual customer orders. There can be at most $|N|(|N| - 1)$ requests in a planning period where $|N|$ is the total number of nodes (transfer stations) in the considered network.

Resources such as pickers, loading/unloading docks or loading/unloading devices are not considered as bottleneck in this study, therefore they are assumed to have infinite capacity. In other words, multiple vehicles can be served at the nodes without waiting for such resources.

The other component of the physical network is the vehicles. Vehicle has three attributes, its initial position at the beginning of a planning period, its capacity with respect to the type of the vehicle, and the maximum allowable driving time of the vehicle's fixed driver. Thus, it is assumed that every vehicle v in the set V is paired with a certain driver in order to keep the track of the driving hours of the driver. Hence, there is no separate index for the drivers. The routes that can be traveled by a specific vehicle depend on its initial position, and its driver's remaining driving time as defined by related regulations. A company can use rental vehicles rented for the day, or company-owned vehicles, or a combination. The cases for rental vehicles and company-owned vehicles form two different operation modes with specific features. When only rental vehicles are used each day's plan becomes independent from each other. In other words, initial conditions are specific to that day, we are not interested in final conditions of the vehicles, and the problem becomes an open routing problem. When company owned vehicles are used initial and final conditions of the vehicles for each day become important, making a longer planning horizon necessary. Longer horizon becomes a huge challenge for the problem we are addressing because of many reasons. First of all, the demand is not known until a short time before the time to make the daily middle-mile problem. Secondly, there is a limited time to come up with a plan before dispatching the trucks. As another remark, the problem can become infeasible when we are using a restricted number of vehicles. So, this company-owned fleet operation mode should be relaxed by allowing vehicle rental when necessary.

Finally, the routes are critical to our problem. While the number of routes on a given node network can be huge, the routes that can be traveled by a specific vehicle depend on its initial position, its type, its driver's remaining driving time as defined by related regulations, and other similar constraints. The route alternatives obeying these constraints can be determined by a pre-processing procedure. The proposed methodology uses a pre-processing step to prepare many sets regarding the vehicles and routes as the data structure for the proposed MILP model. In this manner, the number of variables and constraints used in the model can be reduced by a great deal leading to significant savings in the required computational time, since the computational time of the pre-processing step is minor.

3.1.1. Pre-Processing Strategy for the Driver-Related Constraints

Most of the existing models in the literature have driving regulations constraints in the mathematical model itself. Modeling these regulations bring additional complexity to both the decision variables and to the constraint sets. This study uses a pre-processing strategy in order to implement both driving regulations of the governments. Specific driver-related issues that can vary frequently, diverse problems and circumstances stemming from vehicle maintenance can also be implemented. Let R be the route set constructed by the combinations of the nodes of the network that is generated with respect to all of specific conditions of the environment. For instance, if a driver is not allowed to ride more than ten hours for a specific day, then the candidate routes that are longer than ten hours are not included in R . This strategy allows carrying driving hour information from previous day to the next within the scope of planning. There can be regulatory policies of the government regarding one-day, two-days, one-week and two-weeks maximum possible driving hour limits for the drivers. Carrying information from the previous period of concern by post-processing of the model output creates the initial conditions for the next period without any constraints in the proposed models.

Vehicles are not directly included in the sets of the model, they are implicitly modeled through R in order to reduce the number of indexes in both parameters and

decision variables for the sake of simplicity. R can contain multiple instances of a distinct node combination that is applicable for the operating company if there are more than one alternative vehicle that can undertake that route. On the other hand, a specific route may not be added to R at all if there are no vehicles that can undertake it.

Moreover, a route can only be a candidate for a vehicle if the first node of the route is same with the initial position of a vehicle. If all of the conditions aforementioned are satisfied, then the candidate node combination can be included as an element of the set R by the pre-processing procedure.

As a consequence, R represents all possible node combinations that can be covered by one or more vehicles. A specific range of index in R is dedicated to each vehicle, therefore the selection of route-vehicle pair can be identified by a simple post-processing of the model solution. Model guarantees to select at most one route to each vehicle.

The proposed methodology can both be used for optimizing a single period, i.e., day, and also for planning the operations for multiple consecutive periods. The completion time of the routes at the end of a day depends on many parameters such as starting time of the route, total distance covered for a route, and the speed of the corresponding vehicle. The vehicles that are currently busy completing their routes of the previous planning period can be included in the next operation period by pre-processing. The earliest possible starting time of the vehicles can be calculated as dividing the remaining distance of the route by the speed of the corresponding vehicle. Hence, a parameter for earliest possible start of a particular vehicle for the next operation period can be calculated. Furthermore, since the last node of the route that is currently being traversed is known, the pre-processing strategy eliminates the other candidate routes for the next period that do not have the first node same as the final destination from the previous period. Vehicles can continuously be tracked and can contribute to the multiple periods of operation with such a strategy. All of the aforementioned preprocessing strategy is applied to the existing conditions of the physical transportation environment, in order to create the sets R and Υ_v , where R is the set

representing the combination of the all possible routes that contain individual possible routes of all vehicles, i.e., Υ_v . for every vehicle $v \in V$.

3.2. Mathematical Formulation

Table 3.1 presents the sets used in the models while Table 3.2 shows the parameters and the decision variables.

Table 3.1. Sets used in the models.

Sets	
R	Set of routes, $r \in R$
N	Set of nodes, $i \in N$
N^r	Set of nodes that are included by r
V	Set of vehicles, $v \in V$
P	Set of requests, $p \in P$
Υ_v	Set of routes for vehicle v
OR_p	Set of routes that contain the origin node of p
DR_p	Set of routes that contain the destination node of p
PO_i	Set of requests that are originating from node i
PD_i	Set of requests that are destined to node i
TI^r	Set of routes that have at least one node to transship into r
TO^r	Set of routes that have at least one node to transship from r
$B_{rr'}^p$	Set of possible transshipment nodes of r and r' before the destination of p in r (transshipment from r to r')
$J_{rr'}^p$	Set of possible transshipment nodes of r and r' after the origin of p in r (transshipment from r to r')
$K_{rr'}^p$	Set of possible transshipment nodes of r and r' before the destination of p in r (transshipment from r' to r)
ER_i	Set of routes ending with i

Table 3.2. Parameters and decision variables used in the models.

Parameters	
c_r	Fuel and toll costs of route r
d^p	Aggregated volume of request p
a_r^i	Binary parameter, 1 if r contains i except at the last order, 0 otherwise
b_r^i	Binary parameter, 1 if r contains i except at the first order, 0 otherwise
ϕ^p	Origin node of p
δ^p	Destination node of p
w_r^p	Binary parameter, 1 if origin node is earlier than destination of p in r , 0 otherwise
q_r	Capacity of r with respect to represented vehicle
g_r^n	n^{th} node of r
h_r^i	Position in sequence of node i in r
c'	Fixed cost of using any route with any vehicle
c'_r	Fixed cost of using r with a specific vehicle
ψ^i	Latest delivery time at i with respect to city logistics
σ^i	Earliest start time at i with respect to city logistics
τ_r^i	Driving time to i from previous node using r
λ^p	Loading duration for p per truckload
ω^p	Unloading duration for p per truckload
Decision Variables	
Y_r	Binary variable, 1 if route r is used, 0 otherwise
$F_{rr'}^{pi}$	Amount of transshipped p from r to r' at i
L_r^p	Amount of loading of p at its origin by r
U_r^p	Amount of unloading of p at its destination by r
X_r^i	Used capacity of a vehicle at node i using r
A_r^i	Arrival time of a vehicle to node i using r
D_r^i	Departure time of a vehicle from node i using r
$Z_{rr'}^i$	Binary variable, 1 if any transshipment occurs between r and r' , 0 otherwise

Each route $r \in R$ consists of a set of nodes $N^r \subseteq N$ and is associated with a cost c_r representing both fuel cost, highway tolls and fixed cost for visiting node i . Traversing one leg of the route takes the time τ_r^i : driving time to node i , from the previous node in route r . Each route r can be replicated in the set R multiple times if there are more than one vehicle v that can travel route r . A pre-processing procedure as explained in Section 3.1.1 at length is followed for the driving regulations, therefore resulting with a route set R that may contain multiple copies of the same combination of nodes. Routes that contain same ordered set of nodes, i.e., same sequence of legs, may be replicated in the set R more than once, each time for a different vehicle/driver that is capable of undertaking the route, if there are more than one such candidate vehicles. Therefore, each index r refers to a node combination - vehicle pair. Along the same time, a route r may have different cost c_r , even if it consists of the same legs as of another route r' , because various types of vehicles can consume different amount of fuel while travelling the same distance and the highway tolls can be distinct for each vehicle type. Moreover, the average speed for the vehicle types can also be distinct thus resulting with different driving times τ_r^i and $\tau_{r'}^i$ between identical node pairs. Note that a feasible solution can contain both r and r' if there are adequate vehicles to cover them.

The individual requests of the customers are aggregated with respect to their origin-destination pairs. Hence, each request p is the total commodity volume that should be transported from the origin node $i \in N$ to destination node $j \in N$. Each request p has a source node ϕ^p , a destination node δ^p and a total aggregated volume d^p . The capacity of the largest vehicle is scaled to 1, thus all vehicles have capacity between 0 and 1. Since vehicles are not directly represented in the mathematical model and shown by route alternatives, it can be said that each route has an associated capacity $q_r \in (0, 1]$. The total aggregated volume for a commodity can both be less-than-truckload and more than one. Similarly, the volume unit of a request is also taken as truckload and scaled with respect to the capacity of the largest available vehicle type.

The problem is to find a minimal cost set of routes in R for a set of commodities P , such that the requests can be moved from their origin to their destination by unlimited

number of vehicles and corresponding routes. A node cannot be visited more than once in a specific route r . Let Y_r be a binary variable indicating whether the route $r \in R$ is selected for the specific transportation period or not. Since each request p should be collected from its origin and be unloaded to its destination, two continuous variables called L_r^p and U_r^p represent the total volume of request p that is either loaded or unloaded by route r . The natural upper bound of these variables is one, due to scaling of route capacities with respect to the largest available vehicle. A request p having a volume larger than the capacity of the largest available vehicle should be split into different routes by definition. Commodities can be transshipped from one vehicle to another at a node that is contained by both routes. The transshipment of a request p at a particular node i from route r to r' is represented by the continuous variable $F_{rr'}^{pi}$ which has the natural upper bound of one.

Transshipment of a request p between two routes can occur if and only if there are common node(s) shared by the routes r and r' . Moreover, a vehicle cannot transship commodities to the other vehicles at the first node of its route since the vehicles are assumed to start the tours empty. Similarly, vehicles cannot transship any commodities to a vehicle which is at its last node. Also, the commodities cannot be loaded (unloaded) in the last (first) node. The capacity restrictions may cause requests to be transshipped to routes which do not contain origin or destination of the request.

The parameter a_r^i is equal to 1 if route r contains node i and it is not the last node of route r , 0 otherwise. In the same manner, parameter b_r^i is equal to 1 if route r contains node i and it is not the first node of route r , 0 otherwise. These parameters are used to identify nodes for loading/unloading operations. Making use of the rules given above, the set of routes for possible transshipment can be screened into sets. These sets, in turn, help reducing $F_{rr'}^{pi}$ variables only to those that refer to valid candidates for transshipment. TI^r is the set of routes that have candidate common nodes for transshipping to route r , similarly TO^r is the set of routes that have candidate nodes for transshipping from route r . Given N^r , the set of nodes that a route r contains, the variables $F_{rr'}^{pi}$ are only defined on the sets $r \in R$, $r' \in TO^r$, $i \in N^r$, and $p \in P$.

As an example, let r and r' be two arbitrary routes that contain nodes $\{1, 3, 6, 9\}$ and $\{4, 8, 7, 1\}$, respectively. Then there is not any candidate nodes for route r to transship some requests into route r' , since Node 1 is the last node of route r' . Therefore, route r' will not be present in set TO^r . On the other hand, route r can transship some requests from r' at the beginning of its trip, therefore r' will be included in set TI^r . As a rule, it can be said that if two routes contain the same node in an intermediate position (i.e., not as the first or as the last node), both routes will appear in the sets TI and TO for each other, respectively.

