A Discrete-Continuous Optimization Approach for the Design and Operation of Synchromodal Transportation Networks

by

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This is to certify that I have examined this copy of a Ph.D. thesis by

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and have found that it is complete and satisfactory in all respects,
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ABSTRACT

Modern supply chain systems have become mostly integrated and complex due to the constant pressure to improve their efficiency thresholds. In Europe, some of the important challenges including traffic congestion, carbon emission rates, intermodal transportation integration, the need for new infrastructure developments and maintenance of existing infrastructures as well as ensuring quality, reliability and efficiency of transportation and mobility services have always been a concern for the transportation systems. These challenges are emerging as an urgent issue and there are many visions and solution methodologies addressed by different stakeholders in the transportation domain. The main objective of this thesis is the elaboration, testing and validation of new models for the analysis, design, evaluation, and management of complex sustainable transportation activities. This thesis presents the multi-objective mixed-integer programming problem for integrating specific characteristics of synchromodal transportation (such as real-time planning and bundling of shipments). The problem includes different objective functions including the total transportation cost, travel time and CO_2 emissions of proposed networks while optimizing the network structure. The traffic congestion, time-dependent vehicle speeds and vehicle filling ratios are considered in an integrated manner and computational results for different illustrative cases are presented with real data from the Marmara Region of Turkey. The defined non-linear model is converted into linear form and solved by using a customized implementation of the ϵ-constraint method for the multi-objective mixed-integer linear programming problem. Then, the analysis of Pareto solutions and sensitivity analysis of proposed mathematical models with different pre-processing constraints are summarized for decisions makers. It is shown that the synchromodal transportation model presented in this thesis study is very affective in determining transportation network structures and optimized planning and operation of these networks.

ÖZET

Modern tedarik zinciri sistemleri verimlilik seviyelerinin geliştirilmesi amacıyla meydana gelen yoğun talep ve baskılardan ötürü daha kompleks ve bütünleşik bir forma dönüşmüşlerdir. Avrupa bölgesinde trafik yoğunlukları, karbon emisyon salınımları, çok modlu taşımacılık sistemlerinin entegre edilmesi, yeni altyapı ve üstyapı ihtiyaçları ve bunların bakım süreçleri gibi taşımacılık sistemleri açısından önemli olacak bazı konuların özellikle taşımacılık sistemlerinin güvenilirliğini, kalitesini, sürdürülebilirliğini ve verimliliğini artıracak şekilde ele alınması önemli sorunların başında gelmektedir ve bu bağlamda taşımacılık alanında birçok farklı paydaş grup tarafından yeni vizyon ve çözüm yöntemleri tanımlanmıştır. Bu tez çalışmasının ana amaçlarından bir tanesi de kompleks sürdürülebilir taşımacılık sistemlerinin analizlerinin, değerlendirmelerinin, ve yönetimlerinin yapılabilmesi için geliştirilmiş olan yeni modellerin detaylandırılması, test edilmesi ve doğrulamalarının yapılmasıdır. Tez kapsamında synchromodal taşımacılık sistemlerinin farklı karakteristiklerini (örneğin gerçek zamanlı planlama, kargoların konsolidasyonu gibi) kapsayan çok amaçlı karışık tam sayılı doğrusal programlama modeli sunulmuştur. Problem öngörülen ağ yapısını optimize ederken, toplam taşımacılık maliyeti, zamanı ve karbon emisyon salınım değerleri gibi hedef fonksiyonları da kapsamaktadır. Zamana bağlı araç hızları, trafik yoğunluğu, araç doluluk oranları gibi önemli konular probleme entegre edilmiş ve Marmara Bölgesi için oluşturulmuş örneklemler üzerinde gerçek datalar kullanılarak gösterilmiştir. Doğrusal olmayan model doğrusal bir formata dönüştürüldükten sonra, ϵ-kısıt methodu kullanılarak çok amaçlı karışık tam sayılı doğrusal problem çözülmüştür. Elde edilen çözüm setleri ve önerilen modellerin duyarlılık analizleri karar vericiler için özetlenmiştir. Elde edilen çözümler ve analizler doğrultusunda synchromodal taşımacılık sistemlerinin ağ yapılarının tasarımında ve operasyonel planlama ve yönetimler açısından oldukça etkili olduğu gösterilmiştir.

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Chapter 1

INTRODUCTION

After the 1960s, logistics operations have been playing more important roles for extensive and complex supply chain networks because of globalization. Increasing competition in the sectors, growing customer demands, inefficiency in transportation systems, partially loaded vehicles, high usage of road transportation in operations, and low utilization of transportation infrastructure lead companies to search for new trends to make optimal usage of transportation modes and also increase the awareness in security, social and environmental issues (e.g., carbon emission, carbon footprint). Moreover, the role of the logistics sector in the regional development is also well recognized by the governmental bodies and integrated into the policy making processes. The position and the importance of logistics sector are expressed particularly in most of the popular reports throughout the world such as, White Paper in 2011 on European Transport (COM, 2011). According to these attempts of both private and governmental players, the countries try to transform their logistics processes into a sustainable and competitive system that will further improve mobility activities and continue to support economic growth and employment. The logistics sector has a positive impact over economic growth and development of the countries since it is mostly integrated into industry and service sectors. The study of Stank et al. (2005) indicated that logistics activities should be synthesized with the supply chain and the integration should be considered with the well-established design of the performance systems between strategy, structure and processes (Rodrigues et al., 2004). In order to handle the challenges facing the logistics sector within the world and achieve a smart, sustainable and inclusive economy as outlined in strategy documents, the conventional thinking must be replaced by new ideas, pioneering strategies, and entrepreneurship.

Apart from the economical perspective, there is a serious environmental and social concern of transportation systems. Since the last decade, the total number of global passenger and freight movements has increased by an average of 4%, with global energy usage up by 30% (nearly two billion tons of CO_2 equivalent) (Stern, 2008). However, the most significant part of the carbon dioxide emissions are associated with vehicle movements within the metropolitan areas (such as almost 20% of total U.S CO_2 emissions), so changing patterns of urban development and transportation play an important role over the environmental and social development (EIA, 2009).

Therefore, there are some innovative activities or radical changes in the logistics philosophy to reduce the effect of the transportation activities over the environmental and economic developments. These activities help companies to reduce their operational costs by integrated and more efficient supply chain management, but also by enhancing innovation activities, sometimes through collaboration on product or network design issues. Fostering the development and adoption of advanced technologies, consequently contributing to future sustainable and competitive dynamic transport systems, also they encourage and improve the cooperation on transport-related services by focusing on transport concepts (especially intermodal transportation) to address common transport-related issues (such as economic growth compatible with sustainability, environment, safety, quality assurance, regulation and legislation). Mentzer and Konrad (1991) defined some logistics performance indicators to perform the logistics activities more effectively and efficiently. Also, Schoenherr (2009), Flien et al. (2005), and Gammelgaard and Larson (2001) provide extended and well-structured review of the key parameters in global context for the logistics industry. The given concepts in these studies are the good starting point to explore and identify the logistics sectors. The concept of intermodal transportation has been started to discuss and recognized worldwide as a promising way to efficiently reduce logistics costs. Although there are some successive implementations of intermodal transportation in the world, intermodal transportation has inadequate position for current supply chains. Therefore, new concept, synchromodal transportation, has appeared to monitor the whole chain and make the supply chains more visible. Supply chain management and responsiveness require serious synchronization of the supply and demand and the concept of synchromodal transportation is the key driver for focusing on improving visibility in such complex transportation and logistics networks. The design and operation of intermodal transportation and synchromodal transportation systems which is the more dynamic and complex version of the intermodal transportation are the main purpose of this thesis.

This study consists of six chapters. After this introduction section, Chapter 2 indicates a general overview of the sustainability concept in the transportation operations which is mostly regarding how to convert the traditional transportation operations into sustainable transportation system by showing the state-of-art regarding sustainable transportation performance indexes. Also, the definition of the sustainable transportation and major performance indexes are given to be used in the decision making processes. Recent theoretical developments and studies using such performance indexes are investigated and used to provide the conceptual basis of the sustainability in transportation activities. Also, sample of mixed integer linear programming model is shared to be used in solving the multi-objective sustainable transportation problems via different solution methodologies. In Chapter 3, a multi-objective optimization model for integrating different transportation modes in the design and operation of an intermodal transportation network in a geographical region is presented and the problem is formulated as a mixed-integer optimization problem that accounts for time and congestion dependent vehicle speeds and solved by using the augmented ϵ–constraint method. Also the modeling approach, data analysis and outline of the important characteristics of the mathematical programming problem for minimization of the transportation cost and time simultaneously are given. The proposed approach is illustrated on a real world case using data from the Marmara Region. Chapter 4 indicates the study analyzing the intermodal transportation network in European level and proposing bi-objective mixed-integer linear mathematical model considering cost and carbon emission rates objectives. Also, this chapter gives faster and more sustainable Pareto solutions for decision makers by using new developed solution methodology for bi-objective mixed-integer linear problems in the real-life cases. Pareto solutions of this new algorithm are compared with the ones obtained from the augmented ϵ-constraint method and shared with the decision makers. Chapter 5 presents the multi-objective mixed-integer programming problem for integrating specific characteristics of synchromodal transportation. The problem includes different objective functions including total transportation cost, travel time and CO_2 emissions while optimizing the proposed network structure. Traffic congestion, time-dependent vehicle speeds and vehicle filling ratios are considered and computational results for different illustrative cases are presented with real data from the Marmara Region of Turkey. The defined non-linear model is converted into linear form and solved by using customized implementation of the ϵ-constraint method. Then, the sensitivity analysis of proposed mathematical models with pre-processing constraints is summarized for decisions makers. Then, Chapter 6 summarizes conclusions of this PhD thesis and discusses future research directions.

Chapter 2

TRANSPORT AND LOGISTICS MODELS FOR SUSTAINABILITY

2.1 Introduction

Global concerns about climate change, energy usage, environmental impacts, and limits to financial resources for transportation infrastructure require new and different approaches for planning, designing, constructing, operating, and maintaining transportation solutions and systems. The importance of the sustainability is realized by the decision makers as one of the most essential parameter in transportation planning processes recently. In the literature, there is a widely used definition of sustainability that was introduced by the United Nations in 1987, “sustainability meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). Although, many definitions of sustainability in various disciplines were developed, there is not a clear and basic description concerning the sustainability in transportation operations. The center for sustainable transport (CST, 1998) introduced an approach for sustainable transportation systems which”

- *allow the basic access needs of individuals and societies to be met safely and in a manner consistent with human and ecosystem health, and with equity within and between generations;*
- *are affordable, operate efficiently, offer choice of transport mode, and support a vibrant economy;*
- *limit emissions and waste within the planet’s ability to absorb them, minimize consumption of non-renewable resources to the sustainable yield level, reuse and recycle its components, and minimize the use of land and the production of noise.”*

Turkay (2008) examined the environmentally conscious supply chain systems and indicated that transportation based approaches that should be considered as sustainable transportation are major focal points to include the sustainability considerations in supply chain management. He proposed that development of multi-modal transportation systems will play an important role in reducing the impact of the environment, especially in the emission issues. The implementation of this approach into the transportation processes cannot be achieved easily; the establishment of a sustainable transportation system requires well-defined framework to attract all stakeholders from private sector, public authorities, research and education. Jeon and Amekudzi (2005) stated this framework as in the Figure 1.

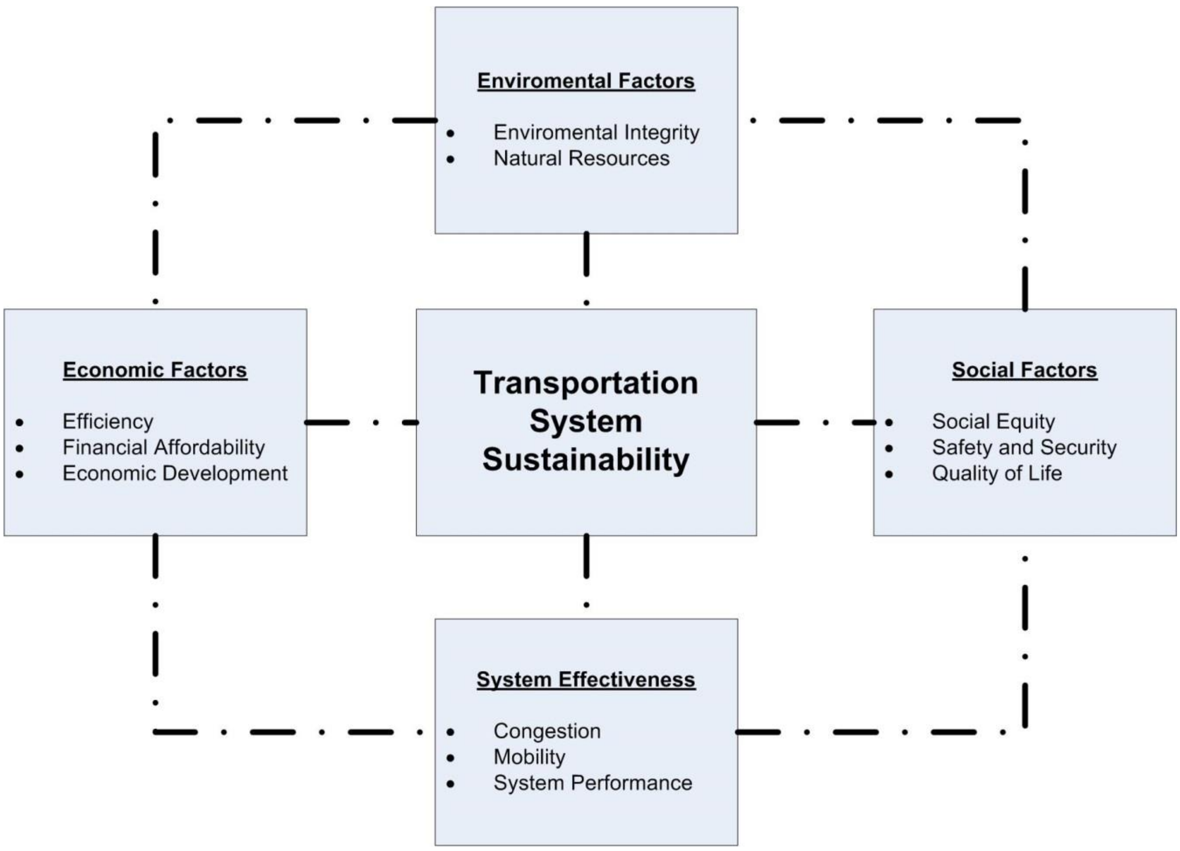

Figure 1: Four essential factors of transportation system sustainability

One of the major difficulties in analyzing sustainability is the conflict between these four essential factors since each of them impose some restrictions over the others which mean that if transportation system is improved by focusing on one of these factors, this attempt will deteriorate the other three factors. Therefore, the sustainability should not be considered as one of these factors and there should be new approach which integrates or strengthens all of these factors to develop more complex transportation decision mechanisms. On the other hand, Low and Gleeson (2003) introduced the “paradox of sustainability”. In their study, they mentioned about the nested box model which indicates that some serious shifts can take place in some of these sustainability factors. In other words, they explained that environmental factors will be the leading parameters in the decision mechanism and especially social and economic conditions will be integrated with each other and this combined system will be captured by the environmental parameters in the long term. Although the goals of the one factor are often consistent with the others, Low and Gleeson (2003) argue that environmental sustainability should have a priority but not be conditionally upon the economic or social sustainability. Additionally, there are many studies upon the conceptualization of the sustainability in the literature (e.g. Haughton, 1999; McGranahan and Satterthwaite, 2000, and Nichols et al., 2008). All of these studies can help the decision maker and stakeholders in the transportation sector to sustain some measurements.

In addition to the factors, there are some main drivers for the stakeholders of the transportation sector to use and integrate these sustainability concepts into their operations and decision mechanisms. A good example is the energy sector that accounts for 29 percent of the total US energy consumption (EIA, 2009). Also, there is an increasing trend in the environmental issues especially on the green concepts. Therefore, the stakeholders in this sector face with a very strict regulations and social awareness in greenhouse gas emissions and energy usage. Additionally, due to the lack of fuel sources, fuel prices are always increasing and this trend leads the sector to be more efficient. Also, safety is another important factor for the sector. Including passenger and product safety for transportation sector, and worker safety involved in manufacturing and operational activities are the one of major triggering topics in the sector.

By considering all of these drivers and factors for transportation sustainability, the stakeholders can easily integrate these concepts into their short and long term plans and also transportation activities by defining some performance indexes. Transportation performance indexes predict, evaluate, and monitor how much percentage of the adopted objectives of the stakeholders is accomplished by the transportation system. However, such performance indexes should be determined according to the factors given in Figure 1 and also assess the regional goals and objectives. They can be easily applied to all stages of transportation decision making process. In Figure 2, the main decision steps in which some of the performance measures can be used in the transportation sector are given.

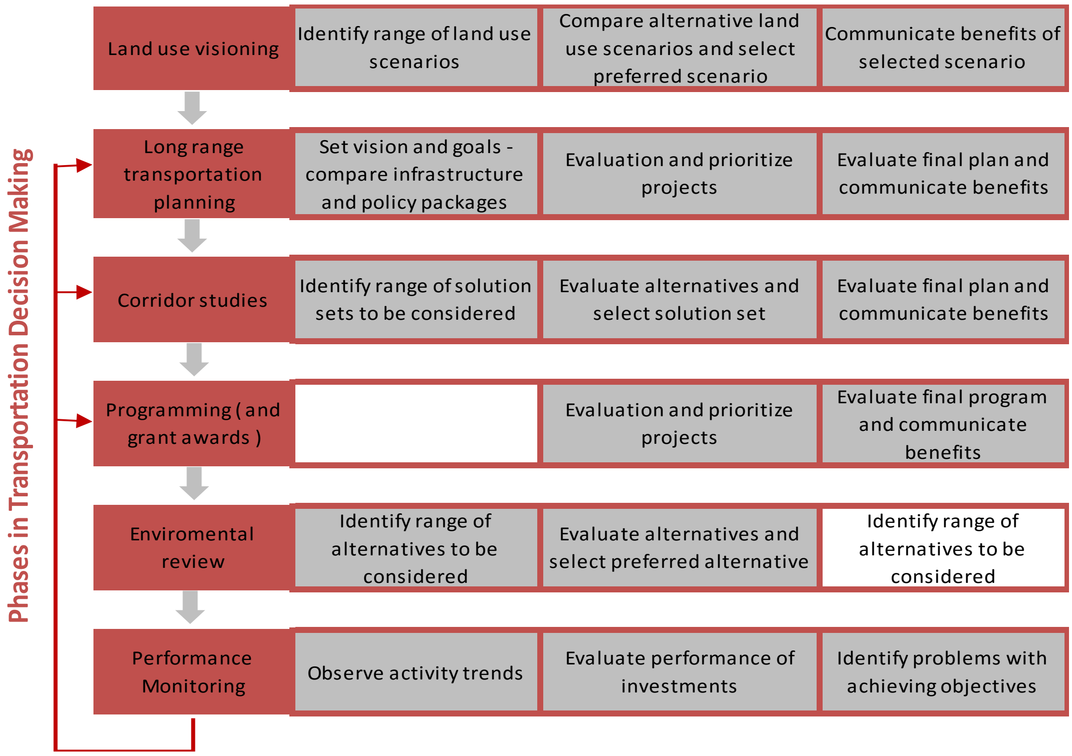

Figure 2: Main Decision Steps in Transportation Sector (EPA, 2011)

Also, there are some performance measures given in Table 1 to achieve the goals or objectives of the sustainability issues in the transportation sector. The classification of these performance measurements are combined in four groups such as economic, social, environmental and effectiveness The most commonly used indicators directly related to transport sustainability are listed below:

There is a greater range of indicators in the social and environmental categories than in the economic ones. The most frequently applied indicator for measuring social sustainability is the number of transport fatalities; for environmental sustainability it is land usage of transport infrastructures and emission rates; and for the economic aspect total transportation costs and public expenditures. All of these sustainability indexes are playing very important role in tracing and tracking the developments of transportation system.

Yevdokimov (2003) proposed an approach for integration of these factors into the general framework of the transportation problem. The study indicated a system with vertical and horizontal linkages of transportation network and analysis of sustainability is proposed to be investigated as a whole system of the supply chain, instead of just focusing on the partial part of the system. In the horizontal case, the transportation network is considered as just combination of environmental and social factors. Therefore, emissions, noise pollution, land use considerations are directly combined with the social links such as safety, mobility, accessibility. In the vertical cases, these horizontal linkages are combined with the economic issues of different parts of the supply chain which means that the approach places the transportation network within the economic perspective of the system and develops its links with environmental and social concepts. These links reflect the idea that transportation network does not exist on its own. It is an integral part of an economy, and there is a common demand among the transportation and other sectors of the economic system.

In the literature, there are many studies focusing on the main factors of the sustainability by considering the performance indexes given in the Table 1. Most of them are adopting the definition of sustainable transportation and proposing some concepts or mathematical models based on the single or synthesis of several performance measurements.

Table 1: Performance Measures for different factors

Sustainability Factors	**Objectives**	**Performance Indexes**
Enviromental	Minimize GHG Emissions	CO_2, Nox Emission Rates
	Minimize Pollutions (Air, Noise etc.)	Noise Level and CO, VOC Emissions
	Minimize Resource Use	Fuel and Land Consumption
Economic	Minimize Transportation Cost	Total Travel Cost
	Maximize Economic Efficiency	Total Spent Time in Traffic
	Maximize Affordability	Land Usage, Accessibility
Social	Maximize Equity	Equatiy of Welfare and Exporsure to Emission
	Maximize Accessibility	Access to the Service/Activity Points
	Increase the Safety and Security	Crash Disabilities, Fatalities
Effectiveness	Improve Mobility	Congestion Rate
	Improve System Performance	Total Carried Quantity
		Total Distanve Travelled

Economic Factors

The economic dimension of sustainable transportation is based on the understanding how transportation contributes to or accelerates economic development. Newman and Kenworthy (1999) and Jeon and Amekudzi (2005) indicated some efficiency concepts in the public transportation activities which directly related with the cost of total system. In addition, there are many studies indicating the importance of the transportation cost and total expenditures in transportation activities. Nicolas et al. (2003); Jeon and Amekudzi (2005); Zhang and Guindon (2006); Zito and Salvo (2011); and Santos and Ribeiro (2013) proposed the some methods to balance the competitiveness of the sector and affordability of the services. Moreover, Haghshenas and Vaziri (2012) and Zegras (2006) indicated the time consideration in transportation activities because they mentioned that total spent time in transportation activities directly affects the competitiveness of the sector.

Also, Sharaki and Turkay (2014) indicated that there are a large number of network design studies focusing on the economic factor indexes of sustainable transportation such as Ban et al., 2006; Kim et al., 2008; Lo and Szeto, 2009.

Environmental Factors

In the literature, there are many studies focusing on the total travel distances travelled by the vehicles which directly have great impact on the environmental issues, such as emissions, use of resources or waste. Newman and Kenworthy, 1999; Savelson et al. (2006); Litman (2009) and Santos and Ribeiro (2013) focused on the total land use of the transportation system and total travelled distances to create a linkage over emissions or use of resources. Also, Nicolas et al. (2003); Zhang and Guindon (2006); Zegras (2006) and Santos and Ribeiro (2013) focused on the emission rates such as CO_2, NO_x, noise intensity levels and energy consumption of the transportation system to reflects the sustainability aspects according to the environmental dimensions.

The integration of different sustainability measures in transportation sector intends to provide insights into the common issues of the world as discussed in the literature. Vreeker and Nijkamp (2005) suggest that the link between transportation and land use is becoming stronger while transportation is a driver of urban development. However, they also indicate that transportation can sometimes deteriorate the balance of urban development because it is seriously difficult to make any balance between the factors of the transportation sector in the real cases. For example, Sharaki and Turkay (2014) indicates that integration of different functionalities such as home, commerce and service sector requires some efficient infrastructures, links among each function and proper land allocation. Also, Liao et al. (2013) proposed that there is a very strict relationship in the transportation sector between the land usage, urbanization and greenhouse gas emissions. Therefore, land use and environmental factors are closely related and there are many studies on this issue to support the decision authorities in transportation planning. As indicated in the study of Waddell et al. (2007), Paulley and Webster, 1991; Southworth, 1995; Garret and Wachs 1996; Miller et al., 1999;

Wegener, 2004; Dowling et al., 2005 proposed some mathematical models for the land allocation problem which are directly related with the environmental concepts.

Also, there is a comprehensive literature survey over the models integrating the network design and land usage in the study of Sharaki and Turkay (2014). Lowry, 1964; Simmonds and Still, 1998; Anderstig and Mattsson, 1998; Wegener, 1998; Putmann, 1983; Martinez, 1996; Timmermans, 2003 introduced the mathematical models and solution algorithms of network designs by considering the environmental issues, especially land usage. Studies of Zhou et al. (2008), Yin and Lu (1999) and Huang et al. (2010) focus on environmental sustainability and total traffic emission rates.

Social Factors

Compared to other factors, social impacts are relatively difficult to measure and assess from the mathematical models or algorithms. In order to sustain in accessibility and equity issues, many studies such as Jeon and Amekudzi (2005); Litman (2009); and Santos and Ribeiro (2013) deal with the density of transportation networks, quality and affordability of public transportation by the citizens. Moreover, Nicolas et al. (2003) and Tanguay et al. (2010) indicate the safety consistency with human health by considering the total distance travelled and transport fatalities within the system. Also, Cidell (2012) introduced the linkages between the social factors and land uses. In that study, it is stated that reducing the mobility activities and increase in the sedentary lifestyles may increase the risks of cancer and mortality rates.

Effectiveness Factors

These factors are mostly combined with the other three main factor criteria. In the literature, there are many works covering to measure and assess the performance of the total transportation network (Vuchic, 2007). The important elements of these networks are the speed, density and frequency in terms of efficiency case. By using these indicators, total movement of the cargos, total distance travelled, total time spent in both transportation activities or mode transfer activities can be easily served for decision makers.

Bi-objective and Multi-Objective Problems

Banister, 2008; Newman and Kenworthy, 1999; and Schiller et al, 2010 studied on the mobility activities and travel time issues. Banister (2008) proposed some balance between the low carbon solutions for the transportation by reducing the total travel distances of the vehicles. Especially, Schiller et al (2010) focused on the linkages between land use and mobility activities. In addition to them, Moavenzadeh and Markow (2007) indicated the concept of congestion which affects the sustainability of the system in terms of economic, social and environmental factors.

There are some studies that are handling with both economic and environmental conditions. For example; Yin and Lawphongpanich (2006), Ferguson et al. (2010), Yang et al. (2010), Sharma and Mathew (2011), Li et al. (2012), and Zhong et al. (2012) proposed bi-objective formulations to focus on the both objective.