$J_{rr'}^p$ is the set of common nodes that is suitable of a transshipment from route r to route r' after the origin of request p ($\emptyset$, if the origin node of request p is not present in r). Similarly, $B_{rr'}^p$ contains the common nodes that is suitable of a transshipment from route r to route r' that appear before destination of request p in route r ($\emptyset$, if the destination node of request p is not present in r). Lastly, $K_{rr'}^p$ is the set of common nodes that is suitable of a transshipment from route r' to route r that appear before destination of request p in route r ($\emptyset$, if the destination node of request p is not present in r).

For example, let r and r' be two arbitrary routes that contain nodes $\{5, 1, 6, 3, 2\}$ and $\{2, 5, 1, 4\}$, respectively. Also, let p be a request that is originating from Node 3 and destined to Node 6. Then, $J_{rr'}^p$ contains $\{2\}$, $B_{rr'}^p$ contains $\{1\}$ and $K_{rr'}^p$ contains $\{5, 1\}$ with respect to the definitions of the sets given above. Note that, route r cannot transship any requests to route r' at Node 5 since it appears on the first sequence in position of r .

The capacity of a route with respect to the corresponding vehicle is represented by the parameter q_r , and should not be exceeded in all of the nodes along the path therefore the load on a route should be monitored.

We will present proposed MILP model in two stages for clarity of exposition. The following first stage reveals all constraints except those that ensure synchronization. The second stage introduces time and synchronization into the model. The proposed

model without time and synchronization can be expressed as

TSNDP-T:

$$\min \quad \sum_{r \in R} c_r Y_r \quad (3.1)$$

$$\text{s.t.} \quad \sum_{r \in \Upsilon_v} Y_r \leq 1 \quad v \in V \quad (3.2)$$

$$\sum_{r \in OR_p} L_r^p = d^p \quad p \in P \quad (3.3)$$

$$\sum_{r \in DR_p} U_r^p = d^p \quad p \in P \quad (3.4)$$

$$L_r^p \leq a_r^{\phi^p} Y_r \quad p \in P, r \in R \quad (3.5)$$

$$U_r^p \leq b_r^{\delta^p} Y_r \quad p \in P, r \in R \quad (3.6)$$

$$\sum_{p \in P} F_{r'r}^{pi} \leq a_r^i Y_r \quad r \in R, r' \in TI^r, i \in N^r \quad (3.7)$$

$$\sum_{p \in P} F_{rr'}^{pi} \leq b_r^i Y_r \quad r \in R, r' \in TO^r, i \in N^r \quad (3.8)$$

$$L_r^p = w_r^p U_r^p + \sum_{i \in J_{rr'}^p} \sum_{r' \in TO^r} F_{rr'}^{pi} \quad p \in P, r \in R \quad (3.9)$$

$$U_r^p = w_r^p L_r^p + \sum_{r' \in TI^r} \sum_{i \in K_{rr'}^p} F_{r'r}^{pi} - \sum_{i \in B_{rr'}^p} \sum_{r' \in TO^r} F_{rr'}^{pi} \quad p \in P, r \in R \quad (3.10)$$

$$X_r^i \leq q_r Y_r \quad r \in R, i \in N^r \quad (3.11)$$

$$X_r^i = X_r^{g_r^{(h_r^i-1)}} + \sum_{p \in PO_i} L_r^p - \sum_{p \in PD_i} U_r^p + \sum_{p \in P} \sum_{r' \in TI^r} F_{r'r}^{pi} - \sum_{p \in P} \sum_{r' \in TO^r} F_{rr'}^{pi} \quad (3.12)$$

$r \in R, i \in N^r$

$$X_r^0 = 0 \quad r \in R \quad (3.13)$$

$$Y_r \in \{0, 1\} \quad r \in R \quad (3.14)$$

$$L_r^p \geq 0 \quad r \in R, p \in P \quad (3.15)$$

$$U_r^p \geq 0 \quad r \in R, p \in P \quad (3.16)$$

$$F_{rr'}^{pi} \geq 0 \quad r \in R, r' \in TO^r, p \in P, i \in N^r. \quad (3.17)$$

The objective function Equation (3.1) minimizes the cost of selected routes associated with the fuel and toll prices of the arcs. A route is included in R if corresponding vehicle can be present at the starting node of r by a given time and can complete the route without violating any driving regulations. Constraints (3.2) indicate that each truck can be assigned to at most one route. It must be mentioned that a truck can be assigned only to a route from its feasible route list Υ_v . Equations (3.3) and (3.4) are the driving constraints of the model ensuring that each commodity should be loaded from its origin node and be unloaded at the destination node. The sets OR_p and DR_p guarantees that the requests should be loaded and unloaded by the appropriate routes that contain corresponding origins and destinations of the requests.

Constraints (3.5) and (3.6) state that requests cannot be loaded (unloaded), if the origin (destination) of the request is not included or in the last (first) node in the sequence of a route. They are also the coupling constraints between $L_r^p - U_r^p$ and Y_r . Equations (3.7) and (3.8) are the coupling constraints between $F_{rr'}^{pi}$ and Y_r . Any transshipment $F_{rr'}^{ip}$ at node i can only occur if route r' is in the set of transshipment candidate routes that any transshipment from r to r' can be done, i.e. TO_r contains r' . Similarly, Any transshipment $F_{r'r}^{pi}$ at node i can only occur if route r' is in the set of transshipment candidate routes that any transshipment from r' to r can be done, i.e. TI_r contains r' . Also, there cannot be any transshipment from route r' to route r at node i if r does not contain i or contains as the last node. In the same manner, there cannot be any transshipment from r to r' if r does not contain i or contains as the first node. The summation over requests p is used to reduce the number of constraints in the model, since the constraints are written for each node and any transfer at a specific node cannot exceed 1 (the capacity of the largest truck), the usage of summation is valid. Moreover, zero RHS will force all $F_{rr'}^{pi}$ variables to be equal to zero.

The conservation of request flows is ensured by Equations (3.9) and (3.10). The parameter w_r^p is equal to 1, if the destination of p appears after the origin of p in route r , 0 otherwise. If w_r^p is equal to 1, then Equations (3.9) indicate that all loaded requests should be either unloaded at the destination node or transshipped to another route. Similarly, Equations (3.10) guarantees that all unloaded request volume should

be equal to the loaded request volume plus the request volume transshipped from other routes minus the request volume transshipped to other routes. On the other hand, if the parameter w_r^p is equal to 0, then Equations (3.9) indicate that all loaded requests should be transshipped to other vehicles. In a similar manner, the volume of all unloaded requests should be equal to the difference between the volume transshipped from other routes and the volume transshipped to other routes. The parameters w_r^p implicitly prevent routes to unload the requests at the destination nodes before loading at the origin node.

Constraints (3.11) are the capacity constraint for truckload X_r^i at every node i . Equations (3.12) are truckload flow conservation constraints of the vehicles. The workload at a node is the summation of load coming from previous node and amounts loaded and unloaded at that node. The combination of Equations (3.11) and (3.12) guarantees the prevention of any violation in truck-capacity. Note that, a route may not contain nodes in ascending/descending sequence of node numbers. The parameter g_r^n represent the n^{th} node of route r (note that $g_r^0 = 0$) and h_r^i is the number that is exactly equal to the position in sequence of node i in route r . Since the load on a node i depends on the balance of loads, unloads, transshipments at the current node and the load coming from the previous node $g_r^{(h_r^i-1)}$, the capacity of a route should be represented in an iterative manner. The upper bound of one is still valid for the used capacity variables X_r^i due the scaling strategy. Equations (3.13) defines the beginning of a route. Lastly, Equations (3.14) - (3.17) specify the domain of each set of decision variables.

The current objective function (3.1) only focuses on the variable cost of fuel and tolls associated with the distance travelled and the used highway options. However, assigning a vehicle to a duty may cause a fixed cost, like driver wage, rental price of a truck, etc. Thus, adding a new component to the existing objective function can also model these particular circumstances. Moreover, adding a fixed cost to selecting or using a vehicle for a route may implicitly minimize the number of vehicles used for the optimal transportation plan. Minimization of the number of used vehicles depends on the magnitude of the fixed cost parameter associated with both drivers, vehicles and

routes to be covered, c'_r . It is obvious that it is appropriate to use the company-related known fixed cost for a real-life application of this proposed mathematical formulation. If the vehicle is currently not in the starting node of route r , this means a deadheading trip should be performed first. The cost of this trip can be included in c'_r . If the vehicle is candidate for renting, its fixed cost component equals to the rental cost.

3.3. Introducing Time into Model

The model proposed above yields a mixed-integer formulation of transportation plan without considering transportation times, synchronization of transshipping vehicles, and due dates for the last-mile delivery at the destination cities. In this section the model will be expanded to take these aspects into consideration.

3.3.1. Parameters of the Time-Expanded Model

First of all, although the travel time between two nodes depends on the weather conditions, traffic jams and other parameters, it can be assumed that each vehicle type has an approximated constant travel time between two transfer stations. τ_r^i is the parameter that is equal to the constant average driving time to node i from the previous node for the vehicle corresponding to route r .

There are the earliest starting and latest ending times for the transfer stations that stem from the city-logistics operations. So, vehicles can be dispatched from a transfer station after σ^i for a specific node i . Similarly, each transfer station has a pre-determined cut-off time at node i , represented by the parameter ψ^i .

The loading, unloading and transshipment times for the requests should be estimated for every problem and company. For the sake of simplicity, it is assumed that the duration of loading, unloading and transshipment operations per unit volume of load are denoted by λ^p and ω^p for request p . Since each request may have unique packing and stacking type, it is appropriate to include p to the parameters.

3.3.2. Decision Variables of the Time-Expanded Model

The arrival times of vehicles to each node should be tracked in order to ensure the delivery of requests before the pre-determined cut-off times of transfer stations as well as synchronization. Hence, the variables A_r^i represent the arrival time to node i of a vehicle while using route r . Similarly, the variables D_r^i denote the end of operations at a given node and serve as the departure time from the node i while using route r .

Lastly, the binary variables $Z_{rr'}^i$ state the existence of any transshipment from the vehicle using route r to the vehicle using route r' at a specific node i . The variable takes the value of one if and only if there is a positive amount of transshipment between the vehicles, zero otherwise. The variables are only defined for the routes that can transship to each other and also on the possible intermediate transfer stations if both routes contain the node i .

3.3.3. Constraints of the Time-Expanded Model

Since a request p can be split into different vehicles in a feasible transportation plan, all vehicles carrying workload from a request should arrive the destination transfer station before the cut-off time of the node. Due date control can be written as

$$D_r^i \leq \psi^i Y_r \quad r \in R, i \in N^r. \quad (3.18)$$

Equations (3.19) can be used for the earliest starting times of the vehicles in their starting nodes of the routes. Therefore, the constraints should only be present for first node of routes, i.e., g_r^1 , and can be computed as

$$A_r^{g_r^1} \geq \sigma^{g_r^1} Y_r \quad r \in R. \quad (3.19)$$

Equations (3.20) link the variables A_r^i and D_r^i with respect to the parameter of the constant travel time parameter between nodes τ_r^i , for all nodes of a route except the first node. Constant travel time can be expressed as

$$A_r^i = D_r^{g_r^{(h_r^i-1)}} + \tau_r^i Y_r \quad r \in R, i \in N^r / \{g_r^1\}. \quad (3.20)$$

A_r^i and D_r^i variables for unselected routes will all be equal to zero due to the Y_r variables appearing in the RHS of the Equations (3.18) - (3.20).

Equations (3.21) show the departure time calculation at a specific transfer station. The departure time of the vehicles from a specific transfer station depends on the arrival time to the same node and the time spent for loading, unloading and transshipment operations. The loading operations are only defined on PO_i , the unloading operations are defined on PD_i for a specific node i , and the transshipment operations are only valid for sets TO^r and TI^r due to the definition of the variable $F_{rr'}^{pi}$. Departure time can be calculated as

$$D_r^i \geq A_r^i + \sum_{p \in PO_i} \lambda_p L_r^p + \sum_{p \in PD_i} \omega_p U_r^p + \sum_{p \in P} \left(\omega_p \sum_{r' \in TO^r} F_{rr'}^{pi} + \lambda_p \sum_{r' \in TI^r} F_{r'r}^{pi} \right) \quad r \in R, i \in N^r. \quad (3.21)$$

Equations (3.22) identify the existence of any transshipment between two routes. Note that, the total amount of transshipment for a vehicle is less than or equal to one at any intermediate transfer station. The mathematical expression can be written as

$$\sum_{p \in P} F_{rr'}^{pi} \leq Z_{rr'}^i \quad r \in R, r' \in TO^r, i \in N^r. \quad (3.22)$$

The aim of the variables $Z_{rr'}^i$ is to check the existence of any transshipment between the vehicles, in order to ensure the synchronization of vehicles between nodes. A vehicle v using route r should not be able to depart from a specific transfer station i without the arrival of vehicle v' using the route r' if there is a positive transshipment $F_{rr'}^{pi}$ from vehicle v' to vehicle v at that node. Since the binary variables $Z_{r'r}^i$ show the corresponding positive transshipment, the synchronization can be enforced by Equations (3.23) defined as

$$D_r^i + (1 - Z_{r'r}^i)M \geq A_{r'}^i + \sum_{p \in P} ((\lambda_p + \omega_p)F_{r'r}^{pi}) \geq 0 \quad r \in R, r' \in TI^r, i \in N^r. \quad (3.23)$$

Note that, a vehicle using route r can unload its requests that will be transshipped to a vehicle using route r' before the arrival of second vehicle to this node. This means that, it is assumed that every transfer station has an unlimited storage capacity for temporary storage of transshipped loads. On the other hand, a vehicle using route r should wait for the vehicle using route r' at an intermediate node used for the transfer

operations, if there is a positive transshipment from r' to r . For this reason, only $F_{r'r}^{pi}$ defined on TI^r for a specific node r is used in Equations (3.23). Furthermore, a transshipment operation requires both loading and unloading of the requests between the vehicles, hence the last term of Equation (3.23) includes both loading and unloading durations per truckload. The value for big M at the LHS of the equations can be taken as the maximum time value that the model uses, i.e., $\max(\psi_i)$. Finally, Equations (3.24) - (3.26) specify sign restrictions on the variables and can be expressed as

$$A_r^i \geq 0 \quad r \in R, i \in N^r \quad (3.24)$$

$$D_r^i \geq 0 \quad r \in R, i \in N^r \quad (3.25)$$

$$Z_{rr'}^i \in \{0, 1\} \quad r \in R, r' \in TO^r, i \in N^r. \quad (3.26)$$

3.4. A Simple Lower Bound without Synchronization and Scheduling

The problem size can result in impractically long solution times if the number of vehicles or the possible distinct node combinations increases. Hence, it may not be possible to solve the model with an increased range of input sets in a reasonable time. A lower bound can be helpful in dealing with such cases. To obtain a simple lower bound, large networks can be modelled in a different manner without modelling the time-related constraints. The aim is to create a less complex model for obtaining a lower bound.

The variable $F_{rr'}^{pi}$ contains both r and r' in order to follow the track of transshipment pairs. However, it is not necessary to keep the information of both routes if synchronization is disregarded. Therefore, the variable $F_{rr'}^{pi}$ can be split into two different variables as L_r^p and U_r^p ; F_r^{pi} is the variable that represents transshipments from other routes, whereas G_r^{pi} is the variable for transshipments to other routes. Note that total number of $F_{rr'}^{pi}$ variables in the proposed model is $|R| \times |TO^r| \times |P| \times |N^r|$ where $\forall r \in R$, whereas the relaxed model has total number of F_r^{pi} and G_r^{pi} variables as $2 \times |R| \times |P| \times |N^r|$ where $\forall r \in R$. Since typical $|TO^r|$ will be larger than two, the

size of second set of variables is expected to be less than the first one. Equations (3.7) - (3.12) can be revised as the Equations (3.27) - (3.34) given as

$$\sum_{p \in P} F_r^{pi} \leq a_r^i Y_r \quad r \in R, i \in N^r \quad (3.27)$$

$$\sum_{p \in P} G_r^{pi} \leq b_r^i Y_r \quad r \in R, i \in N^r \quad (3.28)$$

$$U_r^p = w_r^p L_r^p + \sum_{i \in K_{rr'}^p} F_r^{pi} - \sum_{i \in B_{rr'}^p} G_r^{pi} \quad p \in P, r \in R \quad (3.29)$$

$$L_r^p = w_r^p U_r^p + \sum_{i \in J_{rr'}^p} F_r^{pi} \quad p \in P, r \in R \quad (3.30)$$

$$X_r^i = X_r^{g_r^{(h_r^i-1)}} + \sum_{p \in PO_i} L_r^p - \sum_{p \in PD_i} U_r^p + \sum_{p \in P} F_r^{pi} - \sum_{p \in P} G_r^{pi} \quad (3.31)$$

$r \in R, i \in N^r$

$$\sum_{r \in R} F_r^{pi} = \sum_{r \in R} G_r^{pi} \quad p \in P, i \in N^r \quad (3.32)$$

$$F_r^{pi} \geq 0 \quad r \in R, p \in P, i \in N^r \quad (3.33)$$

$$G_r^{pi} \geq 0 \quad r \in R, p \in P, i \in N^r. \quad (3.34)$$

Flow conservation constraints with respect to loading, unloading and transshipment operations are conserved in both models after just adjusting necessary RHS terms for the variables F_r^{pi} and G_r^{pi} . However, another constraint should be added in order to ensure the flow balance in all of the nodes. Equations (3.32) simply balance the volume of the transshipped requests, hence resulting in conservation of requests at each node i . The model providing a lower bound is referred as $TSND-T \setminus S$ within the scope of this dissertation.

3.5. Vehicle Positioning and Balancing

The proposed model optimizes daily transportation plan by adjusting loading, unloading and transshipment decisions on the requests and minimizing the total fuel and toll costs plus the fixed cost of using a vehicle, respectively. The proposed model can be directly used for the companies that completely outsource vehicles for each

planning period. On the other hand, generating the optimal transportation plan for only one day may be greedy for a company that has at least some owned vehicles in terms of affecting the final destinations of the vehicles with respect to the selected routes. Since vehicles are left in the last node of their used routes, the distribution of the vehicles throughout the network is not considered in the current model. Such a system requires different vehicle movement strategies due to the driver regulations and consideration of a period rather than a single day.

Since the demand for an operating day realizes only after the individual requests occur, the actual aggregated amount of delivery between node pairs is not known before the demand realization. Therefore, a good prediction mechanism should be used for understanding the characteristics under the demand pattern over the periods. The prediction strategy is also important for optimizing the current operating day, since it is crucial to balance the vehicles throughout the node network. Most of the nodes have an unbalanced vehicle movement nature due to the imbalance between the supply and demand from a city or node. In other words, the number of vehicles that leaves a specific node in an operating day is usually not equal to the number of vehicles that ends up in the same node after the transportation plan, as pointed out by Crainic (1999).

In this subsection we do not propose a prediction strategy for demand realization, but generate an idea about how to use the predicted data in the proposed model. Assume that a prediction strategy exists about the daily individual requests that will occur in the next day or days. Then, these forecasted requests can be aggregated as done for creating the input data for the proposed model. As a consequence, the proposed model can be solved with the forecasted data for the upcoming period(s).

The aim is to estimate the required number of vehicles that should be left at a node before the next period. One crucial point to remark is that the actual number of vehicles in the node network for the next period is not known, therefore these forecasted periods should be solved with an infinite number of vehicles, theoretically. However, it is not possible to use an input data with infinite number of vehicles, since it inevitably

will end up with infinite number of routes to be used, and consequently resulting with infinite number of decision variables. Hence, the number of vehicles that should be ready at each node can be found as an upper bound.

The upper bound can be calculated by assuming all aggregated requests are carried by a distinct vehicle without any splitting of the requests and any consolidation in the vehicles. In other words, if a request p has a volume of any arbitrary float number d^p , then $\lceil d^p \rceil$ vehicles should be able to deliver the request p directly from its origin to the destination node as an upper bound. V_i represents the upper bound on the number of vehicles required at a node i . As mentioned earlier, d^p is the volume of the total aggregated individual requests p , which has a origin node ϕ^p and a destination node δ^p . Since the requests originated from a node i are known with set PO_i , the upper bound on the number of vehicles at a node i can be calculated by Equation (3.35) as

$$V_i = \sum_{p \in PO_i} \lceil d^p \rceil \quad i \in N. \quad (3.35)$$

The forecasted demand for the next period can be solved with the proposed model using the upper bound on the number of vehicles required at each node. Then the resulting optimal solution will require an exact number of vehicles starting from each node i that is definitely less than or equal to the upper bound V_i . Let these parameter set of vehicles at each node that are required for transportation plan of the next day be π_i for each node i . In order to balance the number of vehicles after a planning day, vehicles should be assigned to some routes such that the number of vehicles left in every node is aimed to be greater than equal to the desired number π_i , for obtaining an optimal schedule for the forecasted next day. Let ER_i be the set of routes ending by node i . Equations (3.36) show the additional constraints on selecting the routes for a day. Note that π_i values should be calculated by subtracting the number of the stable vehicles at a node which may not have any operations on the current day. Additional constraints can be expressed as

$$\sum_{r \in ER_i} Y_r \geq \pi_i \quad i \in N. \quad (3.36)$$

On the other hand, it may not be feasible to deliver all of the requests to their destinations before the due dates while distributing vehicles with respect to such lower bound

conditions. Therefore, this constraint can be relaxed with a Lagrangian cost parameter λ' and added to the objective function. It should be noted that, only a deficit of vehicles at a particular node creates a cost to the objective function, whereas surplus of vehicles does not. Thus, maximum of zero or the deficit cost is added the objective function. This mathematical expression is modeled by extra decision variables, namely W_i . Equations (3.38) show the necessary coupling constraints that should be added to the model for the variable W_i , whereas the new objective function becomes as Equation (3.37). The proposed model can be expressed as

$$\min \quad \sum_{r \in R} (c_r + c') Y_r + \sum_{i \in N} \lambda'_i W_i \quad (3.37)$$

$$\text{s.t.} \quad 3.2 - 3.26$$

$$W_i \geq \pi_i - \sum_{r \in ER_i} Y_r \quad i \in N \quad (3.38)$$

$$W_i \geq 0. \quad i \in N \quad (3.39)$$

The solution procedure starts with solving *TSNDP-T* before starting a new operational period for building a lower bound on the vehicles required for the next operational period. The connection between forecasted data and the required number of vehicles is provided by this strategy. Then, these lower bounds can be used for vehicle balancing constraints and their relaxation on the objective function of *TSNDP-T* that is being solved for the current operational period. Note that, after the realization of demand for the next period, due to the deviations from forecasted data, there can be deficits of vehicles at the nodes. The difference can again be calculated by solving *TSNDP-T* for the next period, since the optimal solution gives the required number of vehicles at each node.

repeat

π_i = The minimum required number of vehicles for the next period at each i

Compute π_i by solving *TSNDP-T* for the next period

Set $R :=$ the route set for the current period after pre-processing

Solve *TSNDP-T* by using R and vehicle balancing with respect to π_i

until operational days to be planned have left

Figure 3.1. Pseudocode of the operational algorithm.

To sum up, all of the models mentioned earlier create a general operational level strategy. Note that the algorithm given should be repeated for every operational period (e.g. for every day). Figure 3.1 shows the outline of the proposed algorithm for using all models.

3.6. Using the Proposed Model on the Tactical Level

Tactical level decisions mainly concern the service selection and empty vehicle balancing strategies. Service selection refers to decisions on the routes that will be offered and this section will discuss how the proposed model can be used for determining the number and characteristics of the routes used by a company.

The proposed model works on the input set R , which is created by a pre-processing strategy that eliminates infeasible routes from a general route pool. Tactical decisions may be supported by the model in a what-if manner, by augmenting the general route pool. The effect of adding new routes, eliminating some routes or edited routes can be observed by comparing the results. For instance, terminals passed along a route can be changed by introducing or discarding intermediate nodes. Also, some new hub nodes, spoke nodes or transfer station nodes can be added to the route network. Solving the previous operational periods with a new R set can show the difference caused by the tactical decisions without any need for changing the model. To sum up, the usage of pre-processing strategy allows the proposed model to be used in tactical level without effort. Comparison of the operational costs can be used for the mid-range decisions related with changing or improving the infrastructure.

4. NUMERICAL RESULTS AND PERFORMANCE OF THE PROPOSED MODELS

In this section, performance of the solution method developed in this thesis is tested in different experimental settings. To gain insight about the behavior of different problem settings by interpreting the results of the proposed model in different settings, several hypothetical cases are constructed with respect to some assumptions described in this section. Furthermore, the model is also used in a real-life example.