2.2 Mathematical Models

Transportation systems are essential components in realizing the transfer of materials among the nodes of supply chains. Therefore, modern supply chain systems continuously seek to improve efficiency of the transportation activities in terms of cost and environmental objectives. As indicated in the study of Turkay (2008), using the multimodal or intermodal transportation systems has strong effects over the economic and environmental performance of the supply chains. The definition of the intermodal or multimodal transportation is proposed by the Jones et al. (2000) as the integration of more than a transportation mode (road, rail, sea, air, and pipeline) in a single transportation chain. In addition to the using multi transportation modes in the chain, sustainable transportation problems should include multi-objectives because there are many objectives affecting the efficiency of the system as given in the Figure 1. The best way of considering these intermodal transportation activities does not lie in any single

factor in reality, so the optimization of the intermodal transportation network can be considered as a multi-objective optimization problem. Therefore, there should be more than a single objective in these problems which can be cost, emission, and utilization of some social indexes. Resat and Turkay (2015) and Fattahi and Turkay (2014) proposed mixed integer linear (MILP) mathematical models for multi-objective intermodal transportation problems by considering the time, cost and carbon emission objectives.
The indices, scalars, parameters and variables of mixed integer linear programming (MILP) for multi objective problem are given below:

Indices:

i	Set of all nodes in the intermodal transportation network (i=1,…I)
j	Set of all nodes in the intermodal transportation network (j=1,…,J)
k	Set of all transportation modes (k=1,…,K)
l	Set of all transportation modes (l=1,…,L)
r	Set of speed levels of vehicles (r=1,…,R)
v	Set of vehicles used in transportation (v=1,…,V)
t	Set of daily time intervals (t=1,…,T)
h	Set of time intervals in 15 minutes (h=1,..,H)
m	Set of regions of speed module based on congestion (m=0,1,2,3)

Many constants are used in both speed and carbon dioxide emission formulations. Also, some big values are used for linearization of this model.

Scalars:

a	BPR equation constant
A	Carbon dioxide emission rate constant
b	BPR equation constant
B	Carbon dioxide emission rate constant
C	Carbon dioxide emission rate constant

alpha	Initial congestion duration (minutes)
ϵ	Epsilon value
σ	Curb weight (kg)
Ω	Daily period (hour)
M1, M2, M3, M4	Big-M parameter values

Parameters:

$C_{i,k}$ Capacity of the node *i* with respect to transportation mode *k*

Cap_v^{max} Maximum capacity level of vehicle *v*

$d_{i,j,k}$ Distance between node *i* to node j by transportation mode *k*

$D_{i,k,v,t,h}$ Demand of the node *i* with respect to transportation mode *k* in time interval *t*

S_k Speed limit of transportation mode *k* for free-flow transportation

$b_{i,j,k,v,m}$ Time constant of corresponding travel time module *m* for vehicles *v* traveling on link (*i*,*j*) by transportation mode *k*

$$b_{ijkvm} = \begin{cases} 0 & m = 0 \\ \left(alpha - \dfrac{d_{i,j,k}}{S_k^c}\right) & m = 1 \\ alfa & m = 2 \end{cases}$$

$\Delta_{i,k,t}$ Opening time of node *i* for transportation mode *k* in time period *t*

$\mu_{i,k,t,}$ Closing time of node *i* for transportation mode *k* in time period *t*

$\theta_{i,j,k,v,m,r}$ Carbon dioxide emission equation constant

$$\theta_{ijkvmr} = \begin{cases} 0 & m = 1,3 \\ \dfrac{S_k^{2r} - S_k^{3r}}{S_k^{3r}} & m = 2 \end{cases}$$

$\omega_{i,j,k,v,m,r}$ Carbon dioxide emission equation constant

$$\omega_{ijkvmr} = \begin{cases} 0 & m = 0 \\ \frac{d_{i,j,k}}{S_k^{1r}} & m = 1 \\ \frac{d_{i,j,k}}{S_k^{1r}} + (\frac{S_k^{3r} - S_k^{2r}}{S_k^{3r}}) & m = 2 \\ \frac{d_{i,j,k}}{S_k^{3r}} & m = 3 \end{cases}$$

G1 Any large value greater than the upper bound of the secondary objective function

G2 Any large value greater than upper bound of the third objective function

P1 Penalty cost of waiting time because of early arrival

P2 Penalty cost of waiting time because of late arrival

P3 Penalty cost of waiting time because of operational process

$TC_{i,j,k}$ Transportation cost from node *i* to node *j* by transportation mode *k*

$TrC_{k,l}$ Transfer cost from transportation mode *k* to transportation mode *l*

$TrT_{k,l}$ Transfer time from transportation mode *k* to transportation mode *l*

L_{ikv} Loading time of vehicle *v* in node *i* for transportation mode *k*

Variables:

$X_{i,j,k,v,t,h}$ Quantity of carried goods on link (*i*,*j*) by transportation mode *k* in time *t*

$Q_{i,j,k,v,t,h}$ Quantity of carried goods on link (*i*,*j*) by transportation mode *k* in time *t*

$J_{i,j,k,v,t,h}$ Transportation duration of link (*i*,*j*) by transportation mode *k* in time *t*

$TT_{i,j,k,v,t,h}$ Transportation duration of link (*i*,*j*) by transportation mode *k* in time *t*

$ta_{i,j,k,v,t,h}$ Arrival time of vehicle *v* in node *i* for transportation mode *k* in time period *t*,*h*

$td_{i,j,k,v,t,h}$ Departure time of vehicle *v* in node *i by* transportation mode *k* in period *t*,*h*

$EW_{i,k,v,t}$ Waiting time of vehicle v in node i for transportation mode k in time period t because of early arrival.

$LW_{i,k,v,t}$ Waiting time of vehicle v in node i for transportation mode k in time period t because of late arrival.

$NW_{i,k,v,t}$ Waiting time of vehicle v in node i for transportation mode k in time period t because of in time arrival.

$g2_{i,j,k,v,m,r}$ Time duration for vehicle v travelling from node i to node j by transportation mode k and speed level r in time interval m.

$I_{i,k,t}$ Inventory of the node i with respect to transportation mode k in time interval t

$\gamma_{v,k,t,h}$ Occupancy rate of vehicle v for transportation mode k in time period t, h.

U Slack variable of the system

Binary Variables:

$y_{i,j,k,v,t,h}\begin{cases}1 & \text{if transportation mode } k \text{ is chosen on link } (i,j) \text{ vehicle } v \text{ in time interval } t\\ 0 & \text{else}\end{cases}$

$w_{i,k,l,t,h}\begin{cases}1 & \text{if transfer from transportation mode } k \text{ to } l \text{ in node } i \text{ in time interval t, h}\\ 0 & \text{else}\end{cases}$

$z1_{i,j,k,v,t,h}\begin{cases}1 & \text{if vehicle } v \text{ in node } i \text{ for transportation mode } k \text{ in period } t\ arrives\ early\\ 0 & \text{else}\end{cases}$

$z2_{i,j,k,v,t,h}\begin{cases}1 & \text{if vehicle } v \text{ in node } i \text{ for transportation mode } k \text{ in period } t\ arrives\ late\\ 0 & \text{else}\end{cases}$

$z3_{i,j,k,v,t,h}\begin{cases}1 & \text{if vehicle } v \text{ in node } i \text{ for transportation mode } k \text{ in period } t\ arrives\ in\ time\\ 0 & \text{else}\end{cases}$

$g1_{i,j,k,v,m,r}\begin{cases}1 & \text{if vehicle } v \text{ departs node } i \text{ in time interval } m \text{ by mode } k\ and\ speed\ r\\ 0 & \text{else}\end{cases}$

Objective Functions

$$Min \quad f_1 = \sum_{t\epsilon T}\sum_{h\epsilon H}\sum_{v\epsilon V}\sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{k\epsilon K}\left(TC_{ijk}\ X_{ijkvth}\right)+\sum_{t\epsilon T}\sum_{h\epsilon H}\sum_{i\epsilon I}\sum_{k\epsilon K}\sum_{l\epsilon L}(TrC_{kl}\ w_{iklth}\ )+\sum_{i\epsilon I}\sum_{t\epsilon T}\sum_{k\epsilon K}(\ I_{ikt}\ P1) \quad (1)$$

$$Min \quad f_2 = \sum_{t\epsilon T}\sum_{h\epsilon H}\sum_{v\epsilon V}\sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{k\epsilon K}(\mathrm{J}_{ijkvth}) + \sum_{t\epsilon T}\sum_{h\epsilon H}\sum_{i\epsilon I}\sum_{k\epsilon K}\sum_{l\epsilon L}(TrT_{kl}\, w_{iklth}) + \sum_{i\epsilon I}\sum_{t\epsilon T}\sum_{k\epsilon K}\sum_{v\epsilon V}\{((EW_{ikvt} + LW_{ikvt})\mathrm{P2}) - (NW_{ikvt}\ \mathrm{P3})\} \quad (2)$$

In the model formulation, Equation (1) and (2) correspond to the cost and time functions, respectively. In Equation (1) the first part indicates the total transportation cost on the network (multiplication of the total carried quantity X_{ijkvth} with the unit transportation cost), the second part gives the total cost due to the transportation mode changes which is again multiplication of binary variable w_{iklth} with the unit transfer cost and the last term shows the cost of keeping the goods in the inventory with a penalty cost. In Equation (2), the first term gives the total transportation duration of the system, the second term indicates the duration of the transport mode change and the last term corresponds to the penalty costs of early or late arrivals of the vehicles to the nodes. In the last part of the Equation (2) EW_{ikvt} , LW_{ikvt} and NW_{ikvt}corresponds to the total carried quantity arrived early, late and within the operational period, respectively.
In addition to these objectives, another contribution along these lines is from Bektas and Laporte (2011) who present the Pollution-Routing Problem as an extension of the classical Vehicle Routing Problem with Time Windows. Figliozzi (2011); Franceschetti et al. (2013); Demir et al. (2014) developed some models using this pollution routing problems. There is another objective which combines greenhouse gas (GHG) emission rate with the total distance travelled by vehicles and total carried quantities.

$$Min \quad f_3 = \sum_{m\epsilon M}\sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{r\epsilon R}\sum_{k\epsilon K}\left\{\left\{\left(\theta_{ijkmr}g2_{ijkmr} + \omega_{ijkmr}g1_{ijkmr}\right)A + \left(\theta_{ijkmr}g2_{ijkmr} + \omega_{ijkmr}g1_{ijkmr}\right)(S_{kmr})^3B\right\}\right\} + \sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{k\epsilon K}\sum_{r\epsilon R}\left\{\left\{\left(g2_{ijk2r} + \theta_{ijk2r}g2_{ijk2r} + \omega_{ijk2r}g1_{ijk2r} - \alpha g1_{ijk2r}\right)(S_{k3r})^3B\right\} + \left\{\left(\alpha g1_{ijk2r} - g2_{ijk2r}\right)(S_{k2r})^3B\right\}\right\} + \sum_{t\epsilon T}\sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{k\epsilon K}\sum_{v\epsilon V}\sum_{h\epsilon H} \mathrm{d}_{ijk}(y_{ijkvth}\,\sigma + X_{ijkvth}) \quad (3)$$

Equation (3) is for minimizing the total carbon emission rate in the system. First summation indicates that rate caused by the engine module and the speed module, second term shows that total the emissions rate generated by the speed module in the all congestion and in the all free-flow regions and last one represents total the rate induced by the weight module.

Constraints

a. Traffic Congestions

$$TT_{ijkvth} = \frac{d_{ijk}}{s_{mrk}}\left[1 + a\left[\frac{X_{ijkvth}}{C_{ik}}\right]^{b}\right] \quad \forall\ t\epsilon T, i\epsilon I, j\epsilon J, m\epsilon M, r\epsilon R, h\epsilon H, v\epsilon V, k\epsilon K \qquad (4)$$

To handle the traffic congestion problem, Equation (4), the BPR (Bureau of Public Roads) equation which was introduced in the Highway Capacity Manual (1964) was used. The BPR equation was modified to obtain transportation times of the modes for every time interval *t*. The BPR equation constants were obtained from Horowitz (1985). In general BPR equation constant *b* is assumed as "4" but in our case it is taken as "1" to handle the non-linearity of the Equation (18) because BPR equation depends on carried quantity by road transportation. This lower value of constant *b* causes speed to be insensitive to volume/capacity ratio until this ratio gets close to 1.0, and then the speed drops suddenly for higher values of constant b but in our case decrease of the speed more slowly. However, the error gap between these two values is less than 5 %. So, it is acceptable and used in our model.

b. Mode Transfer

Constraint (5) indicates that any material in node *i* must be transported via at least one of the available transportation modes. This constraint forces the solver to obtain minimum transfer cost and transfer time in node *i* in terms of transportation modes. Equation (6) shows that the arrival transportation mode of the node *i* must be the same transportation mode of the leaving mode of the node *j*, otherwise if there is any difference between incoming and outgoing transportation modes, Equation (6) ensures that there should be mode transfer in node *i*.

$$\sum_{l\epsilon L} w_{iklth} \geq 1 \quad \forall\, t\epsilon T, i\epsilon I, k\epsilon K, h\epsilon H \quad (5)$$

$$y_{jikvth} + y_{ijkvth} \geq 2\, w_{iklth} \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K, v\epsilon V, h\epsilon H \quad (6)$$

c. Material Balance, Demand and Supply

Constraint (7) shows that incoming and outgoing quantities of carried goods have to be equal to demand of node *i* for transportation mode *k* in every time period *h, t*.

$$\sum_{v\epsilon V}\sum_{j\epsilon J} X_{jikvth} - \sum_{v\epsilon V}\sum_{j\epsilon J} X_{ijkvth} = \sum_{v\epsilon V} D_{ikvth} \;\; \forall\, t\epsilon T, i\epsilon I, k\epsilon K, h\epsilon H \quad (7)$$

Capacities of vehicle *v* are satisfied by Equation (8) for transportation mode *k* in every time period *h,t*.

$$D_{ikvth}\, y_{ijkvth} \leq X_{ijkvth} \leq (Cap_v^{max} - D_{ikvth})\, y_{ijkvth} \;\forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K, v\epsilon V, h\epsilon H \,(8)$$

Constraint (9) indicates that there is equality between the arriving and leaving quantities in node *i* for each transportation mode *k*.

$$I_{ik(t-1)} + \sum_{t'\epsilon T}\sum_{h'\epsilon H}\sum_{v\epsilon V}\sum_{j\epsilon J} X_{jikvh't'} =$$

$$\sum_{v\epsilon V}\sum_{j\epsilon J} X_{ijkvth} + I_{ikt} \;\; \forall\, t\epsilon T, i\epsilon I, k\epsilon K, h\epsilon H \quad (9)$$

As the solution methodology, all cost matrices of transportation modes, transfer operations and distances between nodes are initialized as indicated in Equations (10)–(11). By using Equations (11), there is assessment of the node *i* and the node *j* whether these two nodes are adjacent or not and also model ensures that there is enough demand of node *i* by using Equations (12). If they are not connected or there is no demand in origin node *i*, it is not possible to transport any goods from node *i* to node *j*.

$$\sum_{j\epsilon J} y_{ijkvth} \geq 0 \;\; \forall\, t\epsilon T, i\epsilon I, k\epsilon K, v\epsilon V, h\epsilon H \quad (10)$$

$$y_{ijkvth} = 0 \quad \forall\ t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K, v\epsilon V, h\epsilon H \ \text{ if}(i,j) \text{ isn't linked} \quad (11)$$

$$\sum_{j\epsilon J} y_{ijkt} = 0 \quad \forall\ t\epsilon T, i\epsilon I, k\epsilon K, v\epsilon V, h\epsilon H \ \text{ if } D_{ikvth} = 0 \quad (12)$$

Constraint (13) indicates that daily keeping inventory of every node *i* has to fulfil the capacity levels for every transportation mode *k*.

$$I_{ikt} \leq C_{ik} \quad \forall\ t\epsilon T, i\epsilon I, k\epsilon K \quad (13)$$

d. Time Windows

In this part of the problem, time dependent travel durations are the step-wise function for 24 hour time period per day. This material balance in Equation (9) has to be satisfied for every time interval *t,h*. However, the relationship between *t* and previous time intervals (*t' < t*) has to be as in Equation (14). Arrival time of vehicle *v* on link (*i,j*) for transportation mode *k* in time period *t, h* which is equal to summation of departure time of vehicle *v* on link (*i,j*) for transportation mode *k* in time period *t, h* and transportation duration on link (*i,j*) for transportation mode *k* has to be in the range of single time period (between t and (t-1)).

$$t - 1 \leq t' + TT_{jikvt'h'} \leq \text{t} \quad \forall\ t'\epsilon T \quad (14)$$

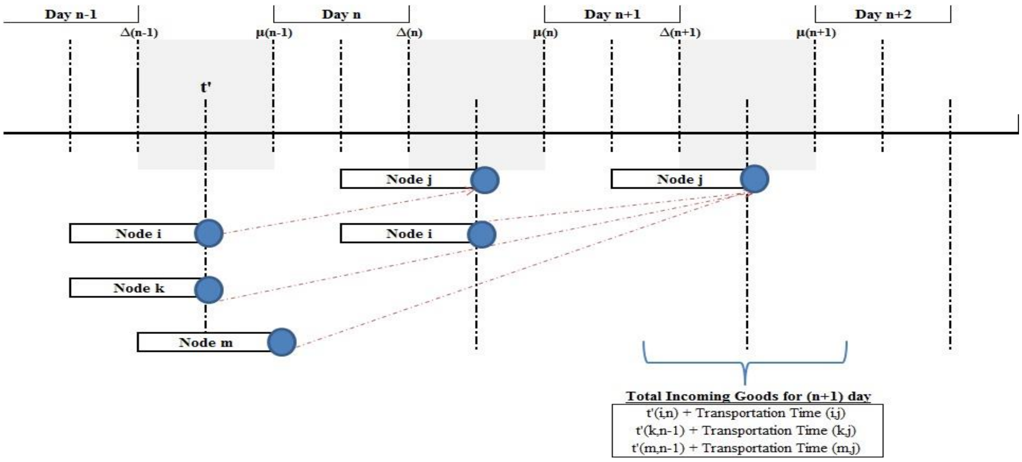

Figure 3: Sample schema of incoming goods

$$EW_{ikvt} \geq \sum_{h\epsilon H}([\Delta_{ikt} - t\alpha_{ijkvth}] + M3(1 - z1_{ijkvth})) \ \forall\ t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K, v\epsilon V \quad (15)$$

$$LW_{ikvt} \geq \sum_{h\epsilon H}([\Omega - t\alpha_{ijkvth} + \Delta_{ik(t+1)}] + M3(1 - z2_{ijkvth})) \ \forall\ t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K, v\epsilon V \quad (16)$$

$$NW_{ikvt} \geq \sum_{h\epsilon H}([td_{ijkvth} - ta_{ijkvth}] + M3(1 - z3_{ijkvth})) \ \forall\ t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K, v\epsilon V \quad (17)$$

$$z1_{ijkvth} + z2_{ijkvth} + z3_{ijkvth} = \ y_{ijkvth} \quad \forall\ t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K, v\epsilon V, h\epsilon H \qquad (18)$$

Constraints (15)–(17) show waiting times of vehicle *v* which arrives early, late or in allowed time period respectively. Constraint (18) ensures that vehicle *v* in node *i* by transportation mode *k* in day *t* has to arrive early, late or in time, if there is any need to be carried goods on link *(i,j)*. Figure 4 shows that waiting times of vehicles according to arrival times. Blue and red arrows indicate the arrival and departure time of vehicle *v* in node *i* by transportation mode *k* respectively.

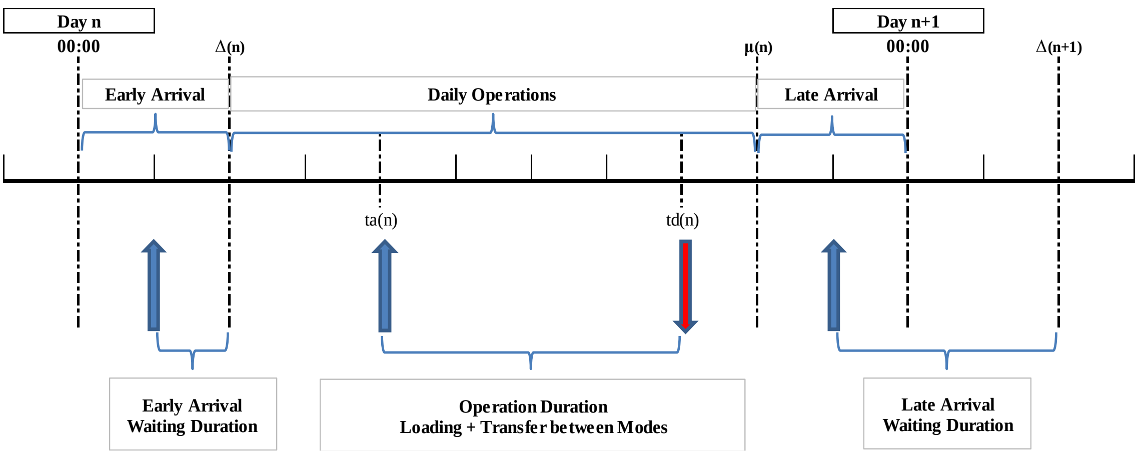

Figure 4: Timeline for daily operations

$$td_{ijkvth} \geq ta_{ijkvth} + L_{ikv} + TrT_{kl} - \mathrm{M4}(1 - \ y_{ijkvth}) \ \forall\ t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K, v\epsilon V, h\epsilon H \qquad (19)$$

$$\Delta_{ikt} \leq td_{ijkvth} \leq \mu_{ikt} \quad \forall\ t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K, v\epsilon V, h\epsilon H \qquad (20)$$

Constraint (19) indicates relationship between departure and arrival times of vehicle *v* (red and blue flows in Figure 5 respectively) in node *i* for transportation mode *k* in time period *t*, *h*. Time duration between arrival and departure time (indicated as ta and td in Figure 5) of vehicle *v* has to be greater than summation of loading time of vehicle *v* for mode *k* and transfer times from mode *k* to *l*. Constraint (20) ensures that departure time of vehicle *v* has to be between opening and closing time of node *i* for transportation mode *k* in time period *t*,*h*.

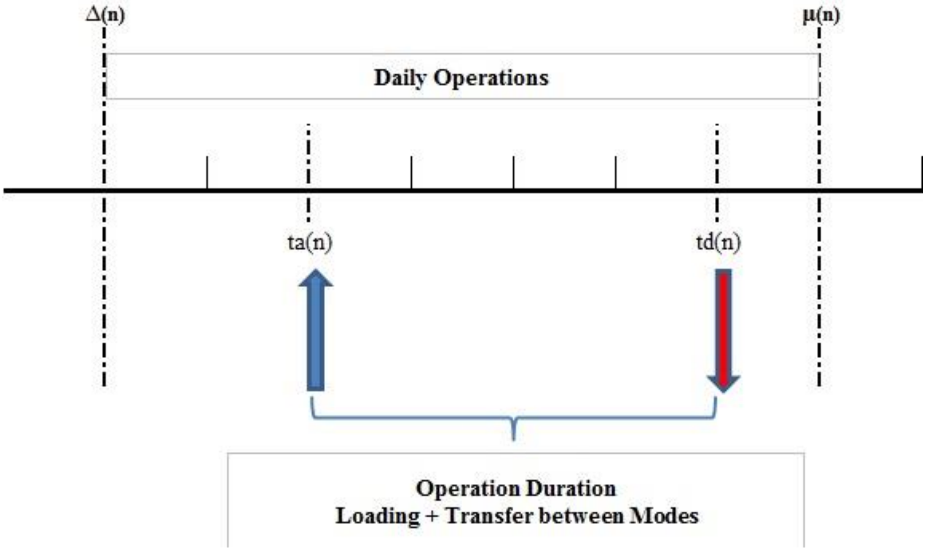

Figure 5: Schedule for Daily Operations

Constraint (21) ensures that time period at which vehicle *v* leaves node *i* by transportation mode *k* under boundary limits.

$$g1_{ijkvmr} b_{ijkv(m-1)} \leq g2_{ijkvmr} \leq g1_{ijkvmr} b_{ijkvm} \forall\ i\epsilon I, j\epsilon J, m\epsilon M, k\epsilon K, v\epsilon V, r\epsilon R \quad (21)$$

Constraint (22) indicates that travel duration (of which vehicle *v* from node *i* to node *j* by transportation mode *k*) used in the carbon dioxide emission calculations is at most equal to transportation duration of speed calculations.

$$\sum_{m\epsilon M} \sum_{r\epsilon R} (\theta_{ijkvmr} g1_{ijkvmr} + \omega_{ijkvmr} g2_{ijkvmr}) \leq \sum_{h\epsilon H} TT_{ijkvth} \ \ \forall\ t\epsilon T, i\epsilon I, j\epsilon J, v\epsilon V, k\epsilon K \quad (22)$$

e. Supplementary Constraints

$$X_{ijkvth} \leq Q_{ijkvth} \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \tag{23}$$

$$X_{ijkvth} \leq M \times y_{ijkvth} \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \tag{24}$$

$$X_{ijkvth} \geq Q_{ijkvth} - M(1 - y_{ijkvth}) \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \tag{25}$$

$$J_{ijkvth} \leq TT_{ijkvth} \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \tag{26}$$

$$J_{ijkvth} \leq M \times y_{ijkvth} \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \tag{27}$$

$$J_{ijkvth} \geq TT_{ijkvth} - M(1 - y_{ijkvth}) \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \tag{28}$$

By using Equations (23)–(25) for cost functions and Equations (26)–(28) for time functions, new linear conditions for the objective functions can be obtained. Constraints (29)–(34) ensure both integer and non-negativity conditions.

$$X_{ijkvth}, Q_{ijkvth}, J_{ijkvth}, TT_{ijkvth,} ta_{ijkvth}, td_{ijkvth} \geq 0 \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, h\epsilon H, v\epsilon V, k\epsilon K \tag{29}$$

$$z1_{ijkvth}, z2_{ijkvth}, z3_{ijkvth} \geq 0 \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, h\epsilon H, v\epsilon V, k\epsilon K \tag{30}$$

$$EW_{ikvth}, LW_{ikvth}, NW_{ikvth} \geq 0 \quad \forall\, t\epsilon T, i\epsilon I, h\epsilon H, v\epsilon V, k\epsilon K \tag{31}$$

$$y_{ijkvth}, w_{iklth,} \in \{0,1\} \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, h\epsilon H, v\epsilon V, k\epsilon K \tag{32}$$

$$g1_{ijkvmr}, g2_{ijkvmr} \in \{0,1\} \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, m\epsilon M, r\epsilon R, v\epsilon V, h\epsilon H, k\epsilon K \tag{33}$$

$$I_{ikth} \geq 0 \quad \forall\, t\epsilon T, i\epsilon I, k\epsilon K, h\epsilon H \tag{34}$$

2.3 Solution Methodologies

For the solution methodology, (AUGMECON) ϵ-constraint method (Mavrotas, 2009) should be used to find the Pareto optimal solutions for decision makers. Relationship between objective functions will be determined and applied for different problem cases. However, finding the optimal solutions for this kind of problems is seriously time–consuming and difficult by the current solvers because proposed problems are very complex and NP–hard due to large number of constraints and indices. Therefore, reducing the complexity of linear integer problems of transportation is the major area of the recent studies. In literature, heuristics, meta–heuristics and hybrid genetic algorithms are some part of the solution methodologies for linear integer problems (e.g. Limbourg and Jourquin, 2009; Ishfaq and Sox, 2011). However, in the study of Resat and Turkay (2015), exact method is used to eliminate the lower accuracy of heuristics methods. Especially, pre-processing and logic-cut methods are used to help solvers to obtain more accurate and optimal solutions by decreasing the complexity and division of problems. Although the logic–cuts increase the number of constraints, it would reduce the relaxation gap and would strengthen convex hull approximation. Therefore, solver will obtain better feasible solutions and finding optimal solution would require shorter CPU times. Also, addition of these extra constraints because of logic-cut and pre-processing methods will not change the integer optimal solutions. As a summary, proposed multi-objective problems can be solved by integer linear optimization models also, as indicated in the study of Fattahi and Turkay (2014), some logic-cuts and pre-processing methods are proposed and solutions are found in better and faster ways with the help of these logic-cuts and pre-processing methods. Additionally, a new exact algorithm for solving mixed-integer multi-objective optimization problems is developed by Fattahi and Turkay (2015). A penalty parameter is added to the objective function of the sub problems. However, there are some efficiency problems and missing solutions in the epsilon constraint algorithm when the solver search for the efficient solutions below the bounds over function of system parameters The proposed algorithm is tested on various benchmark problems including assignment, knapsack and set covering. Analysis of the results indicates that the proposed algorithm is able to obtain the entire efficient set for the benchmark problems more effectively.