4.1. Creating Problem Instances

For the numerical studies, TSNDP instances under different scenarios should be generated. Scenarios corresponding to daily transportation requirements are generated randomly with different number of unique origin and destination of requests over a set of networks by means of a *Python* code.

4.1.1. Route Generation

Our operational level proposed model works on a general route pool which is supposed to be determined as a result of the strategic and tactical level of decisions of a company. Here, for the sake of experimentation this route pool is generated as follows after first selecting a set of cities in Turkey. The distance matrix between the nodes representing these cities is obtained from the currently operating highway network of Turkey and it is known as *a priori*. The length of a route is equal to the distance between two nodes if it consists of only one arc between the corresponding nodes, or the summation of individual distances of the legs in the route.

In each scenario, there are a number of hub and spoke type nodes. The distinction is made based on the population data. If there are n hub nodes and m spoke nodes in the generated scenario, while the n nodes that have the highest population are labelled

as hub nodes. All hubs and spokes can be a candidate both as an origin or a destination node of a request. Hub nodes will have larger flow than spoke nodes when generating the requests. On the other hand, in some of the scenarios there are also third type of nodes named as transfer stations, are not designated as the origin or the destination of any request. Transfer nodes which have an unlimited temporary storage capacity are used as intermediate legs for the routes, thus can be used for transshipments between vehicles in a feasible transportation plan.

All direct connections between any two hubs and between all pairs of hubs and spokes are included in the pool as two-nodes routes. It is important to note that a route cannot consist of only two spoke nodes, therefore a daily request between two spokes can only be delivered by at least one transshipment at an intermediate node, if any.

Three-nodes routes are constructed based on a rule defined with respect to the distance matrix. In this manner, we can avoid having irrational routes in the pool. A specific node is inserted into an existing two-nodes route only if it does not increase the total required distance to be covered by more than 100 kilometers. Therefore, all three-nodes routes are created based on the two-nodes routes, where all three types of nodes can be used as an intermediate node candidate. Four-nodes routes are also generated with respect to the same rule, however there are not many candidates due to the highway network and the geographical distribution of the cities.

The duration of a given route for a specific vehicle can be calculated by means of a simple linear equation by dividing the length in terms of kilometers by the constant speed of the vehicle in kilometers per hour. It is assumed that the average speed of a vehicle is estimated based on the long-term averages since the weather and traffic conditions can vary between the operating hours and days. Also, short breaks with respect to the driving regulations (e.g. 30 minutes break for every 4.5 hours of driving) are considered in this calculation.

4.1.2. Request Generation

Certain rules are followed to create the daily requests for each instance. First of all, the origins of the daily requests should be selected from either hub nodes or spoke nodes. Secondly, the destination node can be both hub node and spoke node if the origin is selected as the hub node, while the destination node is rarely a spoke node if the origin is also a spoke node. Transfer nodes cannot be used for origins or destinations. The volumes of the requests are created by means of an algorithm, such that the total volume that is supplied from a node is correlated with the GDP contribution of the node to the total GDP of the whole set of nodes in the current experimental setting. On the other hand, the total volume that is demanded by a node is correlated with the proportion of the population of the node to the total population of the current node set. A sample daily request plan is shown Table 4.1 below. As mentioned earlier, the volume unit is truckload which is scaled to the largest available vehicle in the transportation environment.

Table 4.1. Sample daily requests.

Origin Node	Destination Node	Volume	Type
1	4	1.10	1
1	6	0.55	1
1	9	1.15	1
2	6	0.55	0
3	14	0.15	1
4	8	0.55	1
4	12	0.50	0
6	7	0.40	1
6	9	1.15	0
6	10	0.15	1
7	9	0.40	1
7	12	0.35	1
9	1	0.15	1
9	2	0.50	1
9	12	0.60	1
11	14	0.50	1
12	1	1.50	0
12	6	0.30	0
13	4	0.25	1
13	6	0.40	0
14	7	0.05	1

The last column in Table 4.1 refers to the type of the request which denotes the stacking strategy of the existing orders of the customers, and it depends to the operating company. For all of the designed experiments within the scope of this thesis, there are two alternative types. Let them be represented by μ_p (0 for the first type and 1 for the second type). These two types only differ in loading and unloading durations per unit of truckload. Let λ_p be the loading and ω_p be the unloading duration for a

request that has a volume of one unit of truckload. It is assumed that it takes 90×30000 seconds for loading and 120×30000 seconds for unloading for the first type for a one full largest truck. The second type requires 30% more variable time to both load and unload due to the different stacking strategy. The vehicles cannot be loaded fully in order to leave a margin for the stacking operations. Thus, the vehicles can be loaded as 65% of their maximum capacity on average. Furthermore, regardless of type of the request, all loading and unloading operations require a fixed time of 15 minutes, added to the variable time. Thus, the loading time parameter λ_p is calculated as

$$\lambda_p = 90 \times 30000 \times 0.65 \times (1 + \mu_p \times 0.3) + 15 \times 60. \quad (4.1)$$

Similarly, the unloading time parameter that is scaled to full truckload unit. The unloading time parameter can be calculated as

$$\omega_p = 120 \times 30000 \times 0.65 \times (1 + \mu_p \times 0.3) + 15 \times 60. \quad (4.2)$$

4.1.3. Earliest Start and Latest Delivery Times

Vehicles should be ready to service before loading requests at a node. The proposed model can be used in two alternative strategies; (1) assigning a fixed earliest start time for a node with respect to city-logistics decisions, and (2) vehicles may have distinct start times concerning driver or vehicle availability. The first strategy requires the parameter set σ^i for each node $i \in N$, whereas the second strategy can be implemented by changing the domain of the parameter set as σ_r^i . The proposed model currently uses a fixed earliest available start time for each node, since the real-life implementation explained in Section 4.3.4 requires to do so. On the other hand, if vehicles are desired to be differentiated from each other, then Equation (3.20) should be revised as

$$A_r^{g_r^1} = \sigma_r^{g_r^1} Y_r \quad r \in R. \quad (4.3)$$

In a similar manner, vehicles should arrive or end the service at a node before a specific due date. Here, again there can be two different strategies: (1) due date depends on the node as given by the city-logistics rules, or (2) due date depends of personally identifiable driver-related and vehicle-related constraints. First strategy is already implemented in the proposed model in Section 3.2, with the parameter set ψ^i

for all nodes $i \in N$. If the due date strategy is aimed to be personalized by driver or vehicle, then the parameter set should be altered as ψ_r^i . It is important for the model to have this flexibility, since some drivers may have special conditions like joining another scheduled trip, family or personal-related issues, etc. Equation (3.18) should be updated to Equation (4.4) as

$$D_r^i \leq \psi_r^i Y_r \quad r \in R, i \in N^r. \quad (4.4)$$

It is important to note that this constraint set can be written for all nodes including the intermediate stations, or only be defined for the last nodes of the specified route r . If all strategy is created based on the vehicles themselves instead of facilities at the nodes, then defining the constraints for only the last nodes on the node list of the routes will be proper. The constraints in their present definition are attaching the importance to city-logistics definitions. Scenarios created for the experimental settings uses the earliest start time of the nodes as zero, whereas the latest delivery times are two hours plus the longest possible duration in the existing origin-destination pairs. This two-hour surplus allows vehicles to load, unload and transship some requests at the intermediate nodes.

4.2. Experimental Design

In this section, test cases with different node networks and request sets are created to investigate the effects of these factors on solution time statistics and objective values. First setting contains fifteen nodes, where six are hub nodes, five are spoke nodes, and the last four are transfer station nodes which cannot be neither origin nor destination of a request. This setting will be referred as *6H5S4T*. Second setting also has fifteen nodes, however the number of hub nodes is eight, and the number of spoke nodes is seven, leaving no transfer nodes. *8H7S* is the abbreviation for the second setting. The aim of designing these two node networks is to observe the effect of transfer station nodes on the system. Moreover, since transfer station nodes cannot be the first and last node of an element of the route set R , *8H7S* will have an increased number of variables due to higher size of the set R . As a consequence, second setting will also show the effect of the size of the route set.

Third setting is the extension of $8H7S$, by adding five new transfer station nodes to the existing fifteen nodes. Therefore, the network has a total of twenty nodes with eight hub nodes, seven spoke nodes and five transfer station nodes and is called $8H7S5T$. The aim of the design is to see the effect of additional transfer station nodes located at possible strategic positions on the road network on both run time and the objective values. In general, three settings are designed for comparing multiple issues for the input network. The results of $8H7S$ and $8H7S5T$ can also be inspiring in terms of using these models as a *tactical* tool for expanding the node network for an already operating company. The methodology for such usage is further discussed in Section 5.

Along with these, different requests for twenty periods of operation are generated. For the scope of this thesis, each operation period lasts for twenty-four hours, thus they will be referred as days. These periods can also be regarded as twenty consecutive days, each having a different number of requests as shown in Table 4.2. The minimum number of requests in a day is fifteen, whereas the number is increased to thirty-four at maximum. The number of requests on each day is not uniformly ordered, but appears randomly throughout the planning period. All node network settings is solved using the same sequence of days with their designated request sets.

Table 4.2. Order of the daily request numbers.

Day	# Number of Requests
1	21
2	19
3	16
4	34
5	31
6	18
7	17
8	22
9	27
10	23
11	28
12	20
13	32
14	24
15	25
16	30
17	29
18	26
19	33
20	15

In this manner, there are 3×20 different experimental design alternatives coming from twenty days of both $6H5S4T$, $8H7S$ and $8H7S5T$. At first, in all of these sixty problems, the size of requests is kept as less-than-truckload. In other words, there are not any origin-destination pairs that has a request volume greater than the largest available truck. Next, some of the requests are increased from LTL to MTL in the settings $6H5S4T$ and $8H7S$ by means three different strategy and will be explained later. Hence, there are 3×20 more operational day instances are present in addition to these

sixty days of interest for observing the difference between less-than-truckload experimental cases and more-than-truckload cases. Table 4.3 shows the whole experimental setting.

Table 4.3. Overview of experimental settings on node network design and requests.

Problem Setting	# of Days	# of Nodes	# of Hub Nodes	# of Spoke Nodes	# of Transfer Station Nodes	# of Requests	Type of Requests
6H5S4T-LTL	20	15	6	5	4	15-34	LTL
6H5S4T-LTL-MTL-1	20	15	6	5	4	15-34	LTL and MTL
6H5S4T-LTL-MTL-2	20	15	6	5	4	15-34	LTL and MTL
8H7S-LTL	20	15	8	7	0	15-34	LTL
8H7S-LTL-MTL	20	15	8	7	0	15-34	LTL and MTL
8H7S5T-LTL	20	20	8	7	5	15-34	LTL

4.3. Computational Results

In this section we present and discuss the numerical results of the test cases defined in the previous section. The proposed model is coded in Python programming language in PyCharm integrated development environment with the version 2020.3.3. All experiments are carried out on a PC with 2.60 GHz Intel ©Core™ i7-1070H CPU and 32 GB RAM, running under Windows 10 Enterprise operating system, and using the commercial solver Gurobi 9.5.2.

4.3.1. Run-Time and Objective Value Comparisons

In this set of experiments, each day is treated independently. Therefore, here vehicle balancing issue is not of concern. Thus, the number of vehicles at each node is taken as the upper bound at the beginning of each day as described in Equation (3.35).

In experimental setting $6H5S4T$, there are three options for the type of requests, one LTL and two LTL-MTL requests. For LTL-MTL combined versions, volumes of LTL is kept same as the LTL for the first setting, whereas the second setting has completely random request volumes that allows MTL. In all of the cases, origins and destinations of the requests are kept as the same. The purpose of such strategy is to compare the run time statistics of these three options independently. Table 4.4 summarizes the results of these sixty distinct runs.

Table 4.4. Comparison of LTL and LTL-MTL versions of 6H5S4T case.

# of Nodes	# of Requests	# of Variables	6H5S4T-LTL		6H5S4T-LTL-MTL-1		6H5S4T-LTL-MTL-2	
			Run Time (s)	Objective	Run Time (s)	Objective	Run Time (s)	Objective
15	15	404826	13.39	41605.80	18.35	51139.40	17.09	60172.31
15	16	431080	37.96	62460.60	36.78	73236.57	15.65	64424.15
15	17	457334	9.20	44750.87	5.80	54602.19	29.84	58391.62
15	18	483588	28.23	50148.13	22.06	59813.10	33.76	62658.62
15	19	509842	212.40	58688.62	260.06	67947.28	35.76	65927.35
15	20	536096	197.28	45526.37	197.87	56277.9	331.98	58071.63
15	21	562350	253.39	56972.66	257.69	65201.78	277.36	67372.97
15	22	588604	203.26	55165.85	242.91	64499.86	493.41	63025.19
15	23	614858	273.20	71832.57	312.65	81544.22	68.69	73058.92
15	24	641112	271.95	74900.38	353.98	84987.25	231.73	77639.38
15	25	667366	346.33	57890.13	416.83	65096.23	3600.27*	73900.40*
15	26	693620	650.02	74325.90	708.03	86227.01	72.51	90478.17
15	27	719874	229.93	70367.65	292.43	86188.35	32.84	80378.42
15	28	746128	338.90	72100.13	435.78	94223.97	1507.27	83241.15
15	29	772382	56.52	75908.66	100.07	98486.29	214.89	75265.18
15	30	798636	356.02	68107.12	650.56	87635.77	76.14	75424.87
15	31	824890	601.11	73341.18	1084.81	89917.89	925.17	76073.76
15	32	851144	1736.29	82265.91	2027.53	89432.27	757.63	88821.68
15	33	877398	840.83	80965.91	2024.13	97405.84	72.70	79563.43
15	34	903652	3600.38*	75494.42*	3600.22*	91772.61*	804.36	96006.22

According to our problem definition, this operational model should typically be solved within an hour for the operating companies. Therefore, maximum allowable run time is kept as one hour, without loss of generality. For the sixty runs for this setting, 95% of the instances are solved optimally within the maximum time limit. However, the commercial solver could not be able to reach to optimal solutions of the instances $6H5S4T-LTL-34$, $6H5S4T-LTL-MTL-1-34$ and $6H5S4T-LTL-MTL-2-25$ within one hour, and the calculated gaps are 3.00%, 1.42% and 0.83%, respectively. These instances are indicated with an (*) in Table 4.4.

One important conclusion from the first sixty runs is that the run time is not directly correlated with the total number of the requests at a day, but also depends on the distribution of the requests and their volumes throughout the node network, since the distribution implicitly affects the number of vehicles that should be used and the number of possible consolidation alternatives. Figure 4.1 shows the run time comparison between settings $6H5S4T-LTL$ and $6H5S4T-LTL-MTL-1$.

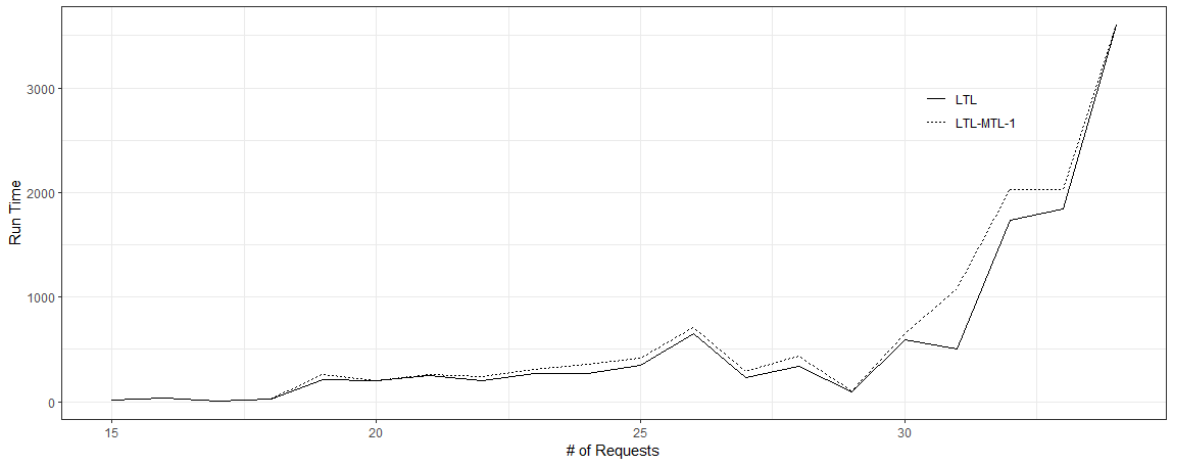


Figure 4.1. Run time comparison of $6H5S4T-LTL$ and $6H5S4T-LTL-MTL-1$.

The other important conclusion of these experimental settings is that adding MTL requests to system tends to increase the objective value significantly since it directly increases the required number of vehicles therefore the required number of arcs to be traversed. As can be seen from Figure 4.2, the objective values are significantly higher in MTL case than LTL, but keeping the same trend with respect to the number of requests. This situation may have occurred due to selecting identical routes several

times in order to carry more amount of requests in MTL case that have the same origin and destination nodes as in the LTL case, thus leading to a linear increase in differences of the lines on the plot.

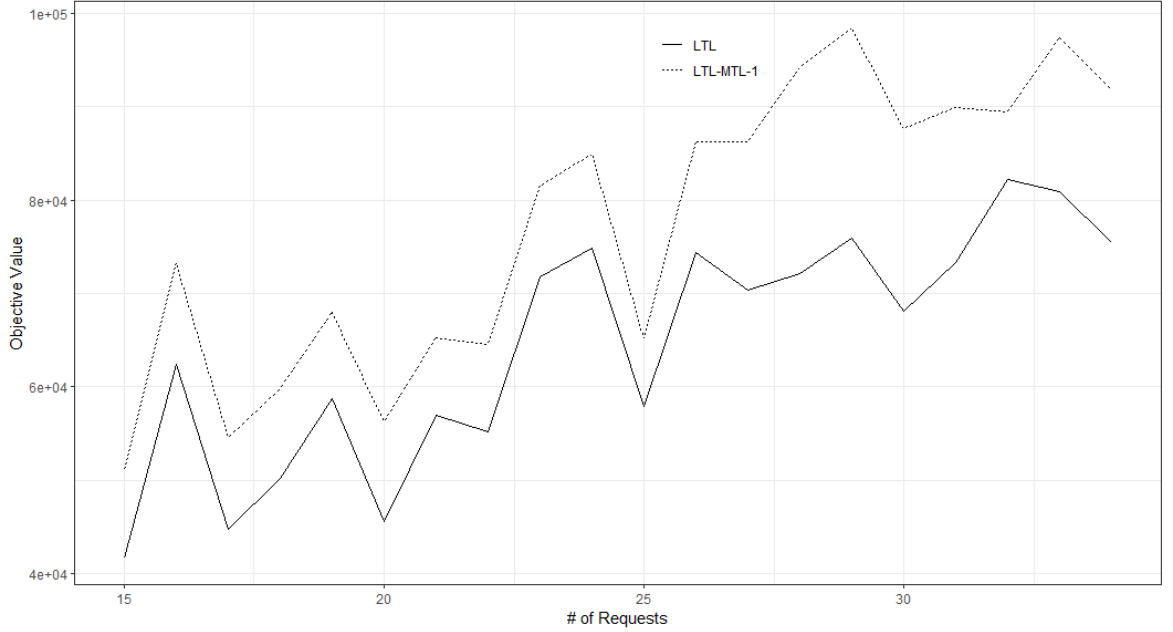


Figure 4.2. Objective value comparison of $6H5S4T-LTL$ and $6H5S4T-LTL-MTL-1$.

Figure 4.3 shows the run time comparison between $6H5S4T-LTL$ and $6H5S4T-LTL-MTL-2$ cases. Allowing the system to have MTL requests does not increase solution time directly.

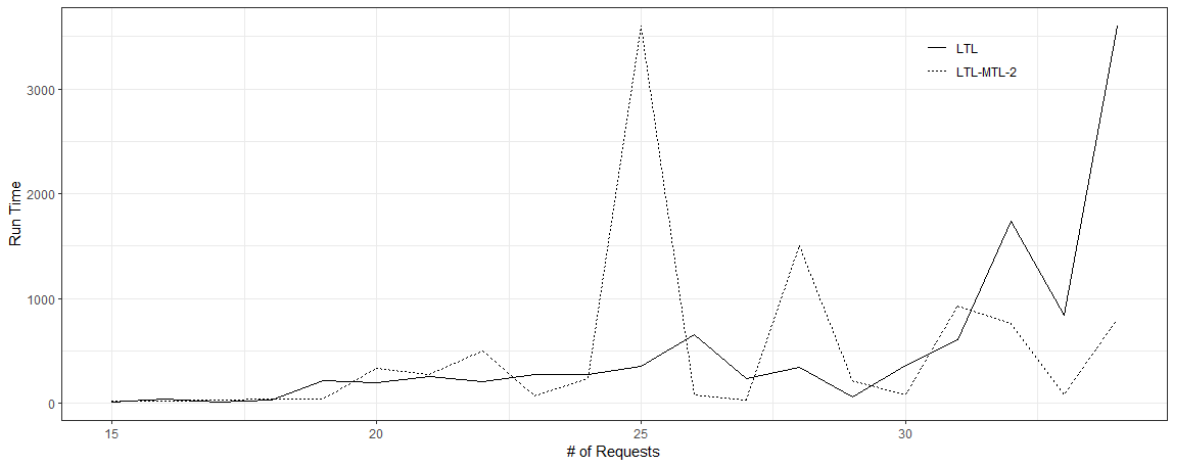


Figure 4.3. Run time comparison of $6H5S4T-LTL$ and $6H5S4T-LTL-MTL-2$.

For the second experimental setting, namely $8H7S$, the node network is changed by increasing the number of hub and spoke nodes. Twenty runs are completed with all

LTL requests. In contrast to earlier examples, another twenty runs are generated by increasing the volume of some requests to MTL, whereas the others are kept the same for this time. The purpose of such comparison is to see the effect of MTL requests on both run time and objective value. In addition to these forty runs, the setting $8H7S5T$ can also be compared with these in terms of run times and objective values, since it is only the expansion of $8H7S$ with five transfer station nodes that cannot be the origin and the destination of a request.

As before, the number of vehicles allowed at any node is kept at the upper bound. The aim is to see the effect of MTL loads and additional transfer station nodes independently. Summary of the results of sixty distinct runs can be seen in Table 4.5. The mean run times for $8H7S-LTL$, $8H7S-LTL-MTL$ and $8H7S5T-LTL$ are equal to 866.95, 917.70 and 1216.03 seconds, respectively.

Furthermore, 96.66% of these sixty runs can be solved optimal within the one-hour maximum time limit. Only the problem instances $8H7S-LTL-MTL-25$ and $8H7S-LTL-MTL-31$ cannot be solved, and their corresponding optimality gaps indicated by (*) are 2.85% and 4.06%. Although the mean run time for $8H7S5T-LTL$ problems are higher than $8H7S-LTL-MTL$ cases, all twenty runs for wide node network are solved optimally.

Table 4.5. Comparison of 8H7S-LTL, 8H7S-LTL-MTL and 8H7S5T-LTL.

# of Nodes	# of Requests	8H7S - LTL		8H7S - LTL - MTL		8H7S5T - LTL	
		Run Time (s)	Objective	Run Time (s)	Objective	Run Time (s)	Objective
15	15	12.12	41394.81	36.35	52991.32	41.40	41394.81
15	16	10.81	41129.01	14.61	54674.25	31.25	40089.55
15	17	388.61	54200.62	952.84	62874.88	917.24	54200.62
15	18	562.41	48353.11	813.37	60891.92	944.23	45869.86
15	19	22.95	39111.35	32.60	46622.34	19.02	39111.35
15	20	76.23	47839.87	1226.36	70643.37	233.81	46907.65
15	21	102.04	52940.16	336.89	64165.43	1067.72	52709.15
15	22	20.46	51793.33	18.28	67477.10	47.56	51793.33
15	23	1357.41	55169.41	1150.31	70411.23	1706.23	55169.41
15	24	66.33	56017.39	88.39	68201.39	179.70	56017.39
15	25	1430.22	61855.43	3600.18*	79355.96*	1402.34	61498.91
15	26	767.97	58994.42	111.68	74841.45	1392.81	58994.42
15	27	1271.37	63350.40	1299.04	76390.66	1709.43	62913.13
15	28	200.23	65165.43	188.88	73494.94	519.43	65165.43
15	29	744.40	73681.22	960.52	85374.94	1164.00	70550.95
15	30	249.36	74572.20	798.19	90470.48	845.31	71039.45
15	31	2252.92	76512.70	3600.26*	88274.22*	2209.65	76512.70
15	32	2698.50	73078.92	268.37	88724.43	3283.66	70748.97
15	33	3275.61	71853.17	619.63	87409.74	3574.89	71853.17
15	34	1829.11	73352.93	2237.28	89290.68	3030.87	69257.48

Figure 4.4 shows that allowing some of the request volumes to have MTL increases the run-time and the objective value for this node network.