2.4 Conclusions

Although there is an increased amount of studies in the literature, unfortunately there is no commonly agreed definition of sustainability in transportation operations. Therefore, this study tries to foster sustainable transportation issue by giving the extended literature survey. Improvement of the transportation systems by developing more sustainable systems or promoting sustainability within the different functionalities of the sector can be achieved through many performance indexes. In this study, main indicators for economic, environmental and social factors of sustainability of transportation are indicated and theoretical studies and methodologies are investigated for decision makers and stakeholders from different areas to assess the current situation of the sector. Moavenzadeh and Markow (2007) suggest the following strategies that are based on learning from multiple contexts to improve the sustainability concept in transportation:

- Focusing on demand and supply which will be able to understand the major requirements and needs of mobility activities.
- Improving existing transport system performance by focusing on specific performance indexes
- Understanding the needs of competitive market and policies by trade-off analysis.
- Improving management capability which directly makes the decisions and flow of information better.

Chapter 3

DESIGN AND OPERATION OF INTERMODAL TRANSPORTATION NETWORKS

3.1 Introduction

Transportation related costs in typical supply chain account for approximately 5–7% of total revenue (ARC, 2008). Therefore, logistics operations started to play an important role in the extensive and complex supply networks. There is a great potential to optimize transportation costs within the supply networks since transportation links all echelons of the network having impact on the performance of each echelon. Transportation is the essential activity that links each echelon of supply networks. Intermodal transportation has been recognized as a promising concept to efficiently reduce logistics costs although it faces some operational challenges for effective usage. According to Jones, Cassady and Bowden (2000), intermodal transportation is "being or involving transportation by more than one form of carrier during a single journey." It is necessary to integrate several transportation modes seamlessly for an effective intermodal transportation.

Most of the developed countries try to shift their transportation systems from road to rail and sea for an effective use of intermodal transportation infrastructure and eliminate congestion on the roads that are primarily designed to move passengers. This setting is not different in Turkey. The Turkish transportation sector has been facing strict reforms under the European Union regulations during the last two decades. Different industrial sectors of Turkey recognized the need for establishing a more advanced transportation infrastructure, regulations for logistics sector, and promotions or incentives to shift from road to sea and rail transportation operations (MARKA, 2013). In Turkey, domestic freight transportation is heavily dominated by road transportation (89.4%) (TUIK, 2012). This unbalanced use of transportation modes creates negative impacts on congestion, carbon emissions, and safety risks. On the other hand, intermodal transportation is a new concept for the Turkish transport industry due to lack of intermodal transportation infrastructure within the country. However, Turkish logistics companies use the available intermodal infrastructure in the Europe. For example, more than 125.000 trucks use RO-RO (Sea+Road modes) lines: most commonly used routes include Pendik, Turkey; Trieste, Italy or Illichecvsk, Ukraine ports and then they use either road transportation or RO-LA lines to reach their customers in Austria and Germany every year. Also, the intermodal transportation routes between Turkey and Central Europe is heavily used by more than 300.000 trucks per year and most of the trips to Germany and Austria are made on the RO-LA (Rail+Road modes) lines from Istanbul, Turkey to Wels, Austria (UND, 2013). Unfortunately, air transportation in Turkey has a negligible share in the intermodal logistics market as in the same for the rest of the world. The available infrastructure for intermodal transportation in Europe is heavily used by the Turkish transportation sector. Although Turkey has a very strategic location in the world trade corridors, intermodal transportation cannot be practiced due to lack of required infrastructure. The main contributions of this paper is to analyze the benefits of intermodal transportation in terms of reducing the total transportation costs and delivery times and indicate the potentials of intermodal transportation within the Marmara region of Turkey. We try to obtain more effective solutions for the transport chains by integrating different transportation modes in the Marmara region. We aim to design a more balanced network to increase the transport safety and also decrease traffic congestion.

Hayuth (1987) provided a theoretical analysis on the requirements of intermodal systems and also showed that each mode has its own advantages in terms of cost, service, reliability, and safety. These advantages create separated transport systems depending on the particular characteristics of the regions. For instance, if we aim to shift the main transportation mode from road to sea in the Marmara region, then sea transportation would be the single dominant transportation mode within the region. Hayuth (1987) claims that high waiting and turnaround times of sea transportation might be eliminated with the help of intermodal systems; so transport cost, transit times, and unreliability could decrease. Therefore, we need to change our operations from single mode transportation to intermodal transportation.

Intermodal logistics has developed into a research stream in the past several decades in transportation research literature. Many papers give a general survey and definition of intermodal transportation problem. Minoux (1989), Daskin (1995), and Drezner (1995) discussed the classical facility location problem in transportation setting and their solution methodologies. Balakrishnan et al. (1997) and Raghavan and Magnanti (1997) discussed network design cases and proposed general concepts for transportation operations. Also, Melkote and Daskin (2001) combined facility location and network design problems to create an integrated solution methodology for transportation activities. In addition to these, there are many papers that examine the intermodal transportation problem and try to develop some models to address this problem. Min (1991); Barnhart and Ratliff (1993); Boardman et al. (1997); Bookbinder and Fox (1998) and Southworth and Peterson (2000) provide a review on intermodal routing and network design. However, these papers review the state-of-art at the time that these papers were published and give a wish list of what could be done for an effective intermodal transportation. Among them, Min (1991) and Bookbinder and Fox (1998) discuss the network design of international intermodal transportation. Boardman et al. (1997) and Bookbinder and Fox (1998) think about only multiple objectives. Min (1991) examines multiple objectives and on-time service requirements.

One of the interesting studies is by Arnold et al. (2001) who developed formulations for the selection of fixed intermodal hubs among candidate locations and these formulations were improved later by Arnold et al. (2004). These studies give a demonstration of each network model as a sub graph with nodes and links. The authors also discussed connection of sub graphs via transfer links. They also focus on one of the intermodal operational issues; how an international intermodal carrier selects the best routes for shipments through the regional intermodal network.

In addition to modeling the intermodal transportation network problem, Nemhauser and Wolsey (1988) provided general information on how network design and operation problems can be solved effectively. Also, Ahuja et al. (1993) proposed models and solution algorithms for network design problems with general constraints including shortest path, minimum cost flows. Almost all of the solution methods available in the literature can be used to solve smaller cases related to sea transportation and container movement operations. For example, Chih and Van Dyke (1987) developed a model for empty container distributions. There are also some models that integrate the road and rail operations into intermodal operations. Especially, Bontekoning (2006) have conducted studies on highway movements of intermodal containers or trailers. Macharis and Bontekoning (2004) and Wu et al. (2011) discussed the importance of network designs in intermodal transportation.

In this paper, integration of network design and operation issues into the problem is one of our contributions. Besides, we can provide evaluation of network alternatives and testing the impact of these changes on transportation cost and travel time. Developed network designs with real world data ensure applicable plans that help organizations to take advantage of the benefits of distribution network designs.

Although there are many papers that address the intermodal transportation and intermodal network design, time dependency on intermodal transportation is not included in most of the models presented. Ziliaskopoulos and Wardell (2000) present a best-route algorithm with the objective of minimizing the transportation time in intermodal transportation network. In addition to minimizing time and cost factors, the interaction between transportation demand and supply leads to traffic congestion. Time dependency or traffic congestion is another important issue in intermodal transportation.

McKinnon (1999) and McKinnon et al. (2008) provided surveys investigating the effects of traffic congestion on the supply network systems. Also, the effect of the traffic congestion on facility location of companies was analyzed by Konur and Geunes (2011). The main difference of our work from the paper by Konur and Geunes (2011) is that in our case, traffic congestion model is time dependent and our problem is modelled as a bi-objective optimization problem. Therefore, our approach represents the dynamic nature of the system that changes depending on the time of the day and also we would be able to observe the compromise between cost and time in the bi-objective model. In addition, they study cases on individual companies; however, we work on a regional case. Also, there is a serious effort to improve the speed-flow relationships in transportation operations; many speed-flow equations have been proposed to predict transportation delays under traffic congestions (Akçelik, 1991). Capacity conditions are other evaluation criteria for congestion problems (Dowling, 2006). Therefore, using the effect of the time factor is another contribution of this study. We have developed time dependent network design and operation problem which includes traffic congestion on links.

Vehicle speed has been predicted using BPR approach (Bureau of Public Roads, 1964) as a function of the link usage. This function is used to predict the speed of the vehicles according to their volume/capacity ratios. The BPR equation was originally fitted to freeway speed flow data given in the highway capacity manual in 1965. Since then, additional research has indicated that while capacity usage of vehicles is increasing the effect of volume/capacity ratio on mean speeds, capacity usage is losing its significance (Highway Capacity Manual, 2000).

Horowitz (1984) used a least squares fitting technique to determine the “*a*” and “*b*” parameters of the BPR equation. After analyzing the data from freeways and multi-lane highways in the highway capacity manual (1985), he proposed that these new parameters have very low deviation from the curves (Horowitz, 1985). Horowitz (1985) suggests that these parameters can be easily updated for the highway capacity manual

(1994), but does not provide specific results. Spiess (1989) developed a revised speed-flow equation. This equation computes the equilibrium of traffic flows much more rapidly than with the standard BPR curve. In 1991, Akcelik introduced the "steady state delay equation for a single channel queuing system". Then, Akçelik (1991 and 1996) proposed the modifications of equation in the study by Davidson (1966) to predict the travel time on any road facility. The delays caused by queuing were considered by new equation explicitly and it can be applied to any facility type. Dowling (1998) investigated the comparative accuracy and model run time performance by studying the BPR and Akcelik equations. This comparative analysis (Dowling, 1998) found that the Akcelik equation results in significantly improved traffic assignment run times and provides more accurate speed estimates over a range of demand conditions than the standard BPR equation. However, the main problem in these vehicle speed prediction approaches is that they make the problems non-linear. There are many researchers working on the linearization of the non-linear BPR function when the exponent *b* is equal to 4. There are some methods to handle the mixed-integer non-linear programs with 4^{th} degree BPR equation to obtain globally optimal solutions. Wang et al. (2010) showed that non-linear BPR equation can be approximated with a piecewise linear function by using the first-order Taylor. Wang et al. (2013) proposed two global optimization methods for the discrete network design problems, and they used relaxation methods for the BPR equation in their illustrative examples. In the papers by Wang et al. (2015) and Liu and Wang (2015), non-linear non-convex BPR equation is relaxed into concave logarithmic functions that can be globally optimized. However, only the global optimal solutions to the relaxed problem can be found in these studies, the local solutions could be missed and additionally they have indicated that computation time becomes a major problem for the large scale problems.

The best way of considering the intermodal transportation activities does not depend on any single factor in real-life situations, so optimization of the intermodal transportation as a multi-objective optimization problem is more realistic. For existing supply chains, optimal design of an intermodal transportation network should minimize the total transportation cost composed of transportation cost among the nodes and transfer cost between different transportation modes in nodes (Reddy, 1995). However, impact of the time should also be considered in supply chain designs for its negative effect on the operations. The concept of optimality is replaced with efficiency or Pareto optimality. However, there is a strict relationship between the objective functions. While finding the Pareto solutions, the model obtains an improved solution for one of the objective function but deteriorates at least one of the other objective function values. Many authors have proposed different solution methodologies and applications to address the bi-objective intermodal transportation problems. According to Hwang and Masud (1979), there are three different class of solving multi objective problems. They are listed as the a priori methods, the interactive methods and the generation or a posteriori methods. Among these methods, the generation methods require serious computational effort and take a long time to obtain an efficient solution. Also, there are some methods which are alternative of the intermodal traffic network models. For example, Nagurney (2000) has developed a multi-class, multi-criteria traffic network equilibrium model to determine the multi-class traffic links by using the multi-objectives.

There are some methods developed by Steuer (1986), Miettinen (1999) and Mavrotas (1998) to generate an approximate representation of the set of Pareto solutions. Their methods produce efficient set for special type of mostly linear multi-objective problems. In general, the most widely used generation methods are the weighting method and the ϵ-constraint method.

The ϵ-constraint method is a more convenient method to obtain solutions which might not be found by the weighting method in some regions. This method optimizes one objective, while the other objectives are used as constraints. To properly apply the ϵ-constraint method, the range of at least one of the objective functions that will be used as constraints should be known. According to Isermann and Steuer (1987); Reeves and Reid (1988) and Steuer (1997), the calculation of the range of the objective functions over the efficient set is not a trivial task. Many studies such as Mavrotas and Diakoulaki

(2005) try to improve the ϵ-constraint method. The former presents an adaptive scheme that finds appropriate constraint values during the run. The latter Mavrotas (2009) proposes a new version of the constraint method: the augmented ϵ-constraint method (AUGMECON). Since the ϵ–constraint method is developed for continuous problems, its application to discrete-continuous problems does not guarantee finding Pareto solutions. Mavrotas (2009) proposed a modification on the original ϵ-constraint algorithm by introducing slack variables for the objective function expressions that are converted into constraints and a penalty term in the objective function. After developing the network design system with these characteristics, intermodal transportation may lead to better utilization of existing infrastructure, sustainable transport systems, reduction in carbon emission, balanced use of all modes of transport, increase in the share of sea and rail modes in transportation systems, better synchronization of customer demand and transportation operations.

The main contribution of this paper is the development of a novel bi-objective mixed-integer linear optimization model with total delivery time and total transportation cost functions for different transportation modes and the consideration of time dependent traffic congestion constraints. The ϵ-constraint method was used to generate the set of Pareto optimal solutions of the bi-objective optimization problem for decision makers in both linear and non-linear mathematical models. We also show that the proposed bi-objective linear model of this study finds the optimal solutions faster requiring much less computational effort while having very similar accuracy levels compared to the non-linear case. We also aim to design a more balanced network to increase the transport safety by decreasing traffic congestion with the integration of different transportation modes in the Marmara region. Therefore, the intermodal transportation network is designed in the Marmara region by considering traffic congestion on links for different transportation modes and the benefits of intermodal transportation are analyzed by using real data for the region in terms of the total transportation costs and delivery times. The importance and potential of intermodal transportation within the Marmara Region is also indicated for authorities.

This chapter is divided into 5 sections. Section 2 presents problem statement and proposition of methods for minimization of time and cost factors in intermodal transportation problem by using the traffic congestion equation. Section 3 provides data used during calculations under the section of computational experiments. Section 4 gives computational results for the corresponding model. Finally, conclusions are discussed in Section 5.

3.2 Problem Statement

In this section, we discuss the intermodal transportation network design, present our bi-objective discrete-continuous optimization model and also outline the optimization algorithm. In addition, we used to generate set of Pareto solutions for bi-objective discrete-continuous optimization problem.

Problem Definition

In this paper, we integrate the intermodal transportation network design problem considering two objectives: minimization of total transportation cost and minimization of delivery times. The proposed model generates many Pareto optimal solutions for intermodal transportation activities in the Marmara Region. Fixed costs of opening any facility in nodes are not included; however, keeping the goods in the inventory is penalized and material handling operations in the nodes are restricted by the capacity levels for each transportation mode in the network. We also generate different transportation mode change scenarios in the nodes for illustrative and real case problems. The allocation of goods in the network sometimes requires keeping inventory with a penalty in the nodes. So, the inventory profile is also decided by the optimization problem. We also monitor the relationship between among product flow quantities, durations and traffic congestion of the routes among nodes and provide information about transportation durations of links among nodes according to total carried quantities on the links. The total number of the vehicles including passenger cars, buses or freight vehicles is considered because the number or type of trucks and interactions of cargo trucks with other type of vehicles are the other effecting factors of transportation durations. The type of cargo trucks are considered as uniform and assumed that they can just carry a 20 ton container. Also the number of other type of vehicles is considered in the BPR equation in Eq. (18). Besides, there are other assumptions on operational hours of some nodes for different transportation modes. Also, the time horizon for the network design was considered as a 24-hour period. We consider a representative day and used the last three years data for the network design purposes. Therefore, we forecasted the traffic on the links and demand of the nodes according to the data obtained from the public authorities. Then, this data is used in our calculations for the 24-hour time horizon. Therefore, our network design problem satisfies the restrictions and provides daily analysis of transported quantities among nodes and oscillation of vehicle movements in a given period.

Model Formulation

The main objective in this paper is the generation of the set of Pareto solutions by minimizing the total transportation cost and total transportation time for a given network topology. Therefore, mathematical model has been developed as a bi–objective mixed-integer linear programming (MILP). The main concepts and characteristic of the intermodal transportation network design and operation problem is formulated as follows:

Indices:

i	Set of all nodes in the intermodal transportation network (i=1,…I)
j	Set of all nodes in the intermodal transportation network (j=1,…,J)
k	Set of all transportation modes (k=1,…,K)
l	Set of all transportation modes (l=1,…,L)

t Set of time intervals (t=1,…,T)

Scalars:

a BPR equation constant

b BPR equation exponent

μ Epsilon constraint constant

ϵ Epsilon value

M Big-M parameter

Parameters:

C_{ik} Capacity of the node i with respect to transportation mode k

d_{ijk} Distance between node i to node j by transportation mode k

D_{ikt} Demand of the node i with respect to transportation mode k in time interval t

G Any large value greater than upper bound of the secondary objective function

S_k Speed limit of transportation mode k for free-flow transportation

TC_{ijk} Transportation cost from node i to node j by transportation mode k

TrC_{kl} Transfer cost from transportation mode k to transportation mode l

TrT_{kl} Transfer time from transportation mode k to transportation mode l

cap_{ijk} Total vehicle capacity of link between i and j for transportation mode k

Variables:

y_{ijkt} $\begin{cases} 1 & \text{if transportation mode } k \text{ is chosen from node } i \text{ to node } j \text{ in time interval } t \\ 0 & \text{else} \end{cases}$

w_{iklt} $\begin{cases} 1 & \text{if transfer from transportation mode } k \text{ to mode } l \text{ in node } i \text{ in time interval } t \\ 0 & \text{else} \end{cases}$

Q_{ijkt} Relaxed Quantity of carried goods on arc (i,j) by mode k in time t

X_{ijkt} Quantity of carried goods on arc (i,j) by transportation mode k in time t

V_{ijkt} Total traffic volume of the arc (i,j) at time t for transportation mode k

J_{ijkt} Relaxed Transportation duration on arc (i,j) by transportation mode k in time t

TT_{ijkt} Transportation duration on arc (i,j) by transportation mode k in time t

I_{ikt} Inventory of the node i with respect to transportation mode k in time interval t

x_s Slack variable of the objective function

$$min \quad f_1 = \sum_{t\epsilon T} \sum_{i\epsilon I} \sum_{j\epsilon J} \sum_{k\epsilon K} TC_{ijk}\, X_{ijkt} + \sum_{t\epsilon T} \sum_{i\epsilon I} \sum_{k\epsilon K} \sum_{l\epsilon L} TrC_{kl}\, w_{iklt} \qquad (1)$$

$$min \quad f_2 = \sum_{t\epsilon T} \sum_{i\epsilon I} \sum_{j\epsilon J} \sum_{k\epsilon K} J_{ijkt} + \sum_{t\epsilon T} \sum_{i\epsilon I} \sum_{k\epsilon K} \sum_{l\epsilon L} TrT_{kl}\, w_{iklt} \qquad (2)$$

subject to:

$$X_{ijkt} \leq Q_{ijkt} \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \qquad (3)$$

$$X_{ijkt} \leq M\, y_{ijkt} \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \qquad (4)$$

$$X_{ijkt} \geq Q_{ijkt} - M(1 - y_{ijkt}) \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \qquad (5)$$

$$J_{ijkt} \leq TT_{ijkt} \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \qquad (6)$$

$$J_{ijkt} \leq M\, y_{ijkt} \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \qquad (7)$$

$$J_{ijkt} \geq TT_{ijkt} - M(1 - y_{ijkt}) \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \qquad (8)$$

$$\sum_{j\epsilon J} y_{ijkt} \geq 0 \quad \forall\, t\epsilon T, i\epsilon I, k\epsilon K \qquad (9)$$

$$y_{ijkt} = 0 \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \;\; \text{if}(i,j) \text{ is not linked} \qquad (10)$$

$$\sum_{j\epsilon J} y_{ijkt} = 0 \quad \forall\, t\epsilon T, i\epsilon I, k\epsilon K \;\; \text{if } D_{ikt} = 0 \qquad (11)$$

$$I_{ikt} \leq C_{ik} \quad \forall\, t\epsilon T, i\epsilon I, k\epsilon K \qquad (12)$$

$$I_{ikt} = 0 \quad \forall\, t\epsilon T, i\epsilon I \;\; \text{for } k = \text{Rail} \qquad (13)$$

$$\sum_{l\epsilon L} w_{iklt} \geq 1 \quad \forall\, t\epsilon T, i\epsilon I, k\epsilon K \qquad (14)$$

$$\sum_{j\epsilon J} X_{ijkt} \geq D_{ikt} \quad \forall\, t\epsilon T, i\epsilon I, k\epsilon K \qquad (15)$$

$$y_{jikt} + y_{ijlt} \geq 2\, w_{iklt} \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \qquad (16)$$

$$I_{ik(t-1)} + \sum_{t'\epsilon T} \sum_{j\epsilon J} X_{jikt'} = \sum_{j\epsilon J} X_{ijkt} + I_{ikt} \quad \forall\, t\epsilon T, i\epsilon I, k\epsilon K \qquad (17)$$

$$TT_{ijkt} = \frac{d_{ijk}}{S_k} \times \left[1 + a \left[\frac{V_{ijkt}}{Cap_{ijk}} \right]^b \right] \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J \;\; \text{for } k = \text{Road} \qquad (18)$$

$$X_{ijkt}, Q_{ijkt}, J_{ijkt}, TT_{ijkt} \geq 0 \quad \forall\, t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \qquad (19)$$

$$I_{ikt} \geq 0 \quad \forall\, t\epsilon T, i\epsilon I, k\epsilon K \qquad (20)$$

$$U \geq 0 \tag{21}$$

$$y_{ijkt},\ w_{iklt} \in \{0,1\} \quad \forall\ t\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \tag{22}$$

The first two equations shows the cost and time expressions corresponding to two objective functions respectively. In Eq. (1), the first part indicates the total transportation cost on the network and the second part gives the total cost due to the transportation mode changes. In Eq. (2), the first term gives the total transportation duration of the system and the second term indicates the duration of the transport mode change. We obtain new linear conditions for our objective functions with Eqs. (3)–(5) for cost and Eqs. (6)–(8) for time. Eq. (9) enforces the conservation of flow among the nodes. The cost matrices of transportation modes, transfer operations, and distances between nodes are initialized with Eqs. (10)–(11). With these two constraints, the connectivity between the origin node *i* and node *j* or level of supply at node *i* are calculated. If the (*i*,*j*) pair of nodes are not connected or there is no demand in origin node *i*, it is not possible to transport any goods from node *i* to node *j*. Eq. (12) and Eq. (13) model the inventory profile at the nodes. We ensure that there the inventory capacity of the nodes are not violated by Eq. (13). Also, we assume that three is no inventory capacity for rail operations in the nodes since there are no inventory storage areas in the nodes of the Marmara Region. However, this can be changed depending on the particular area where storage is possible in rail operations. Eq. (14) indicates that any material in node *i* must be transported via at least one of the available transportation modes. This constraint forces the optimizer to find solutions with minimum transfer cost and transfer time in node *i* in terms of transportation modes. Eq. (15) ensures that demand of each node for every transportation mode at every time interval is satisfied. Eq. (16) shows that the arrival transportation mode of the node *i* must be the same transportation mode of the leaving mode of the node *j*. Eq. (17) indicates that the total quantity of incoming goods and leaving goods in node *i* for each transportation mode *k* are equal to each other. The summation of total incoming quantities and previous stock level must be equal to summation of total outgoing quantities and the current inventory level. The BPR (Bureau of Public Roads, 1964) equation (Eq. (18)) is used to model the travel congestion in the network. The BPR equation constants were obtained from Horowitz (1984) and this equation is used to obtain transportation times of the modes for each time interval t. In general BPR equation exponent b is assumed to be “4” but in our case it is taken as “1” to eliminate non-linearity in Eq. (18) because BPR equation depends on the transported quantity on the road. The lower value of exponent b causes speed to be insensitive to volume/capacity ratio until this ratio gets close to 1.0, and then the speed drops suddenly for higher values of exponent b but in our case speed decreases more slowly. However, the error gap between these two values is less than 5%. So, it is acceptable for our purpose and used in our model. Also, the case of non-linear mathematical model in which the exponent b is taken as “4” is also solved and the difference in results between our case (b = 1) and standard case (b = 4) is calculated between 0.2% and 7.9% and details are given in the Results section. Also, the volume/capacity ratio of BPR equation is designed by considering the total number of the vehicles on arc (i,j) at time t which means that the total amount of passenger and freight vehicles on arc (i,j) at time t is taken as V_{ijkt}. Eqs. (19)–(21) are the non-negativity constraints for the variables in the model.