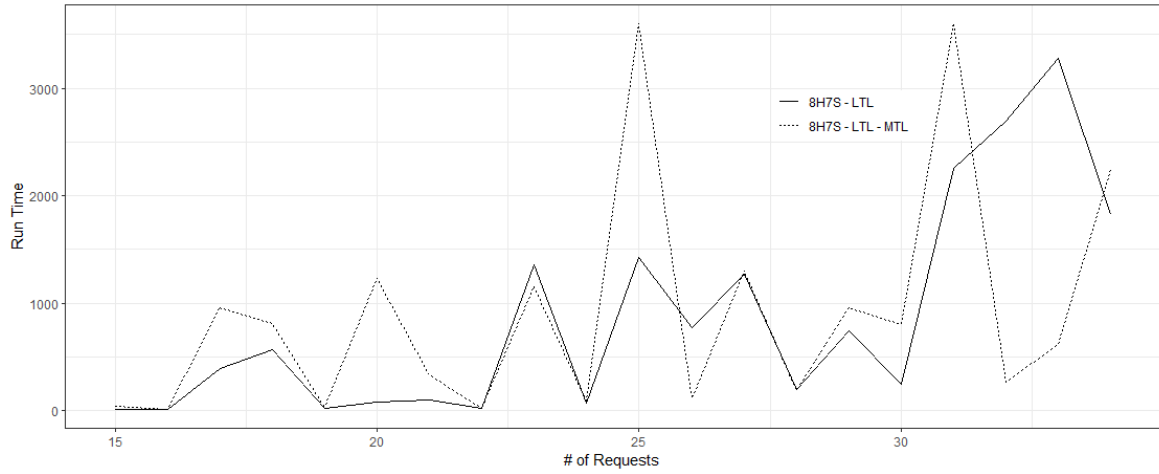


Figure 4.4. Run time comparison of $8H7S-LTL$, $8H7S-LTL-MTL$.

Figure 4.5 and Figure 4.6 show that adding extra five transfer station nodes increases the solution time for every case, however the new network does not generate less expensive transportation plan in some of the cases. Objective values of $8H7S5T-LTL$ problems are always less than or equal to $8H7S-LTL$, as expected. Since the route set of $8H7S-LTL$ is a subset of the route set of $8H7S5T-LTL$ problems, there is no possibility to reach a worse solution in terms of objective function. The proposed model can be used as a tactical decision support system by this methodology.

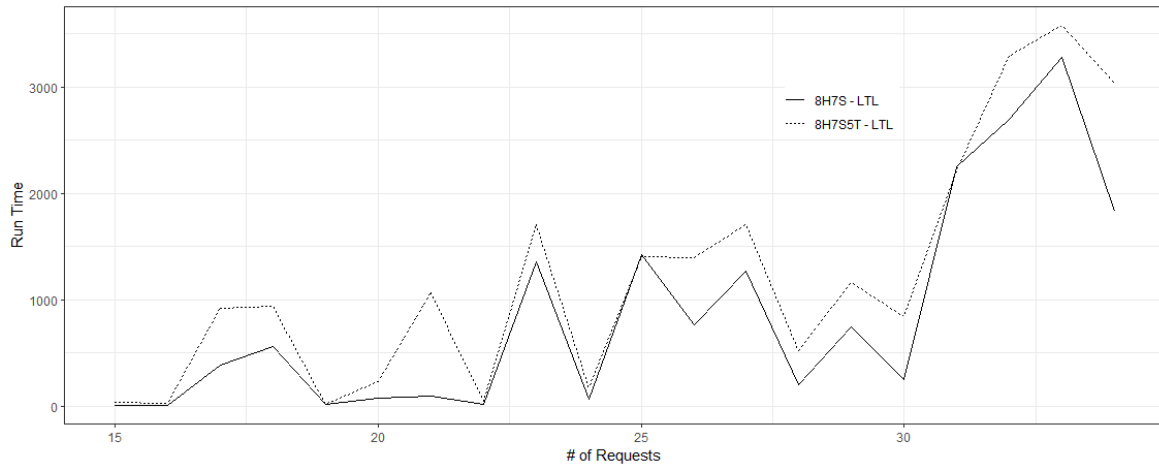


Figure 4.5. Run time comparison of $8H7S-LTL$ and $8H7S5T-LTL$.

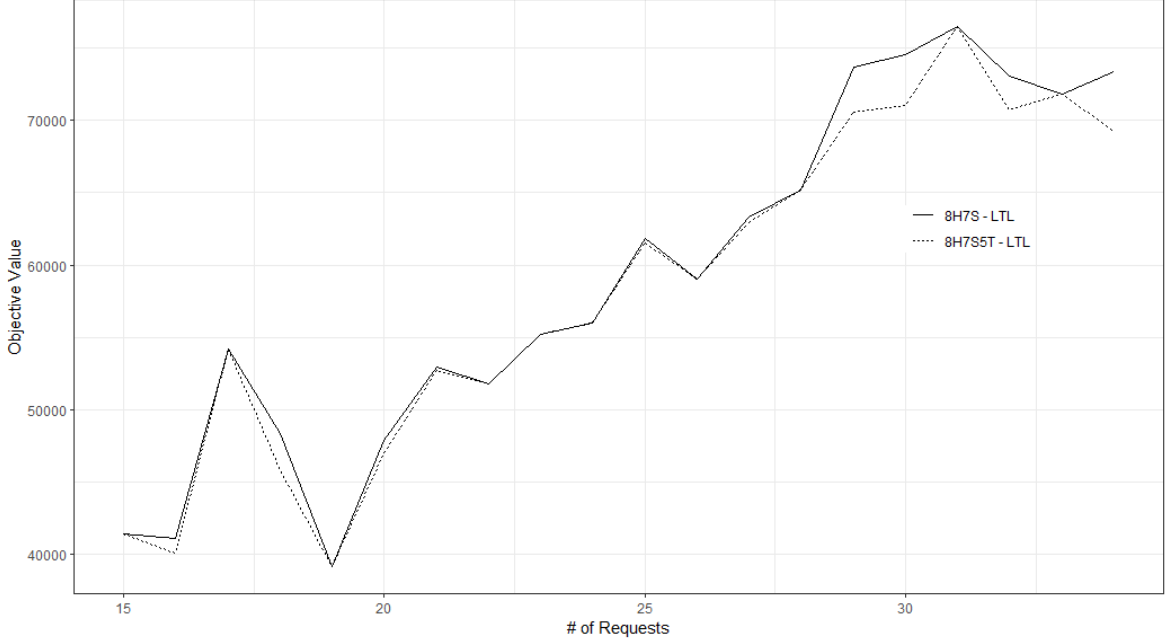


Figure 4.6. Objective value comparison of $8H7S-LTL$ and $8H7S5T-LTL$.

Furthermore, another important interpretation is that there is no distinctly visible relationship between the run times between $8H7S-LTL$, $8H7S-LTL-MTL$ and $8H7S5T-LTL$ cases. Although the mean time increases throughout the order of $8H7S-LTL$, $8H7S-LTL-MTL$ and $8H7S5T-LTL$ experiments, direct correlation or dominance cannot be observed due to interdependency and complexity of the problem definition in the scope of these experimental settings.

4.3.2. Lower Bound Generated by $TSND-T \setminus S$

$6H5S4T - LTL$, $8H7S - LTL$ and $8H7S5T - LTL$ cases are solved using the model $TSND-T \setminus S$ in order to generate a lower bound. The gap between objective values of $TSND-T$ and $TSND-T \setminus S$ is within a range of 1.04% and 33.59%. However, run times for $TSND-T \setminus S$ are significantly lower than $TSND-T$. Table 4.6 shows the comparison between two models where run times are reported in unit of seconds. The maximum run-time for generating a lower bound using $TSND-T \setminus S$ is less than one minute.

Table 4.6. Comparison between the results of $TSNDP-T$ and lower bound obtained by $TSND-T \setminus S$.

# of Requests	6H5S4T - LTL				8H7S - LTL				8H7S5T - LTL			
	Run Time (TSNDP-T)	Run Time (LB)	Gap (%)	Run Time (TSNDP-T)	Run Time (LB)	Gap (%)	Run Time (TSNDP-T)	Run Time (LB)	Run Time (TSNDP-T)	Run Time (LB)	Gap (%)	Run Time (LB)
15	13.39	29.32	1.04	12.12	18.56	6.29	41.40	17.08	10.99	10.99	10.99	10.99
16	37.96	19.08	4.21	10.81	8.64	4.18	31.25	19.48	9.82	9.82	9.82	9.82
17	9.20	8.28	1.58	388.61	23.64	9.28	917.24	28.20	12.29	12.29	12.29	12.29
18	28.23	20.20	6.04	562.41	33.92	7.29	944.23	17.48	10.24	10.24	10.24	10.24
19	212.40	18.92	1.25	22.95	36.68	2.16	19.02	38.80	3.61	3.61	3.61	3.61
20	197.28	16.04	10.27	76.23	10.72	5.30	233.81	15.36	7.06	7.06	7.06	7.06
21	253.39	18.20	5.30	102.04	28.80	3.40	1067.72	15.04	8.35	8.35	8.35	8.35
22	203.26	26.68	8.27	20.46	7.08	11.47	47.56	13.44	13.42	13.42	13.42	13.42
23	273.20	30.76	9.13	1357.41	10.32	14.55	1706.23	9.36	18.50	18.50	18.50	18.50
24	271.95	19.35	9.05	66.33	15.30	10.33	179.70	44.95	16.97	16.97	16.97	16.97
25	346.33	25.85	12.42	1430.22	34.15	12.81	1402.34	7.55	16.76	16.76	16.76	16.76
26	650.02	17.55	16.12	767.97	48.40	19.01	1392.81	20.30	25.84	25.84	25.84	25.84
27	229.93	41.00	14.4	1271.37	10.80	15.89	1709.43	30.60	21.03	21.03	21.03	21.03
28	338.90	46.75	10.85	200.23	34.55	16.87	519.43	44.55	22.32	22.32	22.32	22.32
29	56.52	30.36	14.31	744.40	31.00	14.50	1164.00	65.29	19.08	19.08	19.08	19.08
30	356.02	14.07	18.86	249.36	42.93	19.11	845.31	46.29	20.56	20.56	20.56	20.56
31	601.11	35.29	21.31	2252.92	29.71	20.13	2209.65	44.93	25.71	25.71	25.71	25.71
32	1736.29	67.64	22.79	2698.50	65.50	29.26	3283.66	65.14	33.59	33.59	33.59	33.59
33	840.83	7.57	24.04	3275.61	8.57	27.97	3574.89	13.71	30.86	30.86	30.86	30.86
34	3600.38*	26.29	20.30	1829.11	31.57	24.61	3030.87	32.71	28.25	28.25	28.25	28.25

Note that, the solutions are lack of time, therefore can be infeasible for given day of concern. However, the solutions provide a lower bound for the transportation plan and the infeasibility can be detected by adding slacks to the time-related constraints. Then, the solutions may either be repaired or be used as an initial solution for a heuristic.

4.3.3. The Need for Vehicle Balancing Constraints

The requests originated and destined to a specific node may not be symmetric in terms of imbalance between population and contribution to GDP, as the request pairs are constructed based on these two factors. Such attribute is designed to observe the changes on the number of vehicles at each node throughout the twenty days of inspection since most of the existing logistics companies may face the similar problem in real-life cases. Some nodes are expected to require more vehicles than the number that ends up at the same node at the end of the previous the transportation plan.

When the twenty days are solved consecutively rather than as in dependent periods, i.e., using the vehicles that arrive at node the previous day rather than starting every day with a number of vehicles as given by the upper bound, the changes in the number of vehicles at each node can be observed. As in Table 4.7 and Table 4.8, such situation may cause the transportation plan to be more costly or infeasible due to lack of enough number of vehicles at some nodes. The problem settings *6H5S4T-LTL-MTL-2* and *8H7S5T-LTL* cases are investigated in this context.