Solution Methodology

This bi-objective mixed integer linear programming problem is solved with the augmented ϵ-constraint method (Mavrotas, 2009). The ϵ–constraint method produces non-extreme efficient solutions. On the other hand, with ϵ–constraint method almost every run produces a different efficient solution, thus many obtained efficient solutions are useful for decision makers. After finding the upper and lower bounds of the cost function (f_1 in Eq. (1)) and the time function (f_2 in Eq. (2)) respectively, the ϵ–constraint method is applied as shown below.

$$\text{Min } f_1 - (\mu\, x_s) \tag{23}$$

subject to:

$$f_2 + x_s = f_2^{UP} - \epsilon \tag{24}$$

Eqs. (3)–(22)

In this formulation, f_1 corresponds to “Cost Function”, f_2 corresponds to “Time Function” and constraints in Equations (3)–(22) are used. A new slack variable (x_s) is added to the second objective function and it is set to the upper bound of this objective function for each ϵ value in Eq. (24). Therefore, new f_1 value (f_1^*) is obtained. Modifications in the optimization model are as follows:

$$min\ f_1 = \sum_{t\epsilon T} \sum_{i\epsilon I} \sum_{j\epsilon J} \sum_{k\epsilon K} TC_{ijk}\, X_{ijkt} + \sum_{t\epsilon T} \sum_{i\epsilon I} \sum_{k\epsilon K} \sum_{l\epsilon L} TrC_{kl}\, w_{iklt} - \mu\, x_s \tag{25}$$

subject to:

$$\sum_{t\epsilon T} \sum_{i\epsilon I} \sum_{j\epsilon J} \sum_{k\epsilon K} J_{ijkt} + \sum_{t\epsilon T} \sum_{i\epsilon I} \sum_{k\epsilon K} \sum_{l\epsilon L} TrT_{kl}\, w_{iklt} + x_s = G - \epsilon \tag{26}$$

Eqs. (3)–(22)

We use the big–M parameters to express the relationship between continuous and discrete variables to avoid multiplication of two variables in the objective functions that results in non–linear models. For this, we introduce two new variables X_{ijkt} and J_{ijkt} for cost and time objective functions respectively and obtain new linear expressions by using Eqs. (3)–(5) for cost functions and Eqs. (6)–(8) for time functions. The μ value is set as 10^{-5} in Eq. (25). We add new slack variable to expression of the violation of the time function (Eq. (26)). The right-hand-side value of the time function changes in each iteration of the ϵ–constraint method, by subtracting the ϵ value for the iteration from the upper bound of the time function, G. We also subtract the slack variable from the main objective function to find integer feasible solutions.

Also, time dependent travel durations are expressed as the step-wise function for 24 hour time period per day in the problem. This balance in Eq. (17) has to be satisfied for every time interval *t*. However, the relationship between *t* and previous time intervals (*t'*<*t*) has to be satisfied in the (*t*-1,*t*) time interval as shown in Eq. (27):

$$t-1 \leq t^{'}+TT_{jikt'} \leq \mathrm{t} \quad \forall\, t'\epsilon T \tag{27}$$

The calculation of incoming quantities up to time interval *t*, travel duration of vehicles plays a crucial role as traffic congestion affects the travel duration of vehicles. To obtain the value of $\sum_{t'\epsilon T}\sum_{j\epsilon J} X_{jikt'}$ (incoming goods) in Eq. (17), the following logic for the system is defined:

For time interval *t* >2;

Transportation time matrix is obtained using Eq. (18). Then, the new parameter ($arrival\_time_{jikt\prime}$) is created which recognizes and keeps the arrival times of vehicles which leaves from node *j* at *t'* and reach to node *i* before time interval *t*. This transportation time matrix is constructed for road transportation only with Eq. (28) because transportation times for sea and rail transportations are assumed to be constant and given by Eq. (33).

$$t^{'}+\ TT_{jikt'}=arrival_{time_{jikt'}} \quad \forall\, t'\epsilon T, i\epsilon I, j\epsilon J \ \text{ for } k=Road \tag{28}$$

According to the arrival time values, a new binary matrix (*AT*) is used to indicate whether there are any flows which depart from node *j* at *t'* and arrive node *i* at *t* (is equal to $arrival\_time_{jikt'}$) for transportation mode *k*.

$$AT_{jikt't}=\begin{cases}1 & \text{if } arrival\_time_{jikt'}>0\\ 0 & \text{else}\end{cases} \quad \forall\, t\epsilon T, t'\epsilon T, i\epsilon I, j\epsilon J, k\epsilon K \tag{29}$$

Then, this new parameter (time matrix *AT*) is multiplied with $X_{ijkt'}$ to obtain the new quantities considering the transportation times. Total incoming goods to node *i* by transportation mode *k* until time interval *t*-1 and *t* is modeled in Eq. (30).

$$\sum_{\mathrm{j}\epsilon J}\sum_{t\prime\epsilon T} AT_{jikt't}\ X_{jikt'} \quad \forall\, t\epsilon T, i\epsilon I, k\epsilon K \tag{30}$$

3.3 Computational Experiments

In this section, we present an overview of the basic cost and time data used in the bi-objective mixed-integer linear programming model and analysis of computational results of intermodal transportation in the Marmara Region. We discuss the application of our model on a small scale illustrative case and on a large scale realistic case for the Marmara region. Our model has been implemented in GAMS (CPLEX, 2012).

Data

The data includes distances, transportation rates, average speeds for transportation modes, transfer costs and times, and inventory holding costs. This data involves different location on the transportation network, transportation modes and processes in the logistics activities.

Locations

Locations (departure and arrival nodes) in the intermodal transportation are more important than those of single-mode transportation systems due to high level of interaction between different transportation modes.

Nodes allow the transfer and storage of goods in all transportation modes, as well as departure and arrival of the vehicles. However, there are some restrictions on the location of nodes for road, rail, and sea transportation because of geographical characteristics and already available infrastructures.

In this study, the main ports of the Marmara region and intersection of current and proposed rail transportation links are considered as nodes in the intermodal transportation network. In addition, there is an extensive road transportation network and infrastructure in the Marmara region. Links among all the nodes are available for road transportation. Figure 6 shows a map of the area including 30 nodes and possible links among the nodes for different transportation modes.

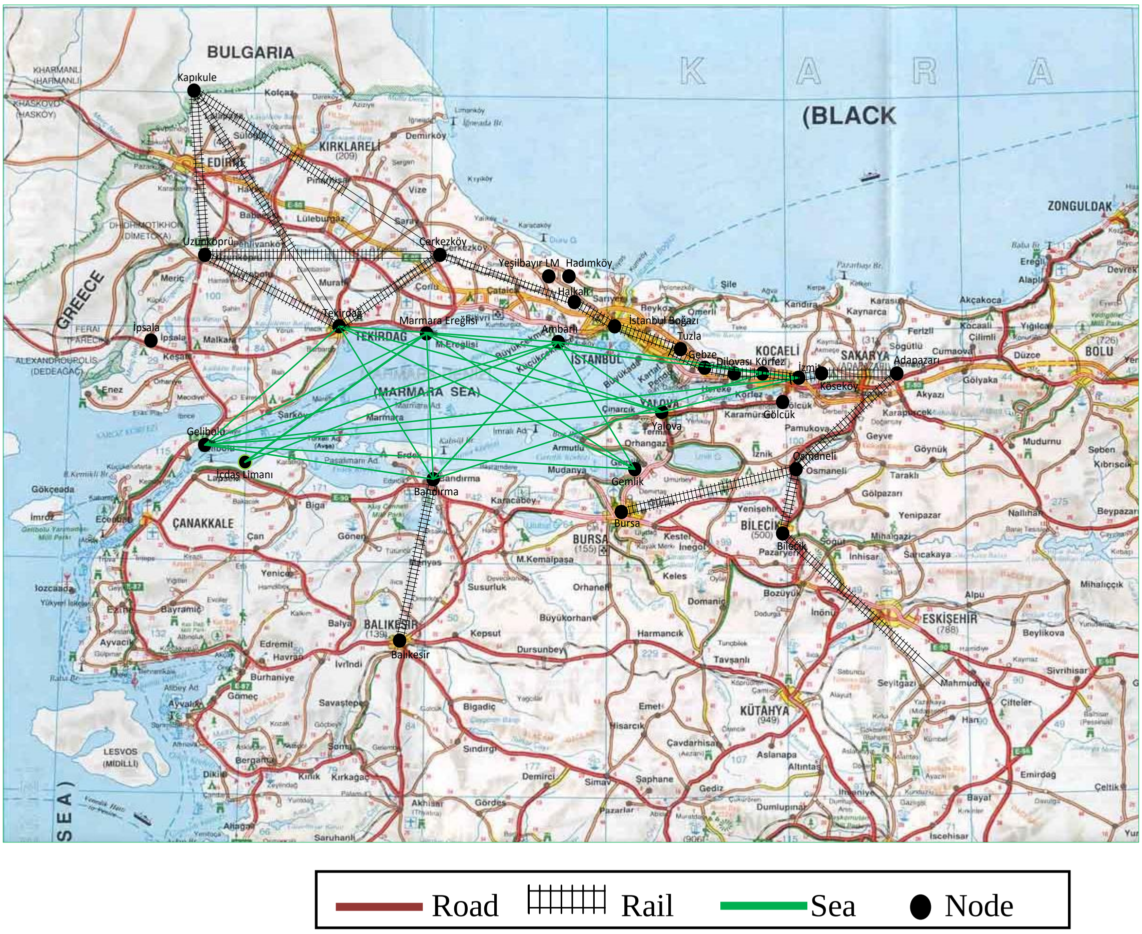

Figure 6: Transportation Hub in Marmara Region

After determining the locations of nodes in the region, distances between the nodes are determined. The data are obtained from the official reports (KGM Reports, 2011; DTM, 2010 and TCDD, 2010). Distances between the nodes are defined in kilometers for different transportation modes separately.

Transportation Types

Only road, rail, and sea transportation modes are used in this study because they cumulatively represent more than 99.5% of the total goods movement due to logistics operations in the Marmara region. One of the main objectives in our problem is the cost minimization that includes different types of transportation cost components: shipment costs between the nodes, transshipment costs in the nodes from one mode to another, and costs related to inventory management activities. The activity based cost analysis method is used to identify the optimal cost solution for the system. Unit cost parameters per kilometer of this model are obtained from UAPS (2005) in terms of investment, fuel, maintenance, and other considerations. All cost parameters for fixed operational costs are listed as in Appendix. Total unit shipment costs per kilometer for different transportation modes *k* are obtained using Equation (31).

$$TC_k = TC_c + TC_f + TC_m + TC_{ex} \;\; \forall\, k \epsilon K \tag{31}$$

After finding total unit shipment costs with 0.9 capacity utilization fraction of vehicles for each transportation mode *k*, total unit shipment cost are multiplied with the distance values between node *i* and node *j* for transportation mode *k* as in Equation (32).

$$TC_{ijk} = TC_k d_{ijk} \;\; \forall\, i \epsilon I, j \epsilon J, k \epsilon K \tag{32}$$

The transfer cost between different modes are obtained from Rossetti and Nachtmann (2005); Boardmann, Trusty and Malstrom (2001). Rate estimations from different sources are averaged to calculate the transportation transfer rates. All rate units are converted into dollars per container. In calculating the cost values, we assumed that on the average, a container with 15 ton cargo is applicable according to Trusty and Malstrom (1998).

The traffic congestion model is also considered as an important characteristic of the intermodal transportation problem in this paper. Therefore, vehicle speed profiles are used in the optimization model. Only the speed of vehicles which are used in road transportation is dependent on goods quantity carried on by vehicles. For other transportation modes (rail and sea), the speed of trains and ships were assumed to be constant as recommended by Rossetti and Nachtmann (2005). The upper limits on speeds for rail and sea transportation modes are given in Appendix. The speed of the vehicles in road transportation is calculated by using BPR equation (1964).

Transportation Processes

Time management plays an important role in transportation network design problems; therefore, the secondary objective of our intermodal transportation problem is the time minimization. Two important time factors are used during the operations: duration of direct transportation and transfer times from one transportation mode to another.

According to Rossetti and Nachtmann (2005), transfer times do not depend on the nodes specifically and represent an average value for all nodes in the network. Corresponding values for transfer times between the modes are listed in Appendix.

Eq. (18) is used to calculate the transportation time for the vehicles using the road transportation. However, transportation times directly depend on the total traffic flow on roads in this equation. Therefore, the load of the vehicles is assumed as a unit of 20 ton-container and total amount of goods carried on links are divided by unit weight of container to find the total traffic flow on that link. It is also assumed that every truck can carry only one container. In addition to the road transportation, the transportation times for sea and rail modes are assumed to be constant and calculated by using the average velocity in Eq. (33). Speed limits of transportation modes for free flow transportation are indicated in Appendix.

$$TT_{ijk} = \frac{d_{ijk}}{S_k} \quad \forall\, i\epsilon I, j\epsilon J \quad for\ k = Rail, Sea \tag{33}$$

There are also some restrictions on the departure and arrival times of rail and sea transportations. Due to operational restrictions on rail transportation and sea transportation in the Marmara region, the road transportation infrastructure must be shared between freight transportation and passenger transportation. Since the region has a population of 23 million (ABPRS, 2013), travel time restrictions are enforced to minimize the risks of accidents involving heavy vehicles. For example, we assumed that there are three time intervals per 24-hour period to departure from or arrival to nodes by rail transportation. The same situation is valid for sea transportation: ships can operate on some specific time intervals. Therefore, we assumed two time intervals per 24-hour period for sea transportation in our model.

3.4 Results

In this section, we illustrate the main concepts and the analysis of the solution on a simple version of the problem first, and then we apply our approach to the case of Marmara region.

Illustrative Example

The illustrative example consists of a five-node network with three different transportation modes (road, rail, and sea). The structure of our illustrative example is shown in Figure 7.

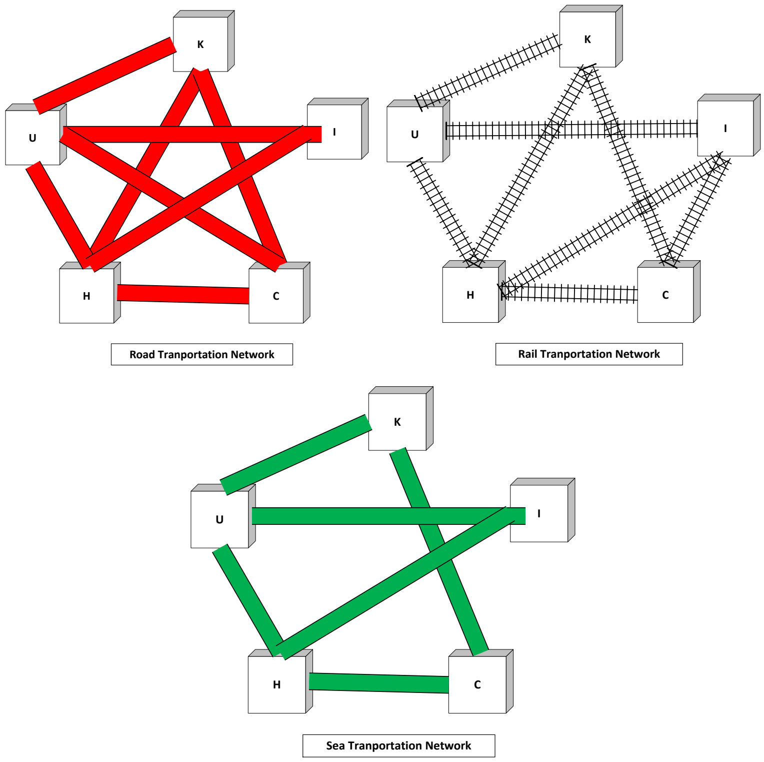

Figure 7: Structure of Network for Transportation Modes

The parameters used in the illustrative example are given in Appendix including distances, transfer costs, transportation costs, and transfer times.

In the illustrative example, we consider two different cases; one of them is our proposed mixed-integer linear mathematical model (Case A) and the other one (Case B) is the non-linear version of it in which the exponent *b* of Eq. (18) is taken as 4.

The models for these two cases are written in GAMS modeling environment, however the CPLEX (2012) is used in mixed-integer linear model (Case A) and solved with IBM ILOG CPLEX 12.1; DICOPT (Duran and Grossmann, 1986) is used to solve the non-linear model (Case B). Both models are executed on the same computer with Intel Core I5 2520 M CPU with 2.50 GHz dual core processor, and with 4.00 GB of RAM. An optimality gap of 1 % is set for the solutions.

The model statistics for this problem are given in Table 2.

Table 2: Model statistics for generating 100 Pareto solutions (Case A)

	Min	Max	Average	Median
Total CPU Usage Time [s]	0.79	539.12	90.19	18.09
Number of Variables	8,042	8,042		
Number of 0-1 Variables	2,880	2,880		
Number of Constraints	10,712	10,712		

Solving the multi-objective linear problem (Case A) with ϵ-constraint method generates the Pareto set that is approximated with hundred different points. The results are obtained for each instance of intermodal transportation problem with traffic congestion (see Figure 8).

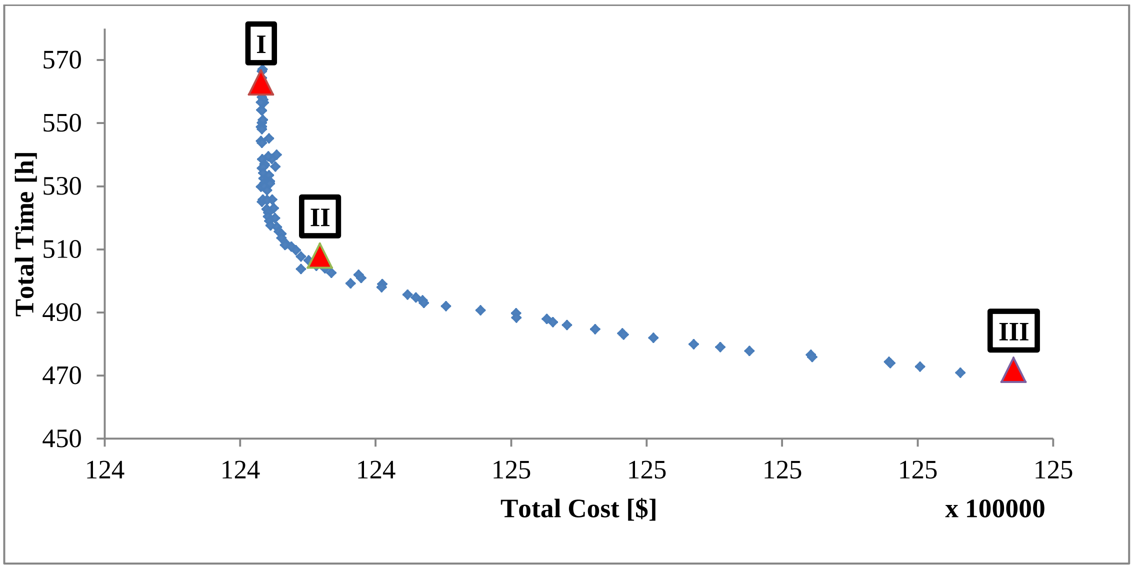

Figure 8: Pareto solutions of Illustrative problem for Case A

Also, we studied Case B for non-linear problem with the exponent *b* is equal to 4. Therefore, we obtained that the difference between solutions of Case A and B is between 0.2% and 7.9%. The results for this case are given in Figure 9.

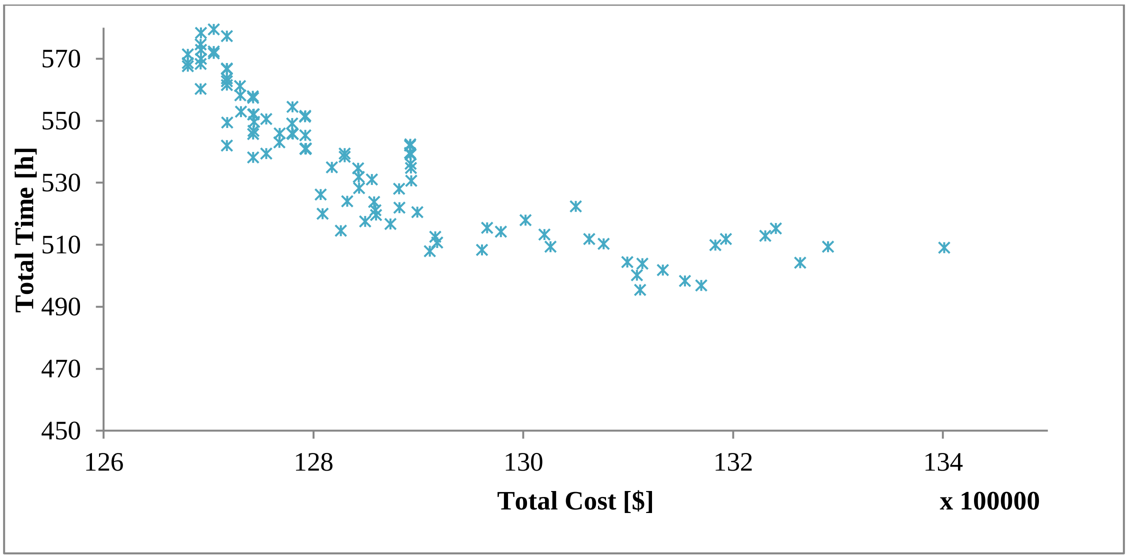

Figure 9: Pareto solutions of Illustrative problem for Case B

We choose three different solutions in different range of Pareto set for further analysis in Case A. These solutions are indicated as I, II, III and marked red triangles in Figure 8. The details and the cost-time matrices of these solutions are given in Figure 10-12 in Appendix. We examine the solution characteristics and analyze the effectiveness of the model below:

The material balance of the all goods transported in intermodal network is given in Figure 10.

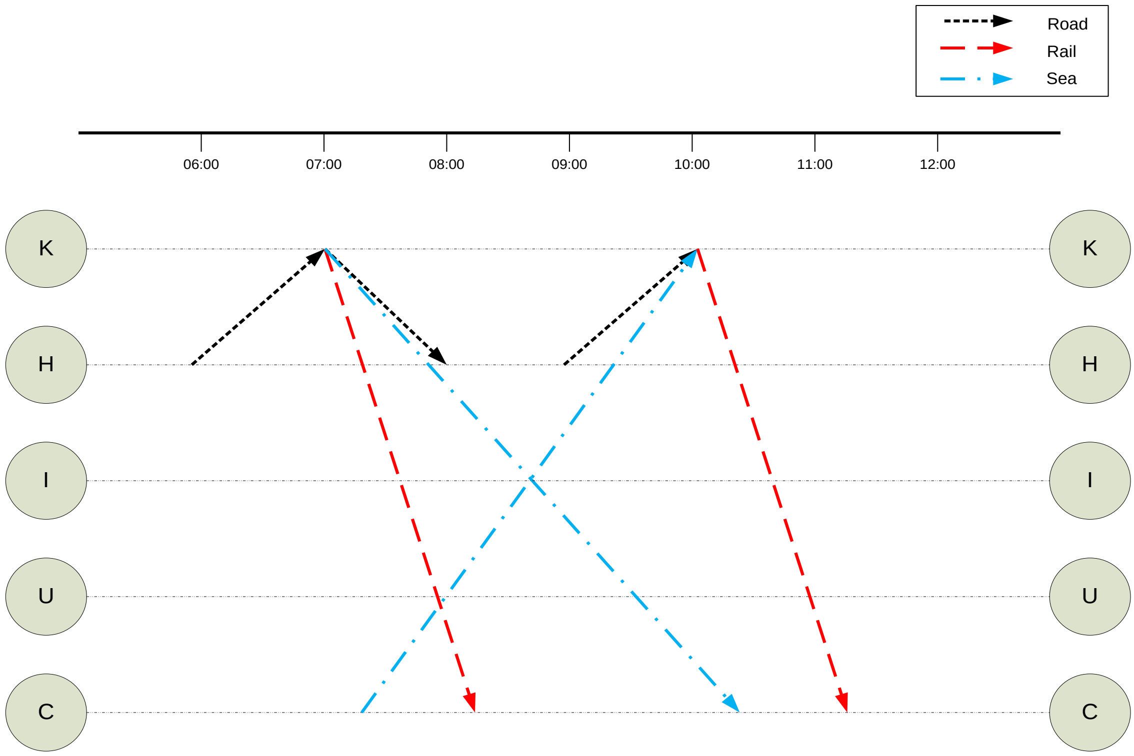

Figure 10: Illustrative network example for some time intervals

Case 1

If we examine Node *K* at 7:00 AM, there are three different outgoing shipments by road, rail and sea modes. There are transshipments from Node K to Node H by road, to Node C by rail and sea respectively. However, distances from Node K to Node C for rail transportation and sea transportation are around 23 km and 86 km, respectively. In our model, average transportation speeds for rail and sea transportation are given in Table A.4 and they are 60 and 35 km/h, respectively. So, if Eq. (33) is used to calculate the transportation durations, they are 0.38 h for rail and 2.45 h for sea transportation, respectively. The extended results are illustrated in Figure A.1. In the Figure A.1, we can see that there are some bars showing connection from Node K to Node C for different transportation modes: the green one indicating sea transportation goes from 7:00 AM to 10:00 AM and the red one for rail transportation goes from 7:00 AM to 8:00 AM.

Case 2

If we examine Figure 10, there has to be mode changes around 10:00 AM in Node K, because before 10:00 AM, there are some flows coming to the Node K. One of them departs from Node H to Node K by road transportation around 9:00 AM and another one departs from Node C to Node K around 7:00 by sea transportation. However, there is only outgoing flow from Node K to Node C by rail transportation which means that incoming cargo whether stored in the inventory or there are some mode transfer operations in the Node K from both road and sea transportation to rail transportation.

Table 3: Cost–Time comparison of different solution points

	Solution I	Solution II	Solution III
Total Cost [$x10^4]	1,243.2	1,243.6	1,248.7
Total Time [hour]	563	508	473
	Solution A & B		Solution B & C
Difference % in Total Cost	0.03		0.41
Difference % in Total Time	10.79		7.44

As shown in Figure 8, there is an inverse relationship between the time and cost values. According to Table 3, while reducing the time factor by 10.79% from solution I to II, 0.03% additional cost is needed on total cost of solution I. On the other hand, if total time decreases by 7.44% from solution II to III, 0.41% extra cost has to be paid to fulfill that requirement.

As shown in Figure 8, it is seen that reduction in time value for solution II is more affordable. In order to reduce the transportation time, there is more effect on cost values in range between solution II and III than the range between solutions I and II.

Results for the Marmara Region

Mathematical model presented in Section 2 is also applied on the Marmara Region with 30 node network containing three different transportation modes (road, rail and sea). The structure of our test example is shown in Figure 6.

The parameter values used in the model are listed in Appendix (e.g., transfer costs, transportation costs and transfer times).

The problem statistics of the optimization model are summarized in Table 4.

Table 4: The model statistics for 65 Pareto Solutions (Marmara Example)

	Min	Max	Average	Median
CPU Usage Time[s]	62.71	6,942	1,071	423.56
Number of Variables	246,243	246,243		
Number of 0 - 1 Variables	71,280	71,280		
Number of Constraints	331,756	331,756		

We generate 65 different Pareto solutions of intermodal transportation problem with traffic congestion. The results are shown in Figure 11.