For the cases in setting *6H5S4T-LTL-MTL-2*, all hub nodes are initially started with fifteen vehicles, where spoke nodes have six vehicles. The transfer station nodes do not have any vehicles since routes cannot start and end with a transfer station node. Table 4.7 shows the number of vehicles at each node at the beginning of each day.

Twelve successive days are completed with the same level of objective function as in the independent runs, however the cost increased from 88821.68 to 89323.20 at the thirteenth day of operation. As expected, the necessary transportations for

the fourteenth day cannot be done due to lack of enough vehicles to have a feasible operational plan.

Similarly, the experiments carried out under the setting $8H7S5T-LTL$ cannot generate a feasible solution at the ninth day of operation. Table 4.8 shows the distribution of the vehicles throughout the nine day of concern. It can be concluded that vehicle balancing and empty trip management should be considered in order to handle the problem.

Table 4.7. The distribution of vehicles throughout the first investigation period.

Node	Number of Available Trucks at the Beginning of The Operational Period													
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14
1	15	15	13	12	13	12	12	10	11	11	10	13	13	14
2	15	15	16	14	15	15	12	10	7	7	7	6	3	5
3	6	7	9	10	10	11	11	13	16	17	19	20	22	22
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	15	13	13	12	11	11	8	6	6	6	5	4	2	1
7	6	7	8	10	11	12	12	14	13	14	14	15	16	14
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	15	13	12	12	14	12	13	13	14	14	15	16	16	15
10	6	7	8	10	11	12	14	14	14	12	11	10	11	13
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	15	15	13	15	13	13	13	12	9	10	10	8	7	8
13	6	7	8	7	7	7	8	9	10	10	9	9	10	10
14	15	16	15	14	12	13	12	12	13	13	13	13	12	9
15	6	5	5	4	3	2	5	7	7	6	7	6	8	9

Next, the twenty days of operation plan are solved with the vehicle balancing constraints as described in Equations (3.37) - (3.39). There are two cases designed such that, first case assumes precise prediction, in other words π_i values for each node i are exactly equal to the number of vehicles required at a node for obtaining the independent optimal solution. The π_i values are found by solving the days with a number of vehicles equal to the upper bound, representing a prediction mechanism that has a zero percentage of error. The alternative cases have on average 10% and 20% error for π_i values, representing inferior prediction cases. The model obviously works different when the quality of statistical forecasting approaches change.

4.3.3.1. Precise Prediction Case. The first prediction case is constructed based on the scenario that all π_i values can be calculated exactly, where π_i values are exactly equal to the number of vehicles required at a node i . This case can be interpreted as a deterministic environment, whereas number of vehicles are best values for a specific operating day obtained in a greedy manner.

The two cases $6H5S4T-LTL-MTL-2$ and $8H7S5T-LTL$ are solved with the updated objective function (3.37) where λ' is exactly equal to the cost of outsourcing a vehicle in a situation of a deficit. Table 4.9 shows the number of vehicles at each node for $6H5S4T-LTL-MTL-2$, whereas Table 4.10 shows the results for $8H7S5T-LTL$.

Table 4.9. The distribution of vehicles in 6H5S4T-LTL-MTL-2 using the first prediction case.

Number of available trucks at the beginning of the operating days.																				
Node	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18	Day 19	Day 20
1	15	15	13	12	13	12	12	10	11	11	10	13	13	13	12	12	13	14	13	12
2	15	15	16	14	15	15	12	10	7	7	7	6	3	6	6	7	6	6	7	9
3	6	7	9	10	10	11	11	13	16	17	19	20	22	22	22	21	18	19	16	18
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	15	13	13	12	11	11	8	6	6	6	5	4	3	3	3	4	3	5	2	4
7	6	7	8	10	11	12	12	14	13	14	14	15	16	14	14	14	14	14	15	14
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	15	13	12	12	14	12	13	13	14	14	15	16	16	14	14	14	16	14	14	13
10	6	7	8	10	11	12	14	14	14	12	11	10	11	13	13	13	14	13	13	12
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	15	15	13	15	13	13	13	12	9	10	10	8	7	8	7	8	8	8	8	9
13	6	7	8	7	7	7	8	9	10	10	9	9	10	9	9	9	9	9	10	9
14	15	16	15	14	12	13	12	12	13	13	13	13	11	10	12	10	11	10	12	11
15	6	5	5	4	3	2	5	7	7	6	7	6	8	8	7	8	8	8	10	9

The total operating cost of optimizing each day independently may not be the optimal cost for the overall period, since the distribution of vehicles at the end of a day affects the cost of next operating day. Besides, the transportation of the requests may not be feasible for the next day due to lack of vehicles at the desired nodes. Table 4.11 shows the summary for twenty days horizon for $6H5S4T-LTL$ before and after the implementation of the Equations (3.37) - (3.39).

Table 4.11. Objective value comparison of 6H5S4T-LTL-MTL-2 with all conditions.

# of Nodes	# of Requests	Daily Minimum	Without Vehicle Balancing	With Vehicle Balancing	Gap (%)
15	21	67372.97	67372.97	67372.97	0.00
15	19	65927.35	65927.35	65927.35	0.00
15	16	64424.15	64424.15	64424.15	0.00
15	34	96006.22	96006.22	96006.22	0.00
15	31	76073.76	76073.76	76073.76	0.00
15	18	62658.62	62658.62	62658.62	0.00
15	17	58391.62	58391.62	58391.62	0.00
15	22	63025.19	63025.19	63025.19	0.00
15	27	80378.42	80378.42	80378.42	0.00
15	23	73058.92	73058.92	73058.92	0.00
15	28	83241.15	83241.15	83241.15	0.00
15	20	58071.63	58071.63	58071.63	0.00
15	32	88821.68	89323.2	90142.52	1.49
15	24	77639.38	Infeasible	79125.69	1.91
15	25	73900.4	—	74356.84	0.62
15	30	75424.87	—	75424.87	0.00
15	29	75265.18	—	75265.18	0.00
15	26	90478.17	—	90478.17	0.00
15	33	79563.43	—	92124.35	15.79
15	15	60172.31	—	60172.31	0.00

The main observation obtained these experiments is that adding Equations (3.37) - (3.39) to the model eliminates the infeasibility from the system while increasing the operational cost within a range 0.00% to 15.79% with a standard deviation of 3.43. The total cost of new model strategy is 1,485,719, whereas the summation of individually optimized days was 1,469,895 for the twenty days horizon. The total gap is calculated as 1.08%. However, it should be noted that this does not lead to a feasible solution for this case after fourteenth day of operation.

In a similar manner, $8H7S5T-LTL$ is solved with vehicle balancing constraints in order to remove infeasibility from the horizon. Table 4.12 presents the results for twenty days of operation for $8H7S5T-LTL$ before and after adding Equations (3.37) - (3.39) to the model. Implementing Equations (3.37) - (3.39) again removes the infeasibility from the model with an increasing total cost changing from 0.00% to 10.33% with a standard deviation of 3.16. The total operational cost of new model setting is 1,208,818 while the total cost of independent runs was 1,180,365. The total gap between these two strategies is calculated as 2.41%, which is usually an increment that is within the tolerance limits for most of the companies. It is important to remember the model without vehicle balancing constraints is not able to generate feasible solutions after ninth day of operation for $8H7S5T-LTL$.

Table 4.12. Objective value comparison of *8H7S5T-LTL* with all conditions.

# of Nodes	# of Requests	Daily Minimum	Without Vehicle Balancing	With Vehicle Balancing	Gap (%)
20	21	52940.16	52940.16	52940.16	0.00
20	19	39111.35	39111.35	39111.35	0.00
20	16	41129.01	41129.01	41129.01	0.00
20	34	73352.93	73352.93	73352.93	0.00
20	31	76512.70	76512.70	76512.70	0.00
20	18	48353.11	48353.11	50214.36	3.85
20	17	54200.62	54200.62	56231.23	3.75
20	22	51793.33	51793.33	57142.36	10.33
20	27	63350.40	Infeasible	66457.23	4.90
20	23	55169.41	—	56478.32	2.37
20	28	65165.43	—	67896.78	4.19
20	20	47839.87	—	48021.03	0.38
20	32	73078.92	—	73078.92	0.00
20	24	56017.39	—	57846.32	3.26
20	25	61855.43	—	61855.43	0.00
20	30	74572.20	—	82356.66	10.44
20	29	73681.22	—	74235.63	0.75
20	26	58994.42	—	58994.42	0.00
20	33	71853.17	—	73568.88	2.39
20	15	41394.81	—	41394.81	0.00

4.3.3.2. Inferior Prediction Cases. The second prediction alternative is based on the scenario that π_i values can be predicted with an average error of 10%, where π_i values can be lower or higher than the exact number of vehicles required at a particular node i . Second case can be seen as a stochastic environment, where the actual number of required vehicles can vary from the forecasts for an operating day. This error may occur due to a poor prediction mechanism based on past data such where the seasonal fluctuations or trends cannot be properly. The proposed model is tested under this prediction mechanism in order to see the changes in the distribution of the vehicles throughout the node network and in the values of objective functions of the days.

Two experimental settings $6H5S4T-LTL-MTL-2$ and $8H7S5T-LTL$ are again solved with the updated objective function (3.37) where λ' is the cost of outsourcing a vehicle. Table 4.13 summarizes the number of vehicles at each node for the setting $6H5S4T-LTL-MTL-2$. Similarly, Table 4.14 presents the distribution of the vehicles for the case $8H7S5T-LTL$.

Table 4.13. The distribution of vehicles in *6H5S4T-LTL-MTL-2* using the second prediction strategy.

Node	Number of available trucks at the beginning of the operating days																			
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18	Day 19	Day 20
1	15	15	13	12	13	12	12	10	11	11	10	13	13	13	13	12	13	14	13	12
2	15	15	16	14	15	15	12	10	7	7	7	6	2	6	6	7	6	6	7	9
3	6	7	9	10	10	11	11	13	16	17	19	20	23	23	22	21	18	19	16	18
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	15	13	13	12	11	11	8	6	6	6	5	4	4	2	3	4	4	5	3	4
7	6	7	8	10	11	12	12	14	13	14	14	15	15	14	14	14	15	14	16	14
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	15	13	12	12	14	12	13	13	14	14	15	16	16	15	14	14	16	14	13	13
10	6	7	8	10	11	12	14	14	14	12	11	10	11	12	13	13	13	13	13	12
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	15	15	13	15	13	13	13	12	9	10	10	8	7	8	7	8	8	8	7	9
13	6	7	8	7	7	7	8	9	10	10	9	9	10	9	9	9	8	9	10	9
14	15	16	15	14	12	13	12	12	13	13	13	13	11	10	12	10	11	10	12	11
15	6	5	5	4	3	2	5	7	7	6	7	6	8	8	7	8	8	8	10	9

The proposed model is expected to satisfy the demand with a higher cost of operations since the prediction mechanism is on average 10% worse than the first case. As the first observation, adding Equations (3.37) - (3.39) to the model still removes the infeasibility from the system. However, the operational cost of transportation plan now varies between 0.00% - 22.97% with a standard deviation of 5.19. The total cost of twenty days under the second prediction strategy is as 1,501,039 for *6H5S4T-LTL-MTL-2*. The percentage of the difference between the total costs of independent runs and the new strategy under poor prediction 2.12%. Table 4.15 presents of the results of the experiments and the comparisons.

In a similar manner, the experiments are carried out for case *8H7S5T-LTL* under poor prediction. The percentage of difference ranges from 0.00% to 14.37% with a standard deviation equal to 4.42. For this setting, total cost is increased from 1,180,365 to 1,223,743, i.e., 3.67% increase between the independent runs and the model that includes vehicle balancing equations. The summary for the case experiments can be found in Table 4.16.

Table 4.15. Objective value comparison of *6H5S4T-LTL* with all conditions using second prediction strategy.