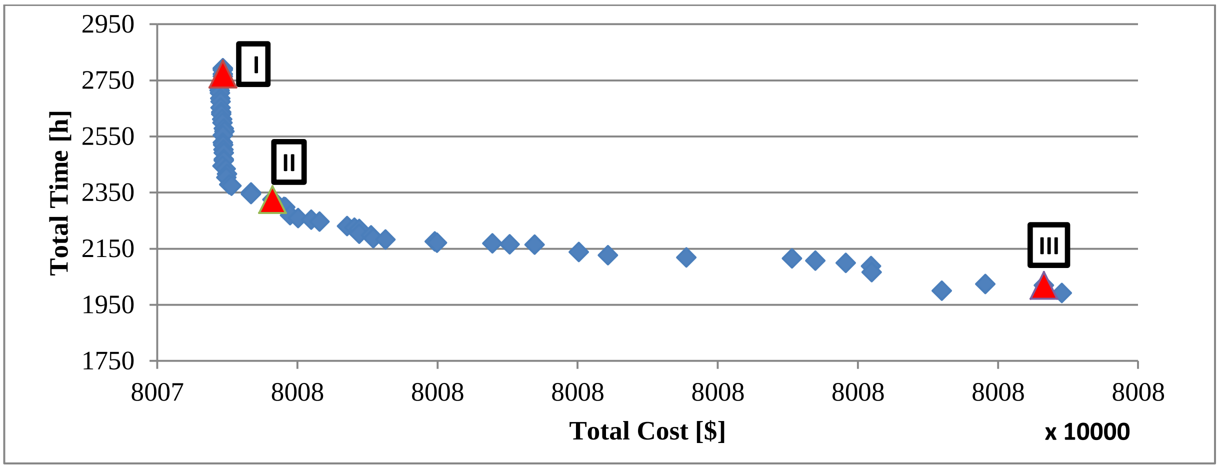

Figure 11: Pareto solutions of Marmara example

We analyze three different solutions in different ranges of the graph that are indicated with red triangles in Figure 11. According to results shown in Figure 11, detailed solutions and cost-time matrix for those solutions are indicated in Table 5:

Table 5: Cost–Time comparison of different solutions

	Solution I	Solution II	Solution III
Total Cost [$x10^4]	8,007.4	8,007.5	8,008.1
Total Time [hour]	2,772	2,324	2,020
	Solution I & II		Solution II & III
Difference % in the Total Cost	0.44		0.69
Difference % in the Total Time	19.28		15.05

Figure 11 shows a reverse proportion between the time and cost values. According to Table 5, while minimizing the time factor 19.28%, only 0.44% additional cost is incurred on the total cost. On the other hand, if total time decrease by 15.05%, only 0.69% extra cost has to be paid to fulfill that requirement.

3.5 Conclusions

This paper analyzes optimization of transportation problem with several transportation modes under the cost minimization and time minimization principle. In addition to minimization of time and cost factors, traffic congestion has been shown to be an important concept, because traffic congestion has an important impact on time factor. The most reliable speed-flow equation the BPR (Bureau of Public Roads) for under capacity conditions was used to predict delays in intermodal transportation.

The solution of resulting non-linear model MINLP (Mixed Integer Non Linear Problem) was converted to a linear model MILP (Mixed Integer Linear Problem). Then, the bi-objective problem was solved with an implementation of the augmented ϵ-constraint method in GAMS. Due to the two objectives (cost and time minimization) in this problem, the concept of optimality is replaced with Pareto optimality. In this method, cost function was kept as the primary function and minimized. Time function is converted into a constraint with different ϵ values and slack variables for the time function are introduced to maintain integer feasibility of the solutions. For each ϵ value, optimal solutions for cost function were found, and then solutions are summarized for the decision makers.

The advantages of our approach are explained in the introduction section of this paper and a bi-criteria optimization method for solving large size discrete-continuous problems is used to generate the set of Pareto solutions. Optimal locations and links for intermodal transportation in the Marmara region are illustrated for different cost and time values. It is shown on the examples that there is an inverse relationship between time and cost values and the marginal cost of reducing time value increases after some point.

To our knowledge, this paper is the first one to presents intermodal transportation problem with traffic congestion. The models and solution methodology presented in this paper can be used to facilitate accurate data support for selection of intermodal hub locations and the design of logistics centers. Also, decision makers can analyze the usage levels of links and hubs from the results of this study. Then, any additional hubs or links should be constructed for effective use of links or nodes in the region.

Future work in this area should include additional considerations related to intermodal and sustainable transportation. Environmental effect of transportation can be included in a larger study because both traffic congestion and transportation modes have direct effect on CO_2 emission of vehicles. Also, different traffic congestion models can be used, such as multi-class traffic equilibrium problems can be added into this problem. In addition to the adding new objectives or constraints into the current model, different types of cargo can be considered. For example, multi-product cases and consolidation activities of the freight can be included.

Chapter 4

A BI-OBJECTIVE MODEL FOR DESIGN AND ANALYSIS OF INTERMODAL TRANSPORTATION SYSTEMS: A CASE STUDY OF TURKEY

4.1 Introduction

The role of the logistics sector in the development of countries is well recognized and has been integrated into policy making processes and expressed particularly in the White Paper in 2011 for European logistics sector. The report of COM (2011) proposes the case for transforming the European logistics sector into a sustainable and competitive system that will further improve mobility and continue to support economic growth and employment. The logistics sector has a positive impact over economic growth and development of the countries, since it is directly integrated into industrial and service sectors. The study of Stank et al. (2005) indicated that logistics activities should be synthesized with the supply chain and the integration should be considered with the well-established design of the performance systems between strategy, structure and processes (Rodrigues et al., 2004). According to the data from EUROSTAT (2015), total carried goods between the European Union countries by different transportation modes are estimated to be around 3,831 billion ton per km in 2013. This tremendous quantity shows the effect and the importance of the logistics sector in European countries. However, the road and sea transportation occupies the significant share of all these transportation activities, such as 45.8% and 36.9% respectively. The increased awareness about environmental factors and changes in customer behavior lead to a need for more qualified and reliable systems because the international assumption is that a transport system depending mostly on road transportation is unsustainable in the medium term owing to growing congestion, negative external factors and not guaranteeing the levels of safety and efficiency required by the growing volume of traffic (Turkay, 2008). In order to handle the challenges facing the European logistics sector and achieve a smart, sustainable and inclusive European economy as outlined in Europe 2020 strategy (COM, 2011), conventional thinking must be replaced by new ideas, pioneering strategies, and entrepreneurship. This means that the share of the road transportation should be decreased and new, more sustainable systems should be developed to decrease the carbon emission rates and traffic congestions on the roads. Turkay (2008) examined the environmentally conscious supply chain systems and indicated that transportation based sustainability approaches should be the major focal points to include the sustainability considerations in supply chain management. He argued that development of intermodal transportation systems will play an important role in reducing the impact of the transportation activities on the environment, especially in terms of emission parameters. Then, the concept of intermodal transportation has been recognized worldwide as a promising way to reduce logistics costs, although it still faces some operational challenges (Resat and Turkay, 2015). The European Commission (1997) defined intermodal transportation as the system of transportation activities by using two or more transportation modes for the same loading unit especially a container based units without loading or unloading of the products themselves. Also, it is considered that intermodal transportation system is the organized and flexible network of various modes of efficient cargo transportation by reducing the total cost of distributing goods, as well as ensuring efficiency, reliability and safety in the movement of goods. Therefore, intermodal transportation has a significant and critical factor in the success of competition among supply chain systems of the current trade activities. According to the report of Association of American Railroads (AAR, 2015), freight movements are expected to grow around 45% from 19.7 billion tons in 2012 to 28.5 billion tons in 2040 and also total cargo volume carried by road transportation is decreased around 4.9% (app. 13 million units) and the share of intermodal is increased 1.9% in 2015. These figures reflect the importance and strength of the intermodal transportation in business activities and it is expected that intermodal transportation generates significant revenues for the transportation companies with increased amount of cargo volumes.

The position of the intermodal transportation in Turkey is parallel with European countries. Turkish government is committed to intermodal or combined transportation as one of the key factors for consolidating economic growth and using the country's geo-strategic location as a world-class logistics platform and tried to convert its transportation system from road transportation to intermodal transportation. Although there are still lack of infrastructure and regulations in Turkey (such as no domestic Road-Rail Lines, lack of ferries in the Marmara Sea, dominant road transportation (90%)), many international companies operate intermodal transportation between the European and Middle East countries. According to the report of Ministry of Transportation in Turkey (TCTS, 2013), Turkey has one of the largest road transportation fleets in Europe and there are many international transportation corridors passing through the Turkey, such as Trans European Roadway, Trans European Railway, etc. In order to ensure the successful use of a country's logistics potential, the existing physical comparative advantages (geographical location, coastline, and well-structured road infrastructure) need to be transformed into competitive advantages by defining and starting up common intermodal transportation systems. Resat and Turkay (2015) reflected the importance of intermodal transportation in Marmara Region of Turkey by sharing some data for usage of intermodal transportation by Turkish logistics companies in the Europe. For example, more than 125,000 trucks mostly use the combination of sea and road transportation (RO-RO lines) between Pendik Port in Turkey and Port of Trieste in Italy or Port of Illichecvsk in Ukraine. Also, more than 300,000 trucks use the combination of road and rail transportation (RO-LA) between Istanbul in Turkey and Cologne or Ludwigshafen in Germany through Hungary, Austria, Slovenia, Germany (UND, 2013).

Due to the significant importance of intermodal transportation in operational and tactical levels, there are many initiative and researchers tried to integrate and improve the connectivity between the different transportation modes and yield some significant results for the logistics industry. The research in the intermodal transportation area is accelerated in recent years and according to the study of Mathisen and Hanssen (2014), almost 33% of the articles are published in the most prestigious journals since last three years and this figure again shows the importance of the intermodal transportation concept. SteadieSeifi et al. (2014) summarized the papers on intermodal transportation into three main levels; strategic, tactical and operational. At the strategical level, Limbourg and Jourquin (2009) proposed some solution methodologies by using heuristic models, also Meng and Wang (2011) discussed the capacitated and multi-commodity problem in order to satisfy the transshipment costs in maximizing marginal profits of carriers. Alamur et al. (2012) proposed some models for hub location problems. Meyer et al. (2009) shared exact solution methodology with two-phase Branch & Boundary algorithm. Bektas et al. (2010), Camargo et al. (2009) and Marin et al. (2006) studied the Benders' decomposition and relaxation method as a solution methodology. Meng et al. (2012) proposed exact solution algorithm by relaxing and decomposing the models.

At the strategic level, capacity parameter has significant importance in consolidation systems because inclusion of congestion in hub location problems leads to more balanced distribution of flows throughout the network. Ishfaq and Sox (2012) modeled the system at a given hub as queueing networks and include the congestion. In the literature, there are many papers proposing the general information on network design of the intermodal freight transportation. Southworth and Peterson (2000) studied the development and design of multi-modal transportation network in international freight movements and used the data from U.S. Commodity flow surveys in 1997. Wang and Regan (2002) proposed a mathematical model for the pick-up and delivery operations by considering the time-windows. Zhang et al. (2003) studied the solution methods to assess the inventory capacities of container terminals. Bontekoning et al. (2004) listed the extensive literature survey by considering the intermodal transportation activities and indicated the main research needs to boost the intermodal transportation in logistics industry. Arnold et al. (2004) proposed one of the most important mathematical models to obtain optimal terminal locations intermodal transportation network. They considered the road and rail transportation modes in their study. Parola and Sciomachen (2005) studied relation between the container traffic and ports hinterlands and assess the effects of the sea transportation over the road and rail transportation activities. Groothedde et al. (2005) and Parola and Sciomachen (2005) studied about network design of the intermodal transportation and tried to obtain optimum locations of intermodal hubs. Roso et al. (2009) studied on dry port concept and tried to link sea and rail transportation by determining the capacities and locations of port hinterlands. Caris, Macharis, and Pekin (2011) studied service network design problem focusing on cooperation of inland terminals and line bundling.

Modern transportation systems cannot depend on a single objective and there are multiple criteria in making decisions. Cost is the most relevant parameter at the time of making transportation mode choices. The logistics providers should satisfy customers by given the services with lower prices and in a faster manner. Also, with the recent regulations and increased awareness about environmental issues lead customers to be very sensitive about the environmental impacts of transportation activities, especially the greenhouse emissions. Therefore, three main objectives of transportation systems should be taken into account extensively and Pareto optimality should take replace to make decisions for cost, time and environmental factors in intermodal problems. There are some solution methodologies to handle the multi-objective problems in the literatures. In general, two conventional methods are used to generate Pareto solutions for multi-objective optimization problems, which are the ϵ-constraint method and the weighting method. In this study, the ϵ-constraint method is used because the weighting method may sometimes miss some of the efficient solutions in some feasible regions (Mavrotas, 2009). In the ϵ-constraint methods, one of the objectives is taken as a single objective function and others are included into a model as constraint. Therefore, a set of solutions can be found by improving one objective and worsening the others. Several approaches are proposed in the literature for the ϵ-constraint methods. Haimes et al. (1971), Hwang and Masud (1979) studied the specific type of linear problems and generate an approximated set of Pareto solutions. The augmented ϵ-constraint (AUGMECON) method by Mavrotas (2009), its improved version (AUGMECON2) by

Mavrotas and Florios (2013), and simple augmented ϵ-constraint by Zhang and Reimann (2014) proposed solution methods to find the set of exact solutions in multi-objective problems by adding slack variables into the objective functions which are taken as constraints and penalty term into the main objective function. Fattahi and Turkay (2016) studied a novel one direction search method to find the exact non-dominated frontier of bi-objective mixed-integer linear problems.

Intermodal transportation can play an important role in reducing vehicle emissions in the road transportation because share of the road transportation is significantly high and improving intermodal connections in freight movements, increased use of sea and rail movements instead of truck only movements may decrease the pollution rates because rail and sea transport has lower emissions per ton mile than road transportation. While considering cost and time functions with traffic congestion, carbon dioxide emission rate is another important objective for current transportation operations. In this kind of problems, decisions over the routes of vehicles are important because given decisions directly affect the total distance occupied by the vehicles which means that total fuel consumption and carbon emissions can increase according to the total distance taken. In the literature, this kind of problem is modelled as *Vehicle Routing Problems (VRPs).* Dantzig and Ramser (1959) was introduced this problem firstly with limited vehicle capacities between depots and customers by minimizing the total number of vehicles and maximizing the total distance travelled. After their study, Laporte et al. (1984) developed a mathematical model with time intervals. In their study, they tried to maximize total distance within the specific time windows by satisfying the capacity constraints. Before the Bektas and Laporte introduced the *Pollution Routing Problem (PRP)* in 2011, there are many studies in the literature focusing on the reduction in the total fuel consumption by reducing the total distance travelled. The survey of Lin et al. (2014) gives and analyzes exhaustive literature review over the vehicle routing problems and they classified them into different application domains. According to this survey, green vehicle routing problems should concern the energy consumptions of the system which means that reducing the fuel consumption and increasing the transportation efficiency will directly affect the green-house gas emissions and this will be main concern of the this type of problems. In this perspective, Bektas and Laporte (2011) argued to extend classical *VRP* problem by considering the amount of green-house emissions, travel times and total transportation costs. In their study, they developed mathematical models with comprehensive objective functions to indicate the vehicle loads and speeds. Also, Conrad and Figliozzi (2011) presented a routing problem for electric vehicles to decide on the charging stations as the *Recharging Vehicle Routing Problem (RVRP).* In their study, they try to decide on recharging operations of the electric vehicles during the transportation operations in which vehicles can be recharged in the locations of customers instead of dedicated stations. Therefore, there can be some savings in the total transportation times because there can be both loading activities and recharging of the vehicles instead of spending time at the dedicated stations for recharging. In 2012, Erdogan and Miller-Hooks developed the green concept in routing problems. They introduced the *Green Vehicle Routing Problem (G-VRP)* by considering the recharging of the vehicles with limited fuel capacities. In *G-VRP* problem, vehicles are eliminated from the risk of running out of fuel and service time of each customer and the maximum duration restriction was posed on each route. After this study, Schneider et al. (2012) extended the *G-VRP* by including the customer time windows for the delivery operations in which electric vehicles are used. The *Electric Vehicle Routing Problem with Time Windows and Recharging Stations (E-VRPTW)* deals with the routing of the electric vehicles with limited capacities by considering the possibility of recharging at any of the dedicated available stations. *E-VRPTW* includes two main objectives which are minimization of total number of used vehicles and total distance travelled. Franceschetti et al. (2013); Demir et al. (2014) developed some models using this pollution routing problems. Then Jabali et al. (2012) proposed a model for time-dependent pollution routing using the same emission functions by considering speed as an additional decision variable. Franceschetti et al. (2013) uses the similar approach in their proposed model for time-dependent pollution routing problems.

Traffic congestion not only contributes to delays in travel times, it also increases fuel consumption that leads to higher carbon emission rates. Therefore, the traffic congestion model should be considered in intermodal transportation problems to reduce carbon emission rates on highways and perhaps avoid additional costs. The traffic congestion is directly depending on the number of total passenger and freight vehicles on the roads and quantity of the carried goods on each vehicle. There are many studies proposing the linkage between vehicle speeds and their volume/capacity ratios in the literature. The Bureau of Public Roads (BPR) introduced the BPR equation (Bureau of Public Roads, 1964) fitted to freeway speed flow data given in the highway capacity manual in 1965 (Highway Capacity Manual, 1965). Akcelik (1996) and Dowling et al. (1998) modified the BPR equation and proposed more complicated speed-time estimation models.

The main contribution of this study is to analyze the intermodal transportation network in European level and propose bi-objective mixed-integer linear mathematical model considering cost and carbon emission rates objectives. The novel approach of this paper is the getting faster and more sustainable Pareto solutions for decision makers by using new developed solution methodology for bi-objective mixed-integer linear problems in the real-life cases. Also, Pareto solutions of this new algorithm are compared with the ones obtained from the augmented ϵ-constraint method and shared with the decision makers.

This chapter is divided into five sections. Section 2 presents necessary technical background on the problem definition of real-life case and some information for solution methodology of this problem and provides detailed information about assumptions for the mathematical model in bi-objective intermodal transportation problem. Section 3 includes the information about the initial data and some parameter which are used during the calculations. Section 4 gives the results for the real-life case and comparative results from two different solution methodologies. Finally, Section 5 shows the general overview and some future steps of the problem.

4.2 Problem Statement

In this section, we indicate the definition and design of the problem and present the formulation of mixed-integer linear optimization model for bi-objective problem which examine cost and carbon emission rate functions for different transportation modes. Also, two different solution methodologies are analyzed and solution algorithms are given.

Problem Definition

In this study, we defined our problem as a bi-objective mixed-integer linear problem and the minimization of total cost for cargo movements and transshipment activities in the nodes is considered as a primary target. Also, the total carbon emission rates are taken into account and defined as a second objective. The main purpose of this problem is the minimization of negative effects of road transportation that leads to high carbon emission rates and fuel consumption for the logistics systems, as well as satisfying the customer expectation about lead time for standard services considering other type of transportation modes. In our problem, the logistics operations start from the important logistics centers located in different cities of Europe and single type of product is considered in unit of containers. The cargos are carried by two different types of trucks between the origin/destination pairs and their capacities are taken as 20 and 40 feet containers. When the trucks come to the transshipment points, there will be a transfer from trucks to the ferries or trains. The capacities of ferries are also assumed as constant and taken as 239 unit 20 feet container per ferry. After the transfer points, last-mile deliveries are made by trucks.

The cases are designed by using the real-life data from the one of the important logistics provider in Turkish intermodal transportation sector. Therefore, the scenario is developed like Turkish cargos are loaded to semi-trailers or trucks that are capable for being used in intermodal transportation and are started their operation from Istanbul, Izmir and Mersin ports. The trucks can either carry their cargos to Central European countries by using road transportation or they can be loaded on the board of Ro-Ro vessels and transported to the Port of Trieste, Italy in a 3 days ship passage or transferred to the trains to be reached to Germany, Austria or Czech Republic by rail transportation. After having arrived in the Port of Trieste, the trucks are transshipped onto the intermodal block train towards Germany or Austria. The train trip to its destination, the intermodal transshipment terminal in Wels or Munich, requires a transit time of less than one day. From these final train stations, the cargos will be distributed to the final destinations such as destinations in Germany or other Western European countries such as Benelux countries, France, United Kingdom, Switzerland, Denmark, Ireland and Spain by road transportation.

The proposed model considers the network design for the intermodal transportation in Europe; however there are many assumptions for the real-life cases. For example, weight capacities of the trains and operational constraints for rail terminals especially in Czech Republic are very limited and restricted. In real-life cases, there are some quotas for the road transportation activities in Europe, such as 19,000 vehicles with EURO5 engines are let to operate under the foreign driving licenses in Italy in 2016 (UND, 2015) and also, there are some quota limitations for international road transportation in Austria and Hungary. Total waiting times in the ports are assumed as the summation of total time spent for transshipment and the customs clearance activities. Also, there are some limitations in the mode changes in the ports due to the customs regulations, but this assumption is not included into the problem.

Model Formulation

This optimization model for intermodal transportation problem is developed as bi-objective mixed-integer linear programming (BOMILP). The main objectives are total transportation cost on the system and the total CO_2 emission amounts. Our model is based on indices which are indicated below:

The problem consists of five sets which are set of nodes, C, set of transportation modes, $K=\{(k,l) \mid k,l \in K,\ k \neq l\}$, set of time intervals, T, set of vehicle speed levels, S and set of regions of speed module based on congestion, R. Lets define W as the set of all nodes $W=C \cup K \cup T \cup S \cup R$. We assumed that all of the initial data for demand of each node for different transportation modes at different time intervals (D_{ikt}), locations and distances between these nodes (d_{ijk}), operational data such as opening (Δ_{ikt}) and closing of the nodes (μ_{ikt}), loading of vehicles in each node for different transportation modes (L_{ik}), capacity of the nodes for each transportation modes (C_{ik}) are given beforehand. Therefore, the process is started from the determined logistics centers (nodes) and conventional vehicles are used to transport cargos in a unit of containers between the customers with a unit transportation costs per transportation modes (TC_{ijk}). Sometimes, there are changes between the transportation modes at the nodes and this operation leads to additional transfer cost (TrC_{kl}) and transfer time (TrT_{kl}) which also take a fixed value for each transportation mode and node. This operation requires the decision on opening links between nodes and how much cargo and which kind of transportation mode is used for cargo carriage on the arcs defined as $A=\{(i,j) \mid i,j \in C,\ i \neq j\}$. Also, problem decides on the penalty costs if there is any waiting process due to the early or late delivery to the customers which are indicated as *P1* and *P2* for early and late arrival situation respectively. The model observes the effect of the environmental aspects by calculating the carbon dioxide emissions in terms of speed levels and some other parameters for this purpose.

S_k Speed limit of transportation mode k for free-flow transportation

b_{ijkm} Time constant of corresponding travel time module m for vehicles traveling on arc (i,j) by transportation mode k

$$b_{ijkm} = \begin{cases} 0 & m = 0 \\ \left(alfa - \dfrac{d_{ijk}}{S_k^c}\right) & m = 1 \\ alfa & m = 2 \end{cases}$$

θ_{ijkmr} Carbon dioxide emission equation constant

$$\theta_{ijkmr} = \begin{cases} 0 & m = 1,3 \\ \dfrac{S_k^{2r} - S_k^{3r}}{S_k^{3r}} & m = 2 \end{cases}$$

ω_{ijkmr} Carbon dioxide emission equation constant

$$\omega_{ijkmr} = \begin{cases} 0 & m = 0 \\ \dfrac{d_{ijk}}{S_k^{1r}} & m = 1 \\ \dfrac{d_{ijk}}{S_k^{1r}} + \left(\dfrac{S_k^{3r} - S_k^{2r}}{S_k^{3r}}\right) & m = 2 \\ \dfrac{d_{ijk}}{S_k^{3r}} & m = 3 \end{cases}$$

Also, there are some mathematical parameters in the calculation of bi-objective problem by using ϵ-constraint method.

G1 Any large value greater than upper bound of the secondary objective function

G2 Any large value greater than upper bound of the time function

There are many scalars for this problem and they are mostly used in speed and carbon dioxide formulations.

Scalars:

a, b	BPR equation constants
A,B,C	Carbon dioxide emission rate constants
alfa	Initial congestion duration (minutes)
ϵ	Epsilon value
σ	Curb weight (kg)
Ω	Daily period (hours)
k	Engine Friction Factor constant
U	Engine Speed constant
H	Engine Displacement constant

There are two main objectives in this problem; cost and carbon emission rate. While the problem takes the cost objective as a prior action and tries to minimize the cost variables; the environmental objectives are also taking into account. Therefore, problem minimizes the total number of carried goods (X_{ijkt}) on arc (i,j) and total number of inventories (I_{ikt}) for each kind of transportation mode in different time intervals. Also, if there is any transfer between the transportation modes, then this will creates some additional cost for the system and model tries to reduce this cost variable. However, the minimization of the cost is not enough for bi–objective problems. Therefore, model considers the total transportation duration (TT_{ijkt}) on arcs (i,j) and also time consumption during the transfer operations. Additionally, model controls the operational movements of the cargos in terms of their time frames, such as arrival (ta_{ijkt}) and departure time (td_{ijkt}) of the vehicles to/from the nodes for different transportation modes; waiting times of the vehicles in each node for different transportation modes (EW_{ikt}, LW_{ikt}, NW_{ikt} for early, late and normal arrival cases respectively).

Also, there are some binary variables to control the transportation operations in an effective way.

Binary Variables:

y_{ijkt} $\begin{cases} 1 & \text{if transportation mode } k \text{ is chosen on arc } (i,j) \text{ in time interval } t \\ 0 & \text{else} \end{cases}$

w_{iklt} $\begin{cases} 1 & \text{if transfer from transportation mode } k \text{ to } l \text{ in node } i \text{ in time interval } t \\ 0 & \text{else} \end{cases}$

$z1_{ijkt}$ $\begin{cases} 1 & \text{if vehicle in node } i \text{ for transportation mode } k \text{ in period } t \text{ arrives early} \\ 0 & \text{else} \end{cases}$

$z2_{ijkt}$ $\begin{cases} 1 & \text{if vehicle in node } i \text{ for transportation mode } k \text{ in period } t \text{ arrives late} \\ 0 & \text{else} \end{cases}$

$z3_{ijkt}$ $\begin{cases} 1 & \text{if vehicle in node } i \text{ for transportation mode } k \text{ in period } t \text{ arrives in time} \\ 0 & \text{else} \end{cases}$

$g1_{ijkmr}$ $\begin{cases} 1 & \text{if vehicle departs node } i \text{ in time interval } m \text{ by mode } k \text{ } and \text{ speed } r \\ 0 & \text{else} \end{cases}$

First, the non-linear model is developed and main objective functions and constraints are listed below:

$$min \quad f_1 = \sum_{t\epsilon T}\sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{k\epsilon K}\left(TC_{ijk} \times X_{ijkt}\right) + \sum_{t\epsilon T}\sum_{i\epsilon I}\sum_{k\epsilon K}\sum_{l\epsilon L}(TrC_{kl} \times w_{iklt}) + \sum_{i\epsilon I}\sum_{t\epsilon T}\sum_{k\epsilon K}(I_{ikt} \times P1) \quad (1)$$

$$min \quad f_2 = \sum_{m\epsilon M}\sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{r\epsilon R}\sum_{k\epsilon K}\left\{\left\{\left(\theta_{ijkmr} \times g2_{ijkmr} + \omega_{ijkmr} \times g1_{ijkmr}\right) \times A + \left(\theta_{ijkmr} \times g2_{ijkmr} + \omega_{ijkmr} \times g1_{ijkmr}\right) \times (S_{kmr})^3 \times B\right\}\right\} + \sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{k\epsilon K}\sum_{r\epsilon R}\left\{\left\{\left(g2_{ijk2r} + \theta_{ijk2r} \times g2_{ijk2r} + \omega_{ijk2r} \times g1_{ijk2r} - \alpha \times g1_{ijk2r}\right) \times (S_{k3r})^3 \times B\right\} + \left\{\left(\alpha \times g1_{ijk2r} - g2_{ijk2r}\right) \times (S_{k2r})^3 \times B\right\}\right\} \quad (2)$$

$$\sum_{t\epsilon T}\sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{k\epsilon K}(TT_{ijkt}) + \sum_{t\epsilon T}\sum_{i\epsilon I}\sum_{k\epsilon K}\sum_{l\epsilon L}(TrT_{kl} \times w_{iklt}) + \sum_{i\epsilon I}\sum_{t\epsilon T}\sum_{k\epsilon K}\{((EW_{ikt} + LW_{ikt}) \times P2) + (NW_{ikt} \times P3)\} \le G_2 \quad \forall\, t\epsilon T, (i,j)\epsilon A, k\epsilon K \quad (3)$$

$$EW_{ikt} \ge \left[\Delta_{ikt} - t\alpha_{ijkt}\right] + M3\left(1 - z1_{ijkt}\right) \; \forall\, t\epsilon T, (i,j)\epsilon A, k\epsilon K \quad (4)$$

$$LW_{ikt} \ge \left[\Omega - t\alpha_{ijkth} + \Delta_{ik(t+1)}\right] + M3\left(1 - z2_{ijkt}\right) \; \forall\, t\epsilon T, (i,j)\epsilon A, k\epsilon K \quad (5)$$

$$NW_{ikt} \geq \left[td_{ijkth} - ta_{ijkt}\right] + M3\left(1 - z3_{ijkt}\right) \; \forall \; t\epsilon T, (i,j)\epsilon A, k\epsilon K \quad (6)$$

$$z1_{ijkt} + z2_{ijkt} + z3_{ijkt} = \; y_{ijkt} \;\; \forall \; t\epsilon T, (i,j)\epsilon A, k\epsilon K \quad (7)$$

$$td_{ijkt} \geq ta_{ijkt} + L_{ikv} + TrT_{kl} - M4\left(1 - \; y_{ijkt}\right) \forall \; t\epsilon T, (i,j)\epsilon A, k\epsilon K \quad (8)$$

$$\Delta_{ikt} \leq td_{ijkt} \leq \mu_{ikt} \;\; \forall \; t\epsilon T, (i,j)\epsilon A, k\epsilon K \quad (9)$$

$$I_{ikt} \;\leq C_{ik} \quad \forall \; t\epsilon T, i\epsilon I, k\epsilon K \quad (10)$$

$$\textstyle\sum_{l\epsilon L} w_{iklt} \;\; \geq 1 \quad \forall \; t\epsilon T, i\epsilon I, k\epsilon K \quad (11)$$

$$\mathrm{y}_{jikvt} + \; \mathrm{y}_{ijkvt} \geq 2 \times \; w_{iklt} \quad \forall \; t\epsilon T, (i,j)\epsilon A, k\epsilon K, \quad (12)$$

$$I_{ik(t-1)} + \textstyle\sum_{t\prime\epsilon T}\sum_{j\epsilon J} X_{jikt\prime} = \sum_{j\epsilon J} X_{ijkt} + \;\; I_{ikt} \quad \forall \; t\epsilon T, i\epsilon I, k\epsilon K \quad (13)$$

$$t - 1 \;\leq t' + TT_{jikt'h'} \leq \mathrm{t} \;\; \forall \; t'\epsilon T \quad (14)$$

$$\textstyle\sum_{j\epsilon J} X_{jikt} - \sum_{j\epsilon J} X_{ijkt} = \; D_{ikt} \, y_{ijkt} \; \forall \; t\epsilon T, i\epsilon I, k\epsilon K \quad (15)$$

$$X_{ijkt} \geq \; D_{ikt} \, y_{ijkt} \; \forall \; t\epsilon T, (i,j)\epsilon A, k\epsilon K \quad (16)$$

$$TT_{ijkt} = \frac{d_{ijk}}{s_{mrk}} \times \left[1 + a \times \left[\frac{X_{ijkt}}{C_{ik}}\right]^{b}\right] \;\; \forall \; t\epsilon T, (i,j)\epsilon A, m\epsilon M, r\epsilon R, k\epsilon K \quad (17)$$

$$X_{ijkt}, TT_{ijkt,} ta_{ijkt}, td_{ijkt} \geq 0 \;\; \forall \; t\epsilon T, (i,j)\epsilon A, k\epsilon K \quad (18)$$

$$z1_{ijkt}, z2_{ijkt}, z3_{ijkt} \geq 0 \;\;\; \forall \; t\epsilon T, (i,j)\epsilon A,, k\epsilon K \quad (19)$$

$$EW_{ikt}, LW_{ikt}, NW_{ikt} \geq 0 \;\;\; \forall \; t\epsilon T, i\epsilon I, k\epsilon K \quad (20)$$

$$y_{ijkt}, \; w_{iklt,} \in \{0,1\} \;\;\; \forall \; t\epsilon T, (i,j)\epsilon A, k\epsilon K \quad (21)$$

$$g1_{ijkmr}, g2_{ijkmr} \;\; \in \{0,1\} \;\;\; \forall \; t\epsilon T, (i,j)\epsilon A, m\epsilon M, r\epsilon R,, k\epsilon K \quad (22)$$

$$I_{ikt} \;\; \geq \;\; 0 \;\;\; \forall \; t\epsilon T, i\epsilon I, k\epsilon K \quad (23)$$

Eq. (1) and (2) show the main objective functions of this model. They are cost and carbon emission rate functions, respectively. In Eq. (1), first term corresponds to total transportation cost of carried goods, second indicates the transfer cost among transportation modes and the last part is penalty cost of keeping inventory in nodes. In Eq. (2) indicates the minimization of total carbon emission rate within the system. First part of this equation shows rate caused by the engine module and the speed module, second term shows total the emission rates generated by the speed module in the all congestion and in the all free-flow regions and last one represents total the rate induced by the weight module (Bektas and Laporte, 2011; Demir et al., 2014). Eq. (3) ensures that if this equation is taken as one of the objective function and problem is solved by just considering this objective, then summation of total transportation durations during the operations and total transfer time in mode changes and also penalty term in minimization of the waiting times of vehicles in nodes should be less than the upper bound of this function. Eq. (4)–(6) indicates the total waiting time of vehicles for each transportation mode. There should be early, late or in time arrival probabilities in allowed time period and Eq. (4)-(6) fulfills this situation respectively. Eq. (7) ensures that if there is any need to be carried on arc (i,j), each vehicle within the nodes for different transportation modes has to arrive early, late or in time. Eq. (8) indicates relationship between departure and arrival times of vehicles within nodes for transportation modes. Time duration between arrival and departure time of each vehicle has to be greater than summation of loading time of vehicle for mode k and transfer times from mode k to l. Eq. (9) ensures that departure time of vehicle has to be between opening and closing time of nodes for each transportation mode. For example, if the summation of loading and transfer time between different transportation modes are exceeding the closing time of node for transportation mode, then vehicle has to wait until the next day and quantity on vehicle will be added to inventory of node for that transportation mode. Eq. (10) indicates that daily keeping inventory of every node i has to fulfill the capacity levels for each transportation mode k. Eq. (11) indicates that any material in node i must be transported via at least one of the available transportation modes. This constraint forces the solver to obtain minimum transfer cost and transfer time in node i in terms of transportation modes. Eq. (12) shows that the arrival transportation mode must be the same transportation mode of the leaving mode over the arc (i,j). On the other hand, if there is any difference between arriving and leaving transportation modes, Eq. (12) ensures that there should be mode transfer within the node. Eq. (13) indicates the mass balance in the nodes. The incoming and outgoing quantities in node i for each transportation mode k should be same and Eq. (13) helps model to fulfill this balance during the operations. However, the relationship between current (*t*) and previous time intervals (*t' < t*) has to be as in Eq. (14). Arrival time of vehicles on arc (*i*,*j*) for different transportation modes, which is equal to summation of departure time of vehicles on arc (*i*,*j*) and transportation duration on arc (*i*,*j*) for different transportation modes, has to be in the range of single time period (between *t* and (*t*-1)). Travel time durations are taken as a step-wise function for 24 hour time period per day in this part of the problem. Eq. (15) shows that incoming and outgoing quantities of carried goods have to be equal to demand of nodes for different transportation modes in every time period. Eq. (16) gives the relationship between the total carries cargo quantity and the decision whether using that arc (*i*,*j*). Eq. (17), the BPR (Bureau of Public Roads) equation (1964) (BPR, 1964) was used to handle the traffic congestion problem. The BPR equation was modified to obtain transportation times of the modes for every time interval *t*. The BPR equation constants were obtained from Horowitz (1985). The BPR constant, *b*, is taken as a '1' in the mathematical model to convert the non-linearity condition into the linear form and the effect of such a change is less than 5% in the transportation times (Resat and Turkay, 2015). Eq. (18)–(23) ensures both integrality and non-negativity conditions.

Solution Methodology

In this study, we used two different solution methodologies. One of them is the solution algorithm developed by Mavrotas (2009), ϵ-constraint method; another one is the one direction search (ODS) method (ENPOBOMIP) to find non-dominated frontier of bi-objective mixed-integer problems that is proposed by Fattahi and Turkay (2016).

In our problem, we examined two objective functions that are total transportation cost (Eq. (1)) and carbon emission rates (Eq. (2)). In transportation industry, the cost objective has more importance than the other objectives due to the high competitive conditions. Therefore, we took cost function (f_1) as a prior function and the carbon emission rate function (f_2) is taken as a secondary objective and inserted as a constraint in the ϵ-constraint method. In this solution algorithm, the multiplication of slack variable with some small constant value (such as this value is $1e^{-5}$ in this study) is subtracted from f_1 to deteriorate the objection function, however the same slack variable is included into the f_2 at the same time and summation of second objective function with this slack variable should be equal to the upper bound of cost emission rate function. The representation of this algorithm is given in the study of Resat and Turkay (2015).

Secondly, we solved our problem by using the new algorithm (ENPOMOBIP). This algorithm has very promising characteristics and it can give the Pareto solutions for bi-objective problems in a faster way than the existing methodologies. Fattahi and Turkay (2016) used a faster-up technique in obtaining the trade-off solutions. The new algorithm is applied in our model as shown below.

$min\, f_1$

Subject to:

$$min\, \beta \text{ subject to } f_2 = \alpha f_1 + \beta \qquad (24)$$

Equations (3)-(23)

In this algorithm, we solve the first objective function (f_1) by considering the same constraints given in Equations (3)-(23). However the second objective function is taken as a function of (f_1) and added new slack variable β into the Eq. (24). The value of α is the set of slope of line between feasible solutions. While solving the Eq. (24), we tried to minimize the variable β and this inner optimization problem leads to correlation between the objective functions. At each iteration, we deteriorate the first objective and this increase the value of second objective function.

4.3 Computational Experiments

In this section, we discuss the initial data used as parameter in the model and also the general overview of real-life case and their application into this study. Additionally, some assumptions used in the design and operation of models are indicated.

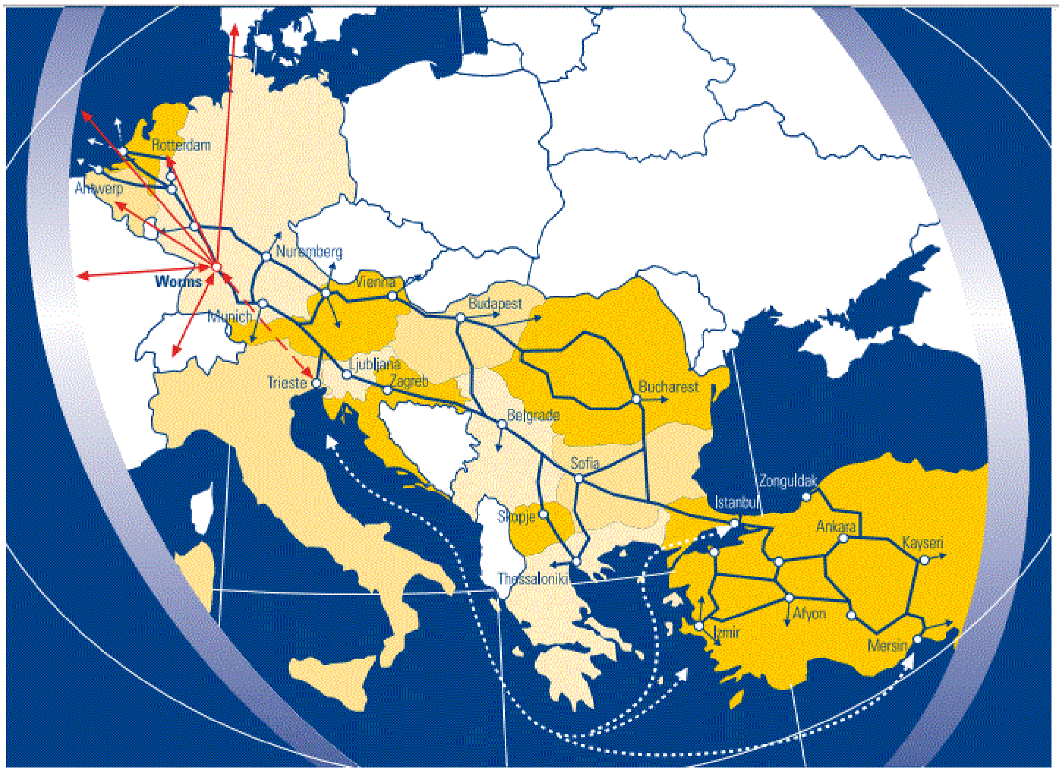

Figure 12: Intermodal Network in the Europe (CREAM, 2010)

We start our problem with the data collection and forecast phase. In our study, we used the real data from the one of the largest logistics provider in Turkey and locations of the important logistics centers and hubs for loading and unloading operations; links between these locations; vehicle types and their capacities; unit transfer times and costs between transportation modes; historical data for customer demands and operational limits and constraints are taken. Also, we used the same parameters and constants in our model given in the study of Resat and Turkay (2015). In our problem, 25 important locations are taken from the European zone and distances between these nodes are taken from studies of European Union for different transportation modes. In our problem, we just consider the existing freight movements by road, rail and sea transportation.

In our case, there are direct Ro-Ro routes carrying the trailers and containers from Pendik, Turkey and Mersin, Turkey to Trieste, Italy; Izmir, Turkey to Sete, France. There can be either transfer from ferries to the block trains in Port of Trieste and Port of

Sete to move to the Ludwigshafen, Cologne in Germany, and Ostrava in Czech Republic or direct movement by road transportation to Western European Countries, Spain and Portugal. Transportation from Europe to Turkey uses the same route back from Cologne, Ludwigshafen and Ostrava to three destinations in Turkey by railway transportation.

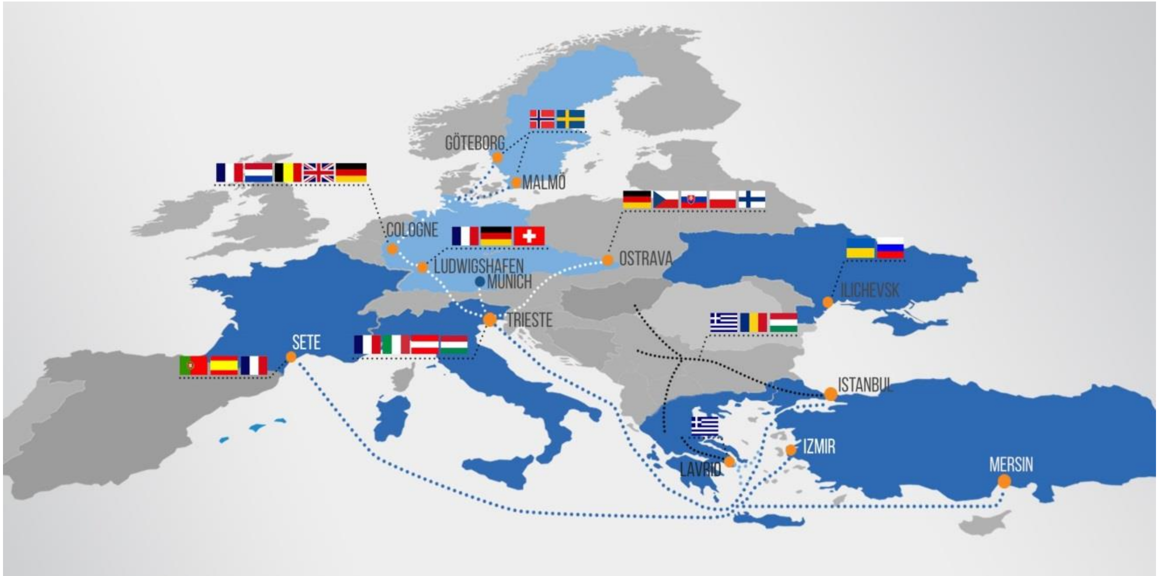

Figure 13: Network Design for the Problem

The speeds of the rail and sea transportation is also taken as constant and road transportation depends on the number of vehicles on the roads and calculated by using the BPR equation. Apart from the cost parameters, again total transportation time is another important constraint of our problem. The transportation times are calculated by the division of the total distance to the speed of the vehicles. The operational restrictions are also taken into account such as, opening and closing times of the ports and rail centers and also the urgent delivery requests of the customers. For the second objective (carbon emission rates), we used the same parameters given in the study of Bektas and Laporte (2011).

The capacities of the vehicles are depending on the type of the vehicles which are assumed to be as below:

Table 6: Vehicle Capacity Information for Different Transportation Modes

Transportation Mode	Unit Capacity
Road	20 or 40 Feet Container Carried by Trailers
Sea	5 Ferries (4 Ferry with capacity of 239 Container + 1 Ferry with capacity of 147 container)
Rail	2 Trains (1 Train with 16 Wagons for Cologne corridor + 1 Train with 14 Wagons for Ostrava Corridor)

Also, there are some waiting times during the boarding, loading/unloading operations and customs. The average waiting times are given in Table 7.

Table 7: Average Waiting Time for Import and Export Operations [in days]

in unit of days	Import			Export	
	Trailer	Container		Trailer	Container
Boarding the Train	1.24	1.57	Boarding the Train	1.33	1.20
Boarding Ferry	1.22	1.77	Waiting in Haydarpasa	0.71	0.59
Leaving the Ports	0.68	0.09	Waiting in Trieste	1.52	2.80
Customs Processes	0.60	0.11	Loading the Ferry	0.50	0.59
Unloading the ferry	1.21	0.46			

Also, the demand of the customers is taken as a parameter and the total carried quantities on the arcs (*i*,*j*) by different transportation modes are calculated by the optimization model. Time period for this case is taken in the unit of hours.

4.4 Results

In this section, we examined our mathematical model and got Pareto solutions by using the real-life data for European intermodal network by using two different solution approaches. During the solution steps, we used different number of nodes which are given in the Appendix and Pareto results for total transportation cost and carbon emission rates and sensitivity analysis of our cases is given in terms of computational performance unit times. The main difference between these cases is the number of the nodes used in the networks. Cases include 5, 10, 15, 20 and 25 nodes respectively. The linear model for this problem is written in GAMS modeling environment and solved with IBM ILOG CPLEX 12.1 (CPLEX, 2009). Both models are executed on a computer with Intel Core I5 2520 M CPU with 2.50 GHz dual core processor, and with 4.00 GB of RAM. An optimality gap of 1% is set for the solutions.

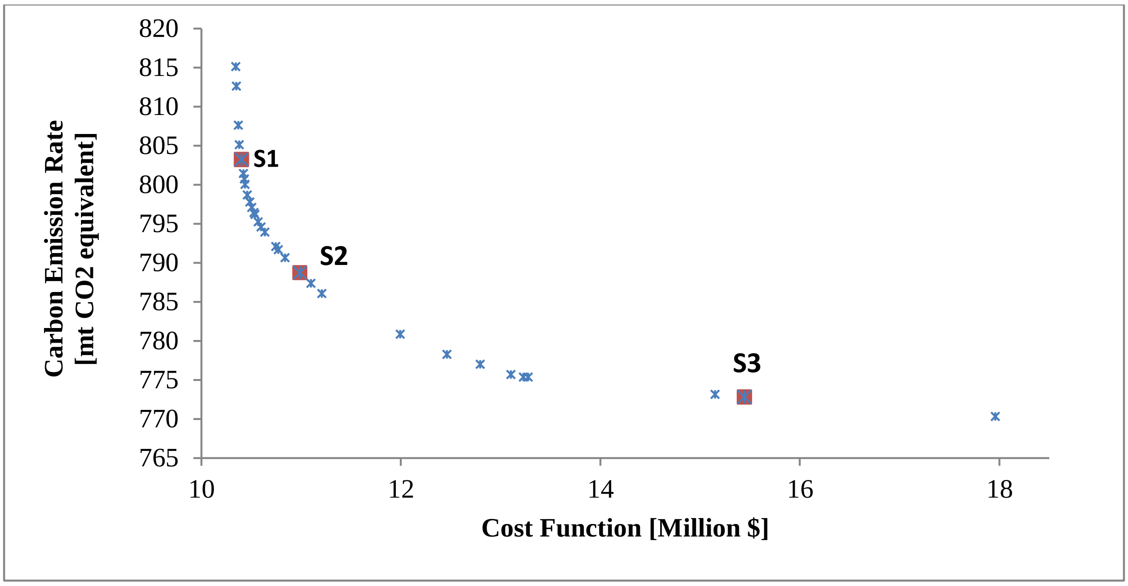

Figure 14: 25 Pareto Results for 25-Node Case

Solving the bi-objective linear problem with new generation method proposed by Fattahi and Turkay (2016) generate the Pareto set with 3 different solutions for decision makers. The results are obtained for each instance of intermodal transportation problem by considering total transportation cost and carbon emission rates in Figure 14. If we analyze the instances in Figure 3 by detail, we should examine the corridor from Turkey to Western Europe countries because this region is the focal point for economic structure and transport volume. Therefore, we selected the link between Pendik Port, Turkey and Rotterdam, The Netherlands in detailed case analysis and the results for the sample solution sets (illustrated as red point in Figure 14) are given below:

Sample #1 (S1):

The graphical network representation of this solution is given in Figure 15 below. There are two transshipments in this solution, operation starts with the road transportation from Pendik to Cerkezkoy and after the transferring the container from trucks to train in Cerkezkoy terminal, it is carried by train till the Duisburg terminal. At this terminal, the container again moved from train to trucks and it is delivered to the customer by road transportation.

Figure 15: Schematic Representation of Sample 1

At this scenario, 7 trucks with 20 feet container depart from the warehouses in Pendik region around 10:00 AM and carries to Cerkezkoy transshipment point and this operation takes approximately 147 km (around 2 hours). There will be some waiting time for loading and transfer operations that is around 1 hour. After that, transportation time between Cerkezkoy and Duisburg takes around 6 days and the containers are taken from trains to the vehicles in Duisgburg train station and trucks travel around 205 km by road transportation to deliver the cargos. The total cost for carrying 7 unit 20 feet container from Pendik to Rotterdam is around 14,855$.

Sample #2 (S2):

The graphical network representation of this solution is given in Figure 16 below. There are three transshipments in this case, operation starts with the road transportation from Pendik to Haydarpasa and after the transferring the container from trucks to train in Haydarpasa terminal, it is carried by train till the Cologne terminal. However, there should be train operator change in Cologne, Germany and it is taken from one operator to other one. At this terminal, the container again carried by rail transportation and it is moved from train to trucks at the transfer point and it is delivered to the customer by road transportation.

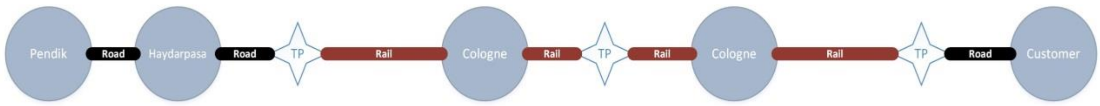

Figure 16: Schematic Representation of Sample 2

At this scenario, there are 11 unit 20 feet container cargo in total and this cargo is carried by trucks from Pendik to Haydarpasa train station. We assumed that there is a train connection between the two sides of the Istanbul by tunnel. Therefore, the cargo is carried by train to Cologne in 5 days. However, there will be operator change in Cologne and cargo will wait around 1 day in Cologne rail terminal and then moved from Cologne to Rotterdam via rail transportation and this operation takes one day. Therefore, the cargo can be carried in around 7 days with a total cost of 24,575$.

Sample #3(S3):

The graphical network representation of this solution is given in Figure 17 below. There are three transshipments in this case, operation starts with the road transportation from Pendik to Pendik Port and after the transferring the container from trucks to Ro-Ro Ferries in Pendik Port, it is carried in around 60 hours by sea transportation till the Port of Trieste, Italy. At Port of Trieste, the container is again transferred to the block trains to move to the Germany by rail transportation. At this transshipment point, there will be one day waiting time at the rail terminal. The link between Trieste and Munich is travelled in 24 hours by train and after reaching to the Munich terminal in Germany, the container is taken from train to trucks at the transfer point and it is delivered to the customer by road transportation. The total transportation takes around 5.5 days with total cost of 17,300$

Figure 17: Schematic Representation of Sample 3

Also, our bi-objective mixed-integer linear model is solved by using two different algorithms which are augmented ϵ-constraint method proposed by Mavrotas (2009) and new solution algorithm (ENPOMOBIP) proposed by Fattahi and Turkay (2016). The Pareto solution sets obtained by ENPOMOBIP are given in Figure 14 and the computational performance unit times of two solution methodologies are compared in Table 8.

Table 8: Sensitivity Analysis of Computational Performance Unit Times of Different Cases

in unit of seconds	**ϵ-constraint Method**	**ENPOMOBIP**	**The Difference Between Methods [%]**
Case with 5 Node	192.18	189.67	1.3%
Case with 10 Node	472.35	451.84	4.3%
Case with 15 Node	1,156.48	1,117.87	3.3%
Case with 20 Node	1,764.32	1,632.45	7.5%
Case with 25 Node	2,391.67	2,274.93	4.9%

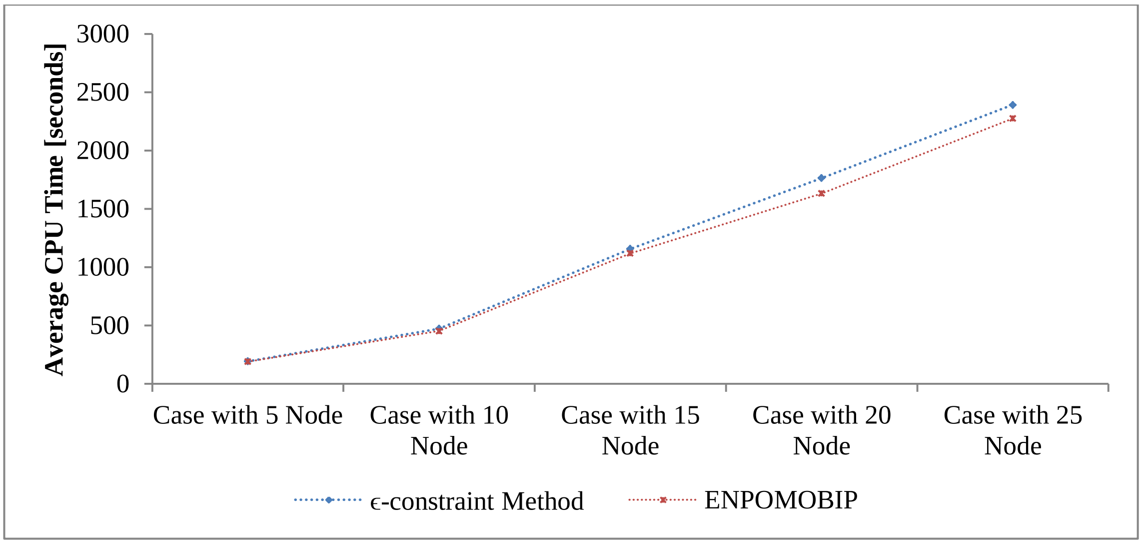

Figure 18: Sensitivity Analysis Results of Different Cases

As shown from the Figure 18, the new solution algorithm (ENPOMOBIP) can reach the feasible solutions in faster way. There is approximately 3-7% difference between the ENPOMOBIP and ϵ-constraint method in total computational performance unit times.