# of Nodes	# of Requests	Daily Minimum	Without Vehicle Balancing	With Vehicle Balancing	Gap (%)
15	21	67372.97	67372.97	67372.97	0.00
15	19	65927.35	65927.35	65927.35	0.00
15	16	64424.15	64424.15	64424.15	0.00
15	34	96006.22	96006.22	96006.22	0.00
15	31	76073.76	76073.76	76073.76	0.00
15	18	62658.62	62658.62	62658.62	0.00
15	17	58391.62	58391.62	58391.62	0.00
15	22	63025.19	63025.19	63025.19	0.00
15	27	80378.42	80378.42	80378.42	0.00
15	23	73058.92	73058.92	73058.92	0.00
15	28	83241.15	83241.15	83241.15	0.00
15	20	58071.63	58071.63	58071.63	0.00
15	32	88821.68	89323.20	93444.12	5.20
15	24	77639.38	Infeasible	83226.79	7.20
15	25	73900.40	—	74356.84	0.62
15	30	75424.87	—	75424.87	0.00
15	29	75265.18	—	77464.45	2.92
15	26	90478.17	—	90478.17	0.00
15	33	79563.43	—	97842.23	22.97
15	15	60172.31	—	60172.31	0.00

Table 4.16. Objective value comparison of *8H7S5T-LTL* with all conditions using second prediction strategy.

# of Nodes	# of Requests	Daily Minimum	Without Vehicle Balancing	With Vehicle Balancing	Gap (%)
20	21	52940.16	52940.16	52940.16	0.00
20	19	39111.35	39111.35	39111.35	0.00
20	16	41129.01	41129.01	41129.01	0.00
20	34	73352.93	73352.93	73352.93	0.00
20	31	76512.70	76512.70	76512.70	0.00
20	18	48353.11	48353.11	51212.11	5.91
20	17	54200.62	54200.62	58765.34	8.42
20	22	51793.33	51793.33	58884.40	13.69
20	27	63350.40	Infeasible	66457.23	4.90
20	23	55169.41	—	57723.56	4.63
20	28	65165.43	—	67896.78	4.19
20	20	47839.87	—	51283.23	7.20
20	32	73078.92	—	73078.92	0.00
20	24	56017.39	—	59123.22	5.54
20	25	61855.43	—	61855.43	0.00
20	30	74572.20	—	85290.04	14.37
20	29	73681.22	—	74235.63	0.75
20	26	58994.42	—	58994.42	0.00
20	33	71853.17	—	74502.05	3.69
20	15	41394.81	—	41394.81	0.00

In order to assess the effect of prediction errors, we test increasing the average error in predicting π_i values to 20%, i.e., π_i values are randomly selected to be 20% lower or higher than the required number of vehicles at each node i . When the proposed model is tested under the inferior prediction information over the twenty days horizon, adding Equations 3.37 - 3.39 to the model allows the transportation plan to be feasible for the horizon as in the previous prediction cases. On the other hand, the operational cost of daily transportation plan increases between 0.00% - 22.97% with a standard deviation of 5.36. The total cost of twenty days under the third prediction strategy is as 1,514,493 for *6H5S4T-LTL-MTL-2*, which is amounts to 3.03% increase from the total cost of independent runs. Table 4.17 shows of the results of the experiments and the comparisons for the third prediction alternative. Similarly, the experiments are carried out for case *8H7S5T-LTL* with third prediction strategy. The percentage of difference varies between 0.00% to 18.33% with a standard deviation of 5.53. Total cost of twenty days is increased to 1,240,604 (5.10% increase) by adding vehicle balancing constraints. The summary of the results of third prediction strategy can be found in Table 4.18. Note that, the increase in cost observed when prediction quality worsens from 10% average error to 20% does not look non-linear.

Table 4.17. Objective value comparison of *8H7S5T-LTL* with all conditions using third prediction strategy.

# of Nodes	# of Requests	Daily Minimum	Without Vehicle Balancing	With Vehicle Balancing	Gap (%)
15	21	67372.97	67372.97	67372.97	0.00
15	19	65927.35	65927.35	65927.35	0.00
15	16	64424.15	64424.15	64424.15	0.00
15	34	96006.22	96006.22	96006.22	0.00
15	31	76073.76	76073.76	76073.76	0.00
15	18	62658.62	62658.62	62658.62	0.00
15	17	58391.62	58391.62	58391.62	0.00
15	22	63025.19	63025.19	63025.19	0.00
15	27	80378.42	80378.42	80378.42	0.00
15	23	73058.92	73058.92	73058.92	0.00
15	28	83241.15	83241.15	83241.15	0.00
15	20	58071.63	58071.63	62121.65	6.97
15	32	88821.68	89323.2	93444.12	5.20
15	24	77639.38	Infeasible	85232.26	9.78
15	25	73900.4	—	77148.12	4.39
15	30	75424.87	—	75424.87	0.00
15	29	75265.18	—	77464.45	2.92
15	26	90478.17	—	93132.44	2.93
15	33	79563.43	—	97842.23	22.97
15	15	60172.31	—	62124.66	3.24

Table 4.18. Objective value comparison of *8H7S5T-LTL* with all conditions using third prediction strategy.

# of Nodes	# of Requests	Daily Minimum	Without Vehicle Balancing	With Vehicle Balancing	Gap (%)
20	21	52940.16	52940.16	52940.16	0.00
20	19	39111.35	39111.35	39111.35	0.00
20	16	41129.01	41129.01	41129.01	0.00
20	34	73352.93	73352.93	73352.93	0.00
20	31	76512.70	76512.70	77523.80	1.32
20	18	48353.11	48353.11	51212.11	5.91
20	17	54200.62	54200.62	58765.34	8.42
20	22	51793.33	51793.33	61284.78	18.33
20	27	63350.40	Infeasible	68433.62	8.02
20	23	55169.41	—	58623.53	6.26
20	28	65165.43	—	67896.78	4.19
20	20	47839.87	—	52453.98	9.64
20	32	73078.92	—	73078.92	0.00
20	24	56017.39	—	60123.23	7.33
20	25	61855.43	—	61855.43	0.00
20	30	74572.20	—	88125.64	18.17
20	29	73681.22	—	76232.55	3.46
20	26	58994.42	—	58994.42	0.00
20	33	71853.17	—	77343.88	7.64
20	15	41394.81	—	42123.46	1.76

An important remark is that the percentages of difference highly depend on the parameter values, such as the starting condition of the number of vehicles at the nodes, the cost parameter λ' which represents the outsourcing cost of a vehicle, and its proportion to the route costs. Another experimental setting with different parameter combinations may end up with completely different results such as infeasibility after an arbitrary day or significantly distinct percentages of differences.

Furthermore, infeasibility due to the lack of required number of vehicles at the nodes can be removed by adding vehicle balancing constraints, while the solution time does not increase at all.

4.3.4. Real-Life Application

The proposed models are solved using data obtained from a large Turkish LTL motor carrier company, namely *Ekol Logistics*. The instance has nineteen nodes that cover most of the provinces of Turkey, however the longest duration between any pair of nodes is less than twenty-four hours, therefore the proposed model can be run for a period of one day. The data provided by the company corresponds to the set of requests that have to be transported from the origin nodes to the destination nodes, while obeying the government rules on driving, not exceeding the due dates of all distribution centers located in the nodes and the capacities associated with the vehicles that are both owned and outsourced. The company works every day of the week, but the data provided for test case only covers for twenty consecutive days as in the hypothetical examples in the previous sections. Hence, the data reflects the actual operational choices including the route pool and the characteristics of operational logic.

The route pool that is currently used by the company are fixed according to the requirement and consists of only a few elements so that the problem can be solved to optimality in a very short time. The routes operated by the company are fixed with respect to requirements of past data. *Ekol Logistics* serves the transportation of the orders of *Amazon.com.tr* which does not provide services to many cities throughout Turkey.

Therefore, the proposed model also can be used for another aspect of SND problems, as a tactical decision support system. The company can consider adding new route alternatives constructed based on new node combinations. Using past data for comparisons between existing route pool and the newly added combinations can be interpreted in order to evaluate the effect of new route alternatives. Furthermore, opening new transfer stations on other locations currently not serving may be geographically advantageous when considering the highway network of Turkey. Adding new routes or nodes to the network may both reduce the operational cost by simply decreasing the kilometers that should be covered for delivering the goods, and also implicitly allow company to operate with a smaller number of trucks.

The provided data for the company is solved with both existing route pool (26 routes) and an extension with some route alternatives (i.e., 63 routes) generated with the logic described in Section 3.2. The transportation network of the company currently consists of nineteen nodes. The number of aggregated requests and vehicles vary between 18 and 40. It can also be noted that the volumes of the requests for these cases consists of both LTL and MTL aggregated demand. Run times are between 8 and 172 seconds for 18 different test cases which is far lower than the one-hour time limit.

Lastly, it is mostly not applicable for the real-life companies to run these models under certain software environment. Therefore, a simple user interface in Microsoft Excel is designed for the employees of the company to run MIP model without directly dealing with the commercial solver. Furthermore, since the results of a MIP model is usually challenging to be interpreted directly, a reporter program is coded to convert the levels of variables into simple tables by a post-processing algorithm. To sum up, the company can solve the operational level daily transportation problem and also can test the new node and route network alternatives, different loading, unloading and transshipment methods and their corresponding durations by using the model as a decision support model to interpret related tactical decisions in the long run.

5. CONCLUSIONS AND FUTURE RESEARCH

In this thesis, the challenges imposed by complex requirements of customer satisfaction and regulatory policies of governments to the middle-mile freight transportation industry are aimed in order to propose a successful and profitable transportation plan for service network design problems.

The proposed model *TSNDP-T* uses variable transshipment times at the intermediate nodes, which requires synchronization and scheduling of the vehicles at all of the transfer stations. To cope with synchronization, most of the models in the literature continuously model time or partial time-expanded networks. However, proposed model can handle synchronization of the vehicles with few decision variables and constraints in an innovative manner. The model determines the flow on the arcs while scheduling and synchronizing the vehicles on their routes.

Nonetheless, the strength of *TSNDP-T* comes from the unique pre-processing strategy for creating the sets of the mathematical model. Driving regulations regarding the durations of the routes, the availability of the vehicles at the nodes, personal requirements of the drivers during the planning period such as the frequency of returning their base nodes, and even the rental strategy of a logistics company can be implemented by pre-processing. The mathematical model itself is kept as same for implementing the aforementioned changes and more due to this innovative pre-processing strategy.

Furthermore, the model can be solved within a reasonable amount of time in medium-size problem instances. Several physical transportation environments are created for testing the model, as well as a real-life application of logistics activities of an existing trucking company in Turkey. The model results also show the exact entrance and exit times of the vehicles at the intermediate nodes throughout their routes. However, as the problem size gets larger in terms of the size of node network and the number of vehicles and aggregated requests from the origin to the destination nodes, it becomes

more difficult to obtain optimal solutions in a reasonable amount of time. Last but not least, matheuristic for generating a transportation plan for multiple periods does not guarantee the global minimum cost of operations for a given planning horizon. As the network size increases, the imbalance of vehicles between nodes is increasing and the gap between the possible minimum cost of transportation and the generated solution increases.

As a further research interest, the models can consider the distribution of workload among the drivers. Most of the models only focus on implementing constraints for regulatory government policies on the maximum continuous driving hours of the drivers. However, crew assignment to the vehicles may include the equal or fair distribution of the workload. Pre-processing strategy of this thesis is also capable of inserting such criteria to the route pool generation, by eliminating relatively long-distance routes from the drivers that have been chosen for long tasks in the previous periods without implementing any other constraints or variables directly to the mathematical model. It is hoped that this work will stimulate further investigation in implementing fair workload distribution algorithms that can be inserted in the pre-processing algorithms.

Moreover, Bauer *et al.* (2010) propose a study focusing on minimizing the greenhouse gas emission in service network design, which is another aspect of current trucking industry. Most of the studies in the literature and also this thesis does not mention about the effects of fuel consumption of the vehicles to the environment. The objective functions of the model could consider minimization of total operating cost while reducing the greenhouse gas emission to the air. Such multi-objective criteria may be used as a future research topic for changing the perspective of routing and trucking network design problems. Bektaş and Laporte (2011) show an extension of the classic vehicle routing problem by considering pollution, and define the problem as pollution-routing-problem (PRP).

Finally, there has been no research that handles both stochastic demand and corresponding scenario analysis, driver regulations, route selection, and possible transshipments between vehicles at the same time. Stochastic optimization of middle-mile

and long-distance freight transportation problems is novel relative to work in the vast majority of applications of various domains. In addition, pickers for loading and unloading of the requests at the intermediate nodes is not considered within the scope of this thesis. A further extension may be the management strategies with respect to generated transportation plans and can be used for better or optimal scheduling of existing resources.

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