4.5 Conclusion

In this study, we examined the bi-objective mixed-integer linear problem for intermodal systems in European level. The proposed mathematical model is solved by using two different solution algorithms, ϵ-constraint method and ENPOMOBIP, to get Pareto solution sets for decision makers. The novel contribution of this study is using the real-life data in our problem that is taken from the one of the biggest intermodal service providers in Turkey and the feasible solution sets are obtained approximately 3-7% faster than the existing solution algorithms. The total carried cargo quantities and total carbon emission rates are calculated for the important intermodal corridors and total carried cargo quantities are found, as well as considering the discrete-continuous time functions.

Chapter 5

A DISCRETE-CONTINUOUS OPTIMIZATION APPROACH FOR THE DESIGN AND OPERATION OF SYNCHROMODAL TRANSPORTATION NETWORKS

5.1 Introduction

The rapid increase in global trade leads to very fast growth of freight transportation across the European countries. The ability to move goods safely, quickly and cost-efficiently to different markets is the most important purpose of the international trade activities and indicates the significance of the logistics operations. The total inland freight transportation in the European zone is estimated to be around 2.100 billion ton-kilometers in 2014 (EUROSTAT, 2015) and the total cargo volume in Europe is expected to double in the next 30 years (Jaarbook, 2011). However, when 75.1% of such a large volume (around 90% in developing countries including Turkey) is transported by road while this type of transportation is the most expensive one per unit cargo and the largest source of carbon emissions and energy consumption (EUROSTAT, 2015); urgent actions are required. Therefore, global concerns and increased awareness about environmental changes lead to new and different approaches for planning, design, construction, operation and maintenance of transportation solutions and systems. Most of the researchers addressed the development of new models to decrease the share of road transportation in the entire transportation network for more efficient, safe and environment-friendly systems. According to the European Environmental Agency (EEA), one of the main reasons behind the inefficient road transportation systems is the low level of the occupancy ratios (empty running) of medium and heavy-duty-vehicles. The load ratio of road transportation is lower than 50% in most of the European countries (EEA, 2015) and this means that most of the vehicles run with partial cargo and there are many relatively small flows in the network due to pressure of customers, insufficient infrastructure and capacity problems. This situation leads to profit losses, increased carbon emissions and traffic congestion tremendously. Therefore, the importance of sustainability is realized by the decision makers as one of the most promising parameter in transportation planning processes to satisfy the recent expectations from industry. Although, many definitions of sustainability in various disciplines were developed, there is not a clear and basic description concerning the sustainability in transportation operations. In the literature, there is a widely used definition of sustainability that was introduced by the United Nations in 1987, "*sustainability meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, 1987). Also, Turkay (2008) examined the environmentally conscious supply chain systems and indicated that transportation based sustainability approaches should be the major focal points to include the sustainability considerations in supply chain management. He argued that development of multi-modal transportation systems will play an important role in reducing the impact of the transportation activities on the environment, especially in terms of emission parameters. Implementation of this approach into the transportation processes cannot be achieved easily; establishment of a sustainable transportation system requires well-defined framework to include all stakeholders from private sector, public authorities, and research and education institutions.

The concept of intermodal transportation has been recognized worldwide as a promising way to reduce logistics costs, although it still faces some operational challenges. The European Commission (1997) defined intermodal transportation as "*the movement of goods in one loading unit, which uses successively several modes of transport without handling of the goods themselves in transshipment between the modes*". The phrase intermodal transportation refers to transportation of containers in a single chain of different transportation modes. Many studies give a general knowledge and definition of intermodal transportation problem in the literature. Minoux (1989); Daskin (2011); Drezner (1995); Balakrishnan et al. (1997); Raghavan and Magnanti (1997); Melkote and Daskin (2001); Resat and Turkay (2015) have examined the intermodal transportation problem and have developed some models to handle this problem. Macharis and Bontekoning (2004); Wu et al. (2011) have studied the importance of network designs in intermodal transportation. Also, Bektas et al. (2010) developed some intermodal network design models on tactical levels. In addition to modeling this kind of problem, Nemhauser and Wolsey (2014); Ahuja et al. (1993) have created some solution methodologies. In the literature, many studies are not convenient for real case problems and multi-modal cases. Most of the studies handle much smaller cases with narrow concepts especially related with sea transportation and container movement operations. The paper by Resat and Turkay (2015) addresses the design and implementation of the intermodal transportation concept in real cases. Although there are some successful implementations of intermodal transportation in the world, its potential to improve service levels, decrease costs and environmental impacts has not been fully exploited by current supply chains. This is evident that the current transportation system in the world cannot keep pace with increased trade activities. Therefore, the new concept, synchromodal transportation, has appeared. The concept of synchromodal transportation is the extension of intermodal transportation and it refers to transportation systems with dynamic adaptation of the planning processes by using the information about changes and disturbances occurred throughout the transportation operations (Riessen, 2013; Lucassen and Dogger, 2012). Although intermodal transportation has been well discussed in the literature, synchromodal transportation is a very new topic for researchers and there are not many studies related with synchromodal transportation. The main objective of this study is to contribute to the modelling approach of the newly introduced concept of synchromodality and to develop models which help to create more effective transportation systems. As shown in Figure 12, there are some differences between the synchromodal transportation and the other two types of transportation systems. Intermodal transportation uses different types of transportation modes for single shipment from one location to another one, but the key characteristic of the intermodal transportation is just handling container based units, not the goods themselves. This term is most often associated with international container traffics. Co-modality is the intelligent use of two or more different transportation modes by a group of shippers in a distribution system on their own or in combination to get the best benefit from each mode, especially in terms of overall sustainability. Then, the new concept, synchromodal transportation, is developed to make the transportation systems more sustainable and efficient. Gorris et al. (2011); TNO (2012); Ham (2012); Mes and Iacob (2016) have introduced some theoretical definitions and potential benefits of synchromodal transportation in their studies. One of the most promising definition of the synchromodal transportation is introduced by Gorris et al. (2011) and they defined synchromodal transportation as follow: "*Synchromodality occurs when the supply of services from different transport modes is integrated to a coherent transport product, which meets the shippers' transport demand at any moment in terms of price, the design of a synchromodal freight transport system due time, reliability and sustainability. This coordination involves both the planning of services, the performance of services and information about services*".

Behdani et al. (2014) and Burg (2012) have examined some industrial case studies in their master thesis. However, their studies do not cover all characteristics of synchromodal transportation.

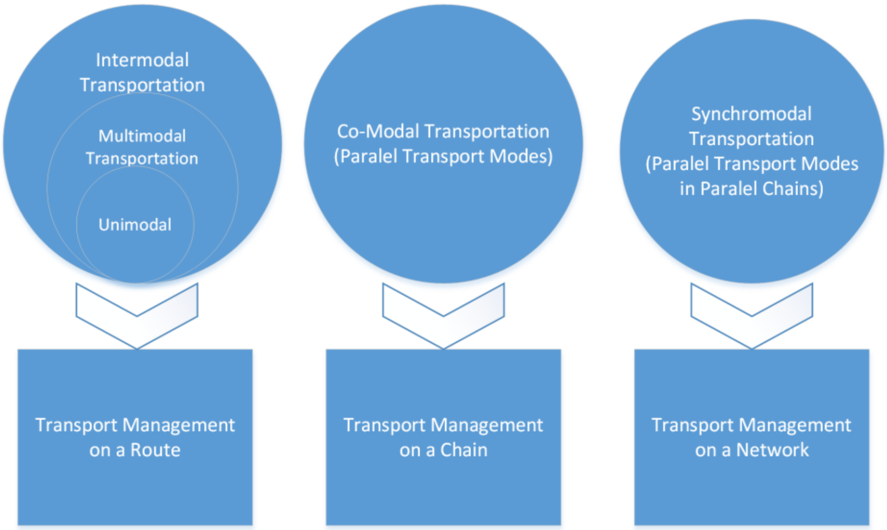

Figure 19: Classification of different transportation types (BCI, 2011)

The main idea behind synchromodal transportation is to minimize cost, time and environmental impact by integrating the capacities of vehicles, transportation modes and customer demands. This means that it cannot depend on a single objective in real-life cases and it should be considered as a multi-objective optimization problem. Therefore, the concept of optimality is replaced with Pareto optimality (efficiency) to make decisions about the cost, time and environmental factors simultaneously. In general, there are two conventional methods to generate Pareto solutions for multi-objective optimization problems, which are the ϵ-constraint method and the weighting method. In this study, the ϵ-constraint method is used because the weighting method may sometimes miss some of the efficient solutions in some feasible regions (Mavrotas, 2009). In the ϵ-constraint method, the proper solution algorithm takes one of the objective functions as a main and other objective functions are used as constraints in the problem. While finding the Pareto solutions, the model obtains an improved solution for one of the objective functions but deteriorates at least one of the other objective function values. Many authors have proposed different solution methodologies and applications to address the multi-objective transportation problems. Steuer (1986), Miettinen and Makela (1999), and Mavrotas and Diakoulaki (1998) generated an approximate representation of the set of Pareto solutions for special type of linear multi-objective problems. Mavrotas and Floris (2013) proposed a new version of the ϵ-constraint method to find the set of exact solutions in multi-objective problems by adding slack variables into the objective functions which are taken as constraints and penalty term into the main objective function.

Apart from the multi-objective characteristic of the synchromodal transportation, the tracking of the real-time transportation times on different arcs is another important part of this problem that directly depends on the traffic congestion (the number of total passenger and freight vehicles on the roads) and quantity of the carried goods on each vehicle. There are many studies proposing the linkage between vehicle speeds and their volume/capacity ratios in the literature. The Bureau of Public Roads (BPR) introduced the BPR equation (Bureau of Public Roads, 1964) fitted to freeway speed flow data given in the highway capacity manual in 1965 (Highway Capacity Manual, 1965). Akcelik (1996) and Dowling et al. (1998) modified the BPR equation and proposed more complicated speed-time estimation models.

While considering cost and time functions with traffic congestion, CO_2 emissions is another important objective for current transportation operations. There are many studies focusing on this concept. For example, Hickmann et al. (1998); Zegeye et al. (2010) proposed some models integrating vehicle speeds and greenhouse gas emissions. Figliozzi (2010) introduced the emission minimizing vehicle routing problem that takes into account traffic congestion to reduce speed-dependent carbon emissions, using a function introduced by Hickman et al. (1998). Another contribution on this area is from Bektas and Laporte (2011) who present the Pollution-Routing Problem as an extension of the classical Vehicle Routing Problem with Time Windows. Figliozzi (2011); Franceschetti et al. (2013); Demir et al. (2014) developed some models using this pollution routing problems. Then Jabali et al. (2012) proposed a model for time-dependent pollution routing using the same emission functions by considering speed as an additional decision variable. Franceschetti et al. (2013) uses the similar approach in their proposed model for time-dependent pollution routing problems.

Definitions and characteristics of synchromodal transportation were tried to be described by several researchers. According to Ham (2012), synchromodal transportation has seven specific characteristics. The most important one is the dynamic planning of network. Synchromodal transportation mainly uses all transportation modes optimally, but the main difference from intermodal transportation is the real-time planning process. This process allows customers to decide their transportation movements according to the actual circumstances such as traffic congestion, instant availability of products, infrastructure or vehicles. According to report of Mes and Iacob (2016), synchromodal transport enables companies to operate more sustainably, at lower costs and at higher quality by using this characteristic. At any moment, customer demand may occur or service can be adjusted for suitable transportation mode (road, rail and sea) according to the customer information (e.g., demand quantity, product type). Therefore, transportation system is no longer fixed to one single transportation mode. This means that waiting time of vehicles at the nodes will be minimized and available transportation modes will be optimized for flexible and combined usage during the operation planning. Second characteristic is the decision making based on network utilization. Demand quantity, product type, availability of transportation mode play essential role in better utilization of existing network capacity and usage of convenient transport modes. Another important characteristic is the transfer between transportation modes in a real-time manner. This characteristic increases the flexibility of transportation operations to satisfy the customer requirements on price, time and reliability. Transportation service has to be pro-active and adjusted its position according to all unexpected situations. For instance, if there is congestion on road or obstacle on rail services, switching to other more efficient modes according to real-time information is important. Forth one is the combination of transport flows (increased volume). Synchromodal transportation helps to allocate product flows with suitable transportation mode (road, rail and sea) according to directives of customers at any moment (e.g. demand quantity, product type, etc.). The study of Spectrum (2012) mentioned that synchromodal transportation fulfills greater flexibility in transportation mode choices, improves the reliability, shortens the lead-time in the transport chains, and increases the utilization of road, rail and sea transportation. This leads to reduction of transportation cost and increase in cargo volumes at the same time. According to study of Gorris et al. (2011), new type of transportation system synchronizes the services and coordinates transport modes by combining together the flows of goods. By this characteristic, system should minimize the empty proportions of vehicles. Another character is information availability and visibility among actors. Coordination of information improves the cooperation among actors to provide an integrated transportation service (Ham, 2012). In synchromodal transport system, the service providers have freedom to decide on how to deliver and which transport modes should be chosen according to their available transport service offerings. This means that there is an agreement between shippers and synchromodal service provider in which shippers only book the transport volume and do not make decisions on the transport modes. Mode free booking allows synchromodal transport service providers to choose the most efficient design of transportation system for specific shippers. Last character is the cooperation (business models) between sector actors in the supply chain (e.g. service providers, main transport operators) to reduce risks and provide efficient logistics operations with available transportation modes. However, after investigating all of these characters, three of them are more valuable than the others for synchromodal transportation; synchronization between customers and suppliers, usage of different transportation modes at the same time and increase volume of product flows by combining the goods. After creating network system with these characteristics, synchromodal transportation may lead to better utilization of existing infrastructure, sustainable transport systems, reduction in carbon emission, maximization of usage of all modes of transport, increase in the position of sea and rail modes in transportation systems, better synchronization of customer demand and transportation operations and change in supply chain system from pull type to push type.

The contribution of this paper is to introduce the theoretical analysis of synchromodal transportation and to present novel models and solution methodologies to be used in real-life cases. The optimization models are analyzed in detail and various new pre-processing approaches were also developed for the problem. It is shown that these pre-processing approaches are highly effective and the proposed solution methodology leads to obtain Pareto solutions faster and decrease the complexity of such large problems. Synchromodality is a new concept in freight transportation and it integrates different transportation modes and provides the customers freedom to use different transportation modes in a flexible way which enables better utilization of existing infrastructure capacities. The Pareto solutions obtained from the proposed models help the stakeholders to make some decisions over their operations.

This chapter is divided into five sections. Section 2 presents necessary technical background on the problem and provides mathematical model for minimization of time, cost and carbon emission factors in synchromodal transportation problem with using the traffic congestion. Section 3 includes the information about the initial data and some parameter which are used during the calculations. Section 4 gives some information for solution methodology of this problem and results of the different illustrative cases. Finally, Section 5 shows the general overview and some future steps of the problem.

5.2 Problem Statement

In this section, we indicate the definition and design of the problem and present the formulation of both mixed-integer linear and non-linear optimization models for multi-objective problem which examine cost, time and carbon emission functions for different transportation modes. While investigating the synchromodal transportation network design and operation, traffic congestion constraint is included into model with the capacity constraints. Also, CO_2 emission rates are evaluated according to vehicle speeds and transportation durations.

Problem Definition

The transportation industry involves many different players throughout its operations such as freight forwarders, customers, suppliers, ports, etc. Our problem is designed to simplify the logistics channels and provide the aspects in operational, tactical and financial levels. While describing the illustrative cases, some critical aspects for freight transportation given in the study of Cane (2012) are considered and listed in Table 9.

Table 9: Key Performance Indexes for Freight Transportation

Area	Performance Indexes
Asset Management	Additional Vehicle Usage for Partial Cargos Additional Travels of Vehicles Utilization of Investments Utilization of Freight Space
Customer Service	Order Fulfillment of Customers Backlog/Waiting Times in Orders Customer Satisfaction
Revenue	Annual Transportation Cost

Management	Additional Revenue due to the service improvements

After observed the key performance indexes in Table 9, the illustrative cases are designed according to these needs. The problem starts with the data collection and prediction phase. In this part, historical traffic data, location of customers, information about fleets (their capacities, numbers per logistics providers etc.) and initial data for customer orders that indicates the information related with transshipments, total cargo types and quantities are taken. By using all of this information, general time-dependent intermodal transportation model proposed by Resat and Turkay (2015) is used to decide on the transportation modes and optimal quantities carried. The model uses the bundled quantity of customer orders as a total cargo volume in initial calculations. The main purpose of this model is to determine which kind of transportation mode should be used and how much cargo should be carried on the links of given network. After determining our cargo routes and transportation mode types, it should be visible for everyone to trace and track their cargos. Information about arrival and departure time of vehicles is one of the main aspects of the synchromodal transportation. After obtaining the results of intermodal transportation model, the fleet optimization method is used to calculate the optimal usage of the fleets for each transportation mode. This part is important to increase the filling ratios of the fleets and find out the number of trucks in road transportation because it will directly affect the traffic congestion and deteriorate the transportation times and carbon emissions. Although the total cargo quantity is assessed as a unit of 40-feet container (20 ton) in intermodal transportation problems, this is not realistic for real-life cases because approximately 77% of the total cargo carriage by road transportation is moved by medium or heavy-duty trucks and containers are not used in such operations (EPA, 2013). The number of vehicles required can be obtained in this problem and this information directly related with traffic congestion is used by time-dependent synchromodal transportation model (TDSTM) to obtain the optimum results of the problem. We can obtain network structure and locations of the vehicles from TDSTM. However, our model has dynamic approach and it starts up its solution methodology after finding the minimum transportation duration from TDSTM. After finding the minimum transportation duration, we can trace the current situation of the vehicles in the networks and also we can assume that there will be some unloading operations in one of the vehicles of the fleet. This means that if there is some free space for new cargo ordered by the customer, our optimization model will assess the new situation and supply new inputs for the TDSTM. If not, our model uses the previous results and continues until the next minimum transportation time period. After this operation, it again checks the new orders and gives decisions over the process.

Also, there can be some disruptions during the operations in real-life cases. In such cases, our problem can assess this situation and start the process with new input from the intermodal optimization problem and decides on new transportation modes and network for just disrupted link. After deciding on the transportation mode and route, fleet optimization model is used to optimize number of vehicles in the network. It can either combine that cargo if there is enough free space in some vehicles or order new vehicles to carry that cargo in determined transportation mode.

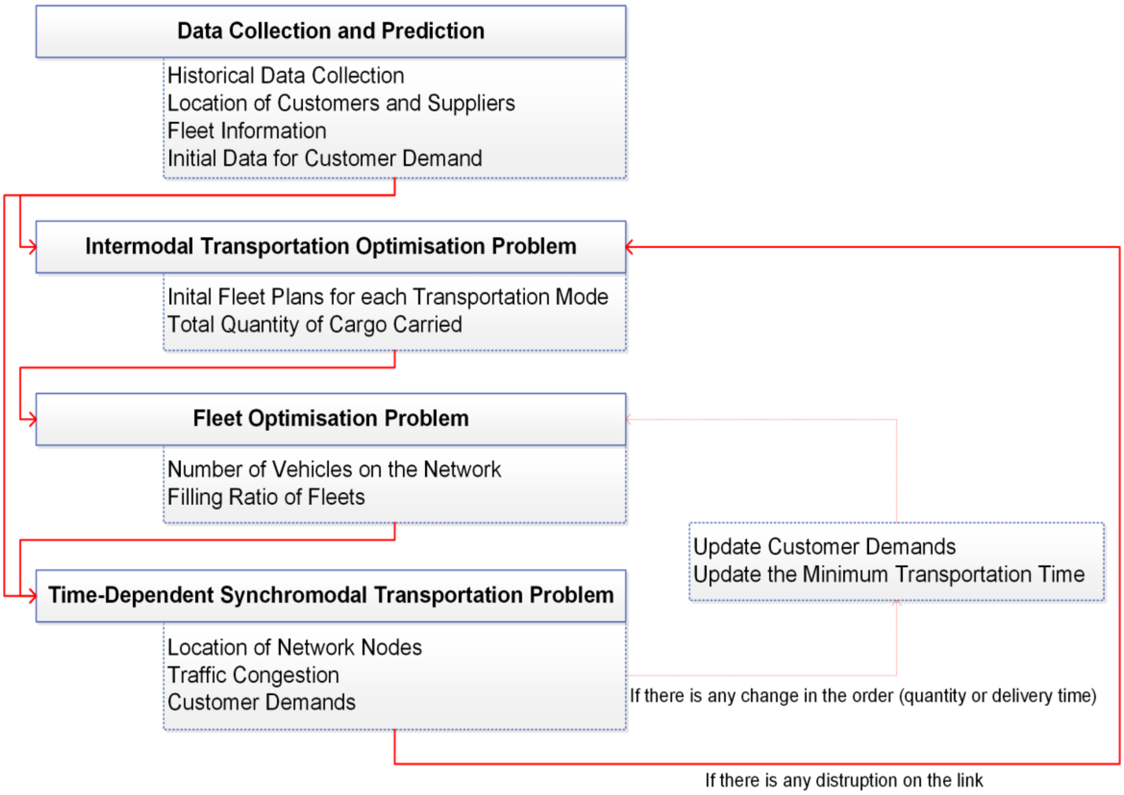

Figure 20: A Flowchart of the Solution Methodology

Model Formulation

This optimization model for TDSTM is developed as both multi-objective mixed-integer linear programming (MILP) and non-linear programming (MINLP). The main objectives are total transportation cost, the total time spent on the system and the total CO_2 emission amounts. Our model is based on indices which are indicated below:

The problem consists of six sets which are set of nodes, C, set of transportation modes, $K=\{(k,l) \mid k,l \in K,\ k \neq l\}$, set of time intervals, T, set of vehicles, V, set of vehicle speed levels, S and set of regions of speed module based on congestion, R. Lets define W as the set of all nodes $W=C \cup K \cup T \cup V \cup S \cup R$. We assumed that all of the initial data for demand of each node for different transportation modes at different time intervals (D_{ikt}), locations and distances between these nodes (d_{ijk}), operational data such as opening (Δ_{ikt}) and closing of the nodes (μ_{ikt}), loading of vehicles in each node for different transportation modes (L_{ikv}), capacity of the nodes for each transportation modes (C_{ik}), number of vehicles and their capacities (Cap_v^{max}) are given beforehand. Therefore, the process is started from the determined logistics centers (nodes) and conventional vehicles are used to transport the bulk or partial cargos between the customers with a unit transportation costs per transportation modes (TC_{ijk}). Sometimes, there are changes between the transportation modes at the nodes and this operation leads to additional transfer cost (TrC_{kl}) and transfer time (TrT_{kl}) which also take a fixed value for each transportation mode and node. This operation requires the decision on opening links between nodes and how much cargo and which kind of transportation mode is used for cargo carriage on the arcs defined as $A=\{(i,j) \mid i,j \in C, i \neq j\}$. Also, problem decides on the penalty costs if there is any waiting process due to the early or late delivery to the customers which are indicated as *P1* and *P2* for early and late arrival situation respectively. The model observes the effect of the environmental aspects by calculating the carbon dioxide emissions in terms of speed levels and some other parameters for this purpose.

S_k Speed limit of transportation mode k for free-flow transportation

b_{ijkvm} Time constant of corresponding travel time module m for vehicles v traveling on arc (i,j) by transportation mode k

$$b_{ijkvm} = \begin{cases} 0 & m = 0 \\ \left(alfa - \dfrac{d_{ijk}}{S_k^c} \right) & m = 1 \\ alfa & m = 2 \end{cases}$$

θ_{ijkvmr} Carbon dioxide emission equation constant

$$\theta_{ijkvmr} = \begin{cases} 0 & m = 1,3 \\ \dfrac{S_k^{2r} - S_k^{3r}}{S_k^{3r}} & m = 2 \end{cases}$$

ω_{ijkvmr} Carbon dioxide emission equation constant

$$\omega_{ijkvmr} = \begin{cases} 0 & m = 0 \\ \dfrac{d_{ijk}}{S_k^{1r}} & m = 1 \\ \dfrac{d_{ijk}}{S_k^{1r}} + (\dfrac{S_k^{3r} - S_k^{2r}}{S_k^{3r}}) & m = 2 \\ \dfrac{d_{ijk}}{S_k^{3r}} & m = 3 \end{cases}$$

Also, there are some mathematical parameters in the calculation of multi-objective problem by using epsilon-constraint method.

G1 Any large value greater than upper bound of the secondary objective function

G2 Any large value greater than upper bound of the third objective function

There are many scalars for this problem and they are mostly used in speed and carbon dioxide formulations. Also, when the problem is designed as a linear problem, some big values are used in linearization process.

Scalars:

a, b	BPR equation constants
A,B,C	Carbon dioxide emission rate constants
alfa	Initial congestion duration (minutes)
$\alpha, \beta, \pi, \lambda$	Carbon dioxide emission rate constants for non-linear model
ϵ	Epsilon value
σ	Curb weight (kg)
Ω	Daily period (hours)
k	Engine Friction Factor constant

U	Engine Speed constant
H	Engine Displacement constant
$M1, M2, M3, M4$	The big-M parameter values

There are three main objectives in this problem; cost, time and carbon emission. While the problem takes the cost objective as a prior action and tries to minimize the cost variables; the time and environmental objectives are also taking into account. Therefore, problem minimizes the total number of carried goods (X_{ijkvt}) on arc (i,j) and total number of inventories (I_{ikt}) for each kind of transportation mode in different time intervals. Also, if there is any transfer between the transportation modes, then this will creates some additional cost for the system and model tries to reduce this cost variable. However, the minimization of the cost is not enough for multi–objective problems. Therefore, model considers the total transportation duration (TT_{ijkvt}) on arcs (i,j) and also time consumption during the transfer operations. Additionally, model controls the operational movements of the cargos in terms of their time frames, such as arrival (ta_{ijkvt}) and departure time (td_{ijkvt}) of the vehicles to/from the nodes for different transportation modes; waiting times of the vehicles in each node for different transportation modes (EW_{ikvt}, LW_{ikvt}, NW_{ikvt} for early, late and normal arrival cases respectively). Moreover, model gets the information about the filling ratio of the vehicles (γ_{vkt}) for different transportation modes in different time intervals.
Also, there are some binary variables to control the transportation operations in an effective way.

Binary Variables:

y_{ijkvt} $\begin{cases} 1 & \text{if transportation mode } k \text{ is chosen on arc } (i,j) \text{ in time interval } t \\ 0 & \text{else} \end{cases}$

w_{iklt} $\begin{cases} 1 & \text{if transfer from transportation mode } k \text{ to } l \text{ in node } i \text{ in time interval } t \\ 0 & \text{else} \end{cases}$

$z1_{ijkvt}$ $\begin{cases} 1 & \text{if vehicle } v \text{ in node } i \text{ for transportation mode } k \text{ in period } t \text{ arrives early} \\ 0 & \text{else} \end{cases}$

$z2_{ijkvt}$ $\begin{cases} 1 & \text{if vehicle } v \text{ in node } i \text{ for transportation mode } k \text{ in period } t \text{ arrives late} \\ 0 & \text{else} \end{cases}$

$z3_{ijkvt}$ $\begin{cases} 1 & \text{if vehicle } v \text{ in node } i \text{ for transportation mode } k \text{ in period } t \text{ arrives in time} \\ 0 & \text{else} \end{cases}$

$g1_{ijkvmr}$ $\begin{cases} 1 & \text{if vehicle } v \text{ departs node } i \text{ in time interval } m \text{ by mode } k \text{ and speed } r \\ 0 & \text{else} \end{cases}$

First, the non-linear model is developed and main objective functions and constraints are listed below:

$$min \quad f_1 = \sum_{t\epsilon T}\sum_{v\epsilon V}\sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{k\epsilon K}\left(TC_{ijk} \times X_{ijkvt} \times y_{ijkvt}\right) + \sum_{t\epsilon T}\sum_{i\epsilon I}\sum_{k\epsilon K}\sum_{l\epsilon L}(TrC_{kl} \times w_{iklt}) + \sum_{i\epsilon I}\sum_{t\epsilon T}\sum_{k\epsilon K}(I_{ikt} \times P1) \qquad (1)$$

$$min \quad f_2 = \sum_{t\epsilon T}\sum_{v\epsilon V}\sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{k\epsilon K}(TT_{ijkvt} \times y_{ijkvt}) + \sum_{t\epsilon T}\sum_{i\epsilon I}\sum_{k\epsilon K}\sum_{l\epsilon L}(TrT_{kl} \times w_{iklt}) + \sum_{i\epsilon I}\sum_{t\epsilon T}\sum_{k\epsilon K}\sum_{v\epsilon V}\{((EW_{ikvt} + LW_{ikvt}) \times P2) + (NW_{ikvt} \times P3)\} \qquad (2)$$

$$min\, f_3 = \sum_{t\epsilon T}\sum_{v\epsilon V}\sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{k\epsilon K}\lambda(kUH + \sigma\pi\alpha\frac{d_{ij}}{TT_{ijkvt}} + X_{ijkvt}\pi\alpha\frac{d_{ij}}{TT_{ijkvt}} + \beta\pi\left(\frac{d_{ij}}{TT_{ijkvt}}\right)^3) \times TT_{ijkvt} \qquad (3)$$

$$EW_{ikvt} \geq \left[\Delta_{ikt} - t\alpha_{ijkvt}\right] + M3\left(1 - z1_{ijkvt}\right) \; \forall\, t\epsilon T, (i,j)\epsilon A, k\epsilon K, v\epsilon V \qquad (4)$$

$$LW_{ikvt} \geq \left[\Omega - t\alpha_{ijkvth} + \Delta_{ik(t+1)}\right] + M3\left(1 - z2_{ijkvt}\right) \; \forall\, t\epsilon T, (i,j)\epsilon A, k\epsilon K, v\epsilon V \qquad (5)$$

$$NW_{ikvt} \geq \left[td_{ijkvth} - ta_{ijkvt}\right] + M3\left(1 - z3_{ijkvt}\right) \; \forall\, t\epsilon T, (i,j)\epsilon A, k\epsilon K, v\epsilon V \qquad (6)$$

$$z1_{ijkvt} + z2_{ijkvt} + z3_{ijkvt} = y_{ijkvt} \quad \forall\, t\epsilon T, (i,j)\epsilon A, k\epsilon K, v\epsilon V \qquad (7)$$

$$td_{ijkvt} \geq ta_{ijkvt} + L_{ikv} + TrT_{kl} - M4\left(1 - y_{ijkvt}\right) \; \forall\, t\epsilon T, (i,j)\epsilon A, k\epsilon K, v\epsilon V \qquad (8)$$

$$\Delta_{ikt} \leq td_{ijkvt} \leq \mu_{ikt} \quad \forall\, t\epsilon T, (i,j)\epsilon A, k\epsilon K, v\epsilon V \qquad (9)$$

$$\sum_{j\epsilon J} y_{ijkvt} \geq 0 \quad \forall\, t\epsilon T, i\epsilon I, k\epsilon K, v\epsilon V \qquad (10)$$

$$I_{ikt} \leq C_{ik} \quad \forall\, t\epsilon T, i\epsilon I, k\epsilon K \qquad (11)$$

$$\sum_{l\epsilon L} w_{iklt} \geq 1 \quad \forall\, t\epsilon T, i\epsilon I, k\epsilon K \qquad (12)$$

$$y_{jikvt} + y_{ijkvt} \geq 2 \times w_{iklt} \quad \forall\, t\epsilon T, (i,j)\epsilon A, k\epsilon K, v\epsilon V \qquad (13)$$

$$I_{ik(t-1)} + \sum_{t'\epsilon T} \sum_{v\epsilon V} \sum_{j\epsilon J} X_{jikvt'} = \sum_{v\epsilon V} \sum_{j\epsilon J} X_{ijkvt} + I_{ikt} \quad \forall\, t\epsilon T, i\epsilon I, k\epsilon K \tag{14}$$

$$t-1 \le t' + TT_{jikvt'h'} \le \mathrm{t} \quad \forall\, t'\epsilon T \tag{15}$$

$$\sum_{v\epsilon V} \sum_{j\epsilon J} X_{jikvt} - \sum_{v\epsilon V} \sum_{j\epsilon J} X_{ijkvt} = D_{ikt} \; \forall\, t\epsilon T, i\epsilon I, k\epsilon K \tag{16}$$

$$D_{ikt} \times y_{ijkvt} \le X_{ijkvt} \le (Cap_v^{max} - D_{ikt}) \times y_{ijkvt} \; \forall\, t\epsilon T, (i,j)\epsilon A, k\epsilon K, v\epsilon V \tag{17}$$

$$TT_{ijkvt} = \frac{d_{ijk}}{S_{mrk}} \times \left[1 + a \times \left[\frac{X_{ijkvt}}{C_{ik}}\right]^b\right] \quad \forall\, t\epsilon T, (i,j)\epsilon A, m\epsilon M, r\epsilon R, v\epsilon V, k\epsilon K \tag{18}$$

$$\gamma_{vkt} = \frac{\sum_{i\epsilon I} \sum_{j\epsilon J} X_{ijkvt}}{Cap_v^{max}} \quad \forall\, t\epsilon T, v\epsilon V, k\epsilon K \tag{19}$$

$$\gamma_{vkt} \le 1 \; \forall\, t\epsilon T, v\epsilon V, k\epsilon K \tag{20}$$

$$X_{ijkvt}, Q_{ijkvt}, J_{ijkvt}, TT_{ijkvt,} ta_{ijkvt}, td_{ijkvt} \ge 0 \; \forall\, t\epsilon T, (i,j)\epsilon A, v\epsilon V, k\epsilon K \tag{21}$$

$$z1_{ijkvt}, z2_{ijkvt}, z3_{ijkvt} \ge 0 \quad \forall\, t\epsilon T, (i,j)\epsilon A, v\epsilon V, k\epsilon K \tag{22}$$

$$EW_{ikvt}, LW_{ikvt}, NW_{ikvt} \ge 0 \quad \forall\, t\epsilon T, i\epsilon I, v\epsilon V, k\epsilon K \tag{23}$$

$$y_{ijkvt}, w_{iklt,} \in \{0,1\} \quad \forall\, t\epsilon T, (i,j)\epsilon A, v\epsilon V, k\epsilon K \tag{24}$$

$$g1_{ijkvmr}, g2_{ijkvmr} \in \{0,1\} \quad \forall\, t\epsilon T, (i,j)\epsilon A, m\epsilon M, r\epsilon R, v\epsilon V, k\epsilon K \tag{25}$$

$$I_{ikt} \ge 0 \quad \forall\, t\epsilon T, i\epsilon I, k\epsilon K \tag{26}$$

Equations (1)–(3) show the main objective functions of this model which are cost, time and carbon emission rate, respectively. In Eq. (1), first term corresponds to total transportation cost of carried goods, second indicates the transfer cost among transportation modes and the last part is penalty cost of keeping inventory in nodes. Eq. (2) shows that minimization of total transportation durations during the operations and total transfer time in mode changes and also third part of this equation tries to give penalty to minimize the waiting times of vehicles in nodes. In Eq. (3) indicates the minimization of total carbon emission rate within the system. First part of this equation shows rate caused by the engine module and the speed module, second term shows total the emission rates generated by the speed module in the all congestion and in the all free-flow regions and last one represents total the rate induced by the weight module (Bektas and Laporte, 2011; Demir et al., 2014). Eq. (4)–(6) indicates the total waiting time of vehicles for each transportation mode. There should be early, late or in time arrival probabilities in allowed time period and Eq. (4)-(6) fulfills this situation respectively. Eq. (7) ensures that if there is any need to be carried on arc (*i*,*j*), each vehicle within the nodes for different transportation modes has to arrive early, late or in time. Eq. (8) indicates relationship between departure and arrival times of vehicles within nodes for transportation modes. Time duration between arrival and departure time of each vehicle has to be greater than summation of loading time of vehicle for mode *k* and transfer times from mode *k* to *l*. Eq. (9) ensures that departure time of vehicle has to be between opening and closing time of nodes for each transportation mode. For example, if the summation of loading and transfer time between different transportation modes are exceeding the closing time of node for transportation mode, then vehicle has to wait until the next day and quantity on vehicle will be added to inventory of node for that transportation mode. Eq. (11) indicates that daily keeping inventory of every node *i* has to fulfill the capacity levels for each transportation mode *k*. Eq. (12) indicates that any material in node *i* must be transported via at least one of the available transportation modes. This constraint forces the solver to obtain minimum transfer cost and transfer time in node *i* in terms of transportation modes. Eq. (13) shows that the arrival transportation mode must be the same transportation mode of the leaving mode over the arc (*i*,*j*). On the other hand, if there is any difference between arriving and leaving transportation modes, Eq. (13) ensures that there should be mode transfer within the node. Eq. (14) indicates the mass balance in the nodes. The incoming and outgoing quantities in node *i* for each transportation mode *k* should be same and Eq. (14) helps model to fulfill this balance during the operations. However, the relationship between current (*t*) and previous time intervals ($t' < t$) has to be as in Eq. (15). Arrival time of vehicles on arc (*i*,*j*) for different transportation modes, which is equal to summation of departure time of vehicles on arc (*i*,*j*) and transportation duration on arc (*i*,*j*) for different transportation modes, has to be in the range of single time period (between *t* and (*t*-1)). Travel time durations are taken as a step-wise function for 24 hour time period per day in this part of the problem. Eq. (16) shows that incoming and outgoing quantities of carried goods have to be equal to demand of nodes for different transportation modes in every time period. Capacities of vehicles are satisfied by Eq. (17) for each transportation mode in every time period. Eq. (18), the BPR (Bureau of Public Roads) equation (1964) (BPR, 1964) was used to handle the traffic congestion problem. The BPR equation was modified to obtain transportation times of the modes for every time interval *t*. The BPR equation constants were obtained from Horowitz (1985). Eq. (19)–(20) indicates the occupancy rate of vehicles for different transportation modes. Eq. (21)–(26) ensures both integrality and non-negativity conditions.

Solution Methodology

For the solution methodology, (AUGMECON2) ϵ-constraint method (Mavrotas and Florios, 2013) is used to generate the Pareto optimal solutions for decision makers. Relationship between objective functions will be determined and applied for different problem cases. However, finding the optimal solutions for this kind of problems is seriously time–consuming and difficult by the current solvers because proposed problems are very complex (if it is used in the real cases) and NP–hard due to large number of constraints and indices (Mahlke et al., 2010). Therefore, firstly the problem is converted into the mixed-integer linear programming model.

Linearization of the model

$$min\ \ f_1 = \sum_{t\epsilon T}\sum_{v\epsilon V}\sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{k\epsilon K}\left(TC_{ijk} \times X_{ijkvt}\right) + \sum_{t\epsilon T}\sum_{i\epsilon I}\sum_{k\epsilon K}\sum_{l\epsilon L}(TrC_{kl} \times w_{iklt}) + \sum_{i\epsilon I}\sum_{t\epsilon T}\sum_{k\epsilon K}(I_{ikt} \times P1) \quad (26)$$

$$min\ \ f_2 = \sum_{t\epsilon T}\sum_{v\epsilon V}\sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{k\epsilon K}(\mathrm{J}_{ijkvt}) + \sum_{t\epsilon T}\sum_{i\epsilon I}\sum_{k\epsilon K}\sum_{l\epsilon L}(TrT_{kl} \times w_{iklt}) + \sum_{i\epsilon I}\sum_{t\epsilon T}\sum_{k\epsilon K}\sum_{v\epsilon V}\{((EW_{ikvt} + LW_{ikvt}) \times \mathrm{P2}) + (NW_{ikvt} \times \mathrm{P3})\} \quad (27)$$

$$X_{ijkvt} \leq Q_{ijkvt} \quad \forall\ t\epsilon T, (i,j)\epsilon A, k\epsilon K \quad (28)$$

$$X_{ijkvt} \leq M \times y_{ijkvt} \quad \forall\, t \epsilon T, (i,j) \epsilon A, k \epsilon K \tag{29}$$

$$X_{ijkvt} \geq Q_{ijkvt} - M(1 - y_{ijkvt}) \quad \forall\, t \epsilon T, (i,j) \epsilon A, k \epsilon K \tag{30}$$

$$J_{ijkvt} \leq TT_{ijkvt} \quad \forall\, t \epsilon T, (i,j) \epsilon A, k \epsilon K \tag{31}$$

$$J_{ijkvt} \leq M \times y_{ijkvt} \quad \forall\, t \epsilon T, (i,j) \epsilon A, k \epsilon K \tag{32}$$

$$J_{ijkvt} \geq TT_{ijkvt} - M(1 - y_{ijkvt}) \quad \forall\, t \epsilon T, (i,j) \epsilon A, k \epsilon K \tag{33}$$

The Eq. (28)-(33) indicates the linearization of the model because the multiplication of carried quantity on arc (*i*,*j*) for each transportation mode and the binary variable giving decision whether using that arc (*i*,*j*) by the same transportation mode makes the model non-linear and model can be converted into a linear one by the help of Eq. (28)-(30). Same situation is also valid for transportation time calculations. The multiplication of two variables creates non-linear conditions and relaxation of these equations by using the Eq. (31)-(33) converts our problem into a linear form.

Also, BPR equation (BPR, 1963), Eq. (18), makes the problem non-linear because the transportation time is directly related with the number of vehicles on arc (*i*,*j*). In the conventional way, the constant *b* of BPR equation is taken as "4" and this makes the model non-linear, but study of Resat and Turkay (2015) indicates that constant *b* can be taken as "1" to handle the non-linearity of the Eq. (18) and this change creates approximately less than 5% difference in the results and the effect of this change can be negligible.

Additionally, carbon emission rate calculation is the one of our objectives and this factor directly related with the fuel consumption same as total travelled distance by the vehicles and the equation used in this model makes the problem non-linear. However, we replace this objective function with the linear one developed by the recent studies of Bektas and Laporte (2011). It combines the speed of the vehicles with the carbon emission rate in terms of the time dependency. The equations are given below.

$$min \quad f_3 = \sum_{m\epsilon M}\sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{r\epsilon R}\sum_{k\epsilon K}\left\{\left\{\left(\theta_{ijkmr} \times g2_{ijkmr} + \omega_{ijkmr} \times g1_{ijkmr}\right) \times A + \left(\theta_{ijkmr} \times g2_{ijkmr} + \omega_{ijkmr} \times g1_{ijkmr}\right) \times (S_{kmr})^3 \times B\right\}\right\} + \sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{k\epsilon K}\sum_{r\epsilon R}\left\{\left\{\left(g2_{ijk2r} + \theta_{ijk2r} \times g2_{ijk2r} + \omega_{ijk2r} \times g1_{ijk2r} - \alpha \times g1_{ijk2r}\right) \times (S_{k3r})^3 \times B\right\} + \left\{\left(\alpha \times g1_{ijk2r} - g2_{ijk2r}\right) \times (S_{k2r})^3 \times B\right\}\right\} \quad (34)$$

$$g1_{ijkvmr} \times b_{ijkv(m-1)} \leq g2_{ijkvmr} \leq g1_{ijkvmr} \times b_{ijkvm} \forall\ (i,j)\epsilon A, m\epsilon M, k\epsilon K, v\epsilon V, r\epsilon R \quad (35)$$

$$\sum_{m\epsilon M}\sum_{r\epsilon R}(\theta_{ijkvmr} \times g1_{ijkvmr} + \omega_{ijkvmr} \times g2_{ijkvmr}) \leq \sum_{h\epsilon H} TT_{ijkvt} \quad \forall\ t\epsilon T, (i,j)\epsilon A, v\epsilon V, k\epsilon K \quad (36)$$

Eq. (35) ensures that time period at which vehicle *v* leaves the node *i* by transportation mode *k* under boundary limits. Eq. (36) indicates that travel duration (of which vehicle *v* on arc (*i*,*j*) by transportation mode *k*) used in the carbon dioxide emission calculations is at most equal to transportation duration of speed calculations.

After converting the problem into the linear version, the problem still requires serious amount of computational effort and reduction of the complexity of linear integer problems is the major area of the recent studies. In literature, heuristics, meta–heuristics and hybrid genetic algorithms are some part of the solution methodologies for integer linear problems such as (Ishfaq and Sox, 2012; Limbourg and Jourquin, 2009; Mahlke et al., 2010). However, exact method is used to eliminate the lower accuracy of heuristics methods in the study of Resat and Turkay (2015). Especially, pre-processing and logic-cut methods help solvers to obtain more accurate and optimal solutions by decreasing the complexity and division of problems. Although the logic-cuts increase the number of constraints, it would reduce the relaxation gap and would strengthen convex hull approximation. Therefore, solver will obtain better feasible solutions with shorter CPU times. Also, addition of these extra constraints because of logic-cut and pre-processing methods will not change the integer optimal solutions. As indicated in the study of Fattahi and Turkay (2014), some logic-cuts and pre-processing methods help to find solutions in better and faster ways.

Pre-Processing

After modelling our problem in the linear form, we introduced some pre-processing steps and valid inequalities to increase the efficiency of the model and to decrease the dimension of the problem.

$$y_{ijkvt} = 0 \quad \forall\ t\epsilon T, (i,j)\epsilon A, k\epsilon K, v\epsilon V \ \text{ if } (i,j) \text{ isn't linked} \quad (37)$$

$$\sum_{j\epsilon J} y_{ijkt} \ = 0 \quad \forall\ t\epsilon T, i\epsilon I, k\epsilon K, v\epsilon V \quad \text{if } D_{ikvt} = 0 \quad (38)$$

Firstly, all cost matrices of transportation modes, transfer operations and distances between nodes are initialized as indicated in Eq. (37)-(38). With Eq. (37)-(38), there is assessment of the set of arcs (*i*,*j*) to see whether there is a link between these two nodes or there is enough demand of node *i*. If they are not connected or there is no demand in origin node *i*, it is not possible to transport any goods from node *i* to node *j*.
The pre-processing steps aiming to remove infeasible arcs from the problem as described below:

$$D_{ikt} + D_{jkt} \geq \sum_{j\epsilon J} Cap_v^{max} \quad \forall\ t\epsilon T, (i,j)\epsilon A, k\epsilon K \quad (39)$$

$$\Delta_{ikt} + L_{ikv} + J_{ijkvt} \geq \mu_{jkt} \ \ \forall\ t\epsilon T, (i,j)\epsilon A, k\epsilon K, v\epsilon V \quad (40)$$

Eq. (39) ensures if demand of the subsequent nodes exceeds the total capacity of the vehicles for each transportation mode in every time interval, then system eliminates this arc. Eq. (40) indicates that if the delivery will be later than the closing time of the following node, then this arc will be eliminated. Also, in our problem, time-dependent travel durations are the step-wise function for 24 hour time period per day. This quantity balance in Eq. (14) has to be satisfied for every time interval *t*. However, the relationship between *t* and previous time intervals (*t’* < *t*) has to be as in Eq. (15). To obtain the incoming quantities up to time interval *t*, travel duration of vehicles plays a crucial role as traffic congestion affects the travel duration of vehicles. To obtain the value of $\sum_{t'\epsilon T}\sum_{j\epsilon J} X_{jikvt'}$ (incoming goods) in Eq. (14), the following logic system was created for time interval t >2.

Transportation time matrix is obtained by the help of Eq. (18). Then the new parameter ($arrival\_time_{jikt'}$) is created which recognizes and keeps the arrival times of vehicles which leaves from node *j* at *t'* and reach to node *i* before time interval *t*. This transportation time matrix is constructed for road transportation only by using Eq. (41) because transportation times for sea and rail transportations are assumed to be constant and they are calculated by dividing the total distance on arc (*i*,*j*) to the speed of the vehicles.

$$t' + TT_{jikvt'} = arrival\_time_{jikvt'} \; \forall \, t'\epsilon T, (i,j)\epsilon A \quad \text{for } k = Road \quad (41)$$

According to the arrival time values, a new binary matrix (*AT*) is used to indicate the whether there are any flows which depart from node *j* at *t'* and arrive node *i* at *t* (is equal to $arrival\_time_{jikt'}$) for transportation mode *k*.

$$AT_{jikvt't} = \begin{cases} 1 & \text{if } arrival\_time_{jikvt'} > 0 \\ 0 & \text{else} \end{cases} \quad \forall \, t\epsilon T, t'\epsilon T, (i,j)\epsilon A, k\epsilon K \quad (42)$$

Then, this new parameter (time matrix *AT*) is multiplied with $X_{ijkt'}$ to obtain the new quantities regarding with transportation times. Total incoming goods to node *i* by transportation mode *k* until time interval *t*-1 and *t* is modeled in Eq. (43).

$$\sum_{j\epsilon J}\sum_{t'\epsilon T} AT_{jikvt't} \; X_{jikvt'} \; \forall \, t\epsilon T, i\epsilon I, k\epsilon K \quad (43)$$

5.3 Computational Experiments

In this section, we discuss the initial data used as parameter in the models and also the general overview of illustrative cases and their applications into this study.

Additionally, some assumptions used in the design and operation of models are indicated.

Firstly, we start our problem with the data collection and prediction phase. In this part, historical traffic data, location of customers, information about fleets (their capacities, number of vehicles per logistics providers etc.) and initial data for customer orders (their coordinates, total cargo type and quantities) are obtained. At this stage, we used the same benchmark data given in the study of Resat and Turkay (2015). They proposed real-case data for the Marmara Region in Turkey. For our illustrative cases, we took the 5-10-25 nodes which are the mostly important ports and logistics centers in the Marmara Region. After defining the nodes for our illustrative cases, we get the data about distances between nodes from official reports which were issued by the Ministry of Transportation and some public bodies of Turkey (DTM, 2010; KGM, 2011; TCDD, 2010). Resat and Turkay (2015) indicates that almost 98% of the freight transportation activities are made by using road, rail and sea transportation. Therefore, we took into consideration only these types of transportation modes in this study. We used similar unit costs for transportation operations and transfer activities within the nodes which are as given in Resat and Turkay (2015). The speeds of the rail and sea transportation is also taken as constant and road transportation depends on the number of vehicles on the roads and calculated by using the BPR equation. Apart from the cost parameters, again total transportation time is another important objective of our problem. The transportation times are calculated by the division of the total distance to the speed of the vehicles. The operational restrictions are also taken into account such as, opening and closing times of the ports and rail centers and also the urgent delivery requests of the customers. For the third objective (carbon emission rate), we used the same parameters given in the study of Bektas and Laporte (2011).

The capacities of the vehicles are depending on the type of the vehicles which are assumed to be either 15 or 30 ton trucks. However, fleet optimization model can fill up these trucks with the products of different customers. This is the main difference from the intermodal transportation because only the container-unit products can be assessed in intermodal transportation.

Also, the initial demand of the customer is assumed to be known at the beginning of the day. They can share such information with the details of sender/receiver/location, and then the model can automatically make arrangements to optimize the fleets and networks to distribute the cargos in an effective way. The time period is taken as 24 hour period and the time intervals are changing with the request of the customers which means that each time interval will equal to the minimum transportation time of the network. System will update its position and get new information from the outside at the beginning of each iteration and if necessary, the plans will be revised.

5.4 Results

In this section, we illustrate the main concepts and the analysis of the solutions on three different cases and then we will give sensitivity analysis of the illustrative cases with additional pre-processing constraints in terms of the average computational performance unit times. We used three sets of parameters for different cases. The main difference between these cases is the number of the nodes used in the networks. Cases include 5, 10 and 25 nodes respectively. The linear model for this problem is written in GAMS modeling environment and solved with IBM ILOG CPLEX 12.1 (CPLEX, 2009) and the non-linear one is solved by the DICOPT (Duran and Grossmann, 1986). Both models are executed on a computer with Intel Core I5 2520 M CPU with 2.50 GHz dual core processor, and with 4.00 GB of RAM. An optimality gap of 1 % is set for the solutions.

5-Node Case

This illustrative example consists of five different nodes in the network with different transportation modes. The transportation mode connections and distances are given in the Appendix and operational information (opening, closing times, etc.) are obtained from the studies of DTM (2010), KGM (2011), and TCDD (2010).

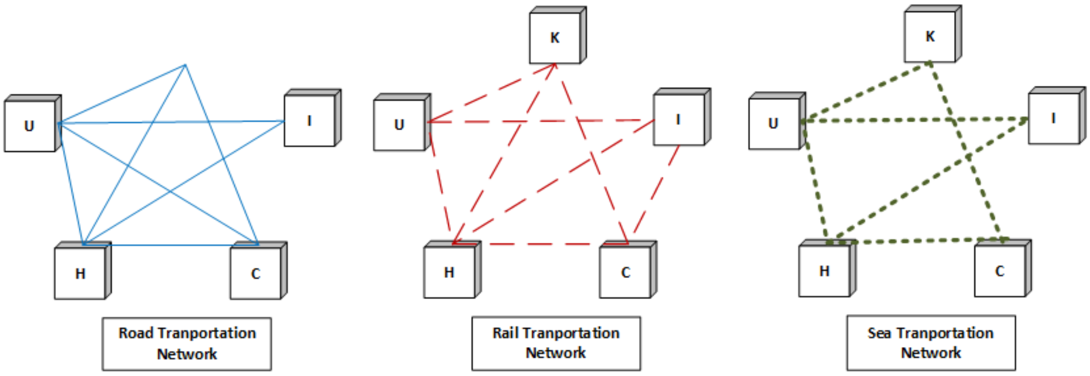

Figure 21: Network design of the 5-node case for different transportation modes

Firstly, the problem is solved without any disruptions during the operations and obtained results for rail and sea transportation are given in Figure 22.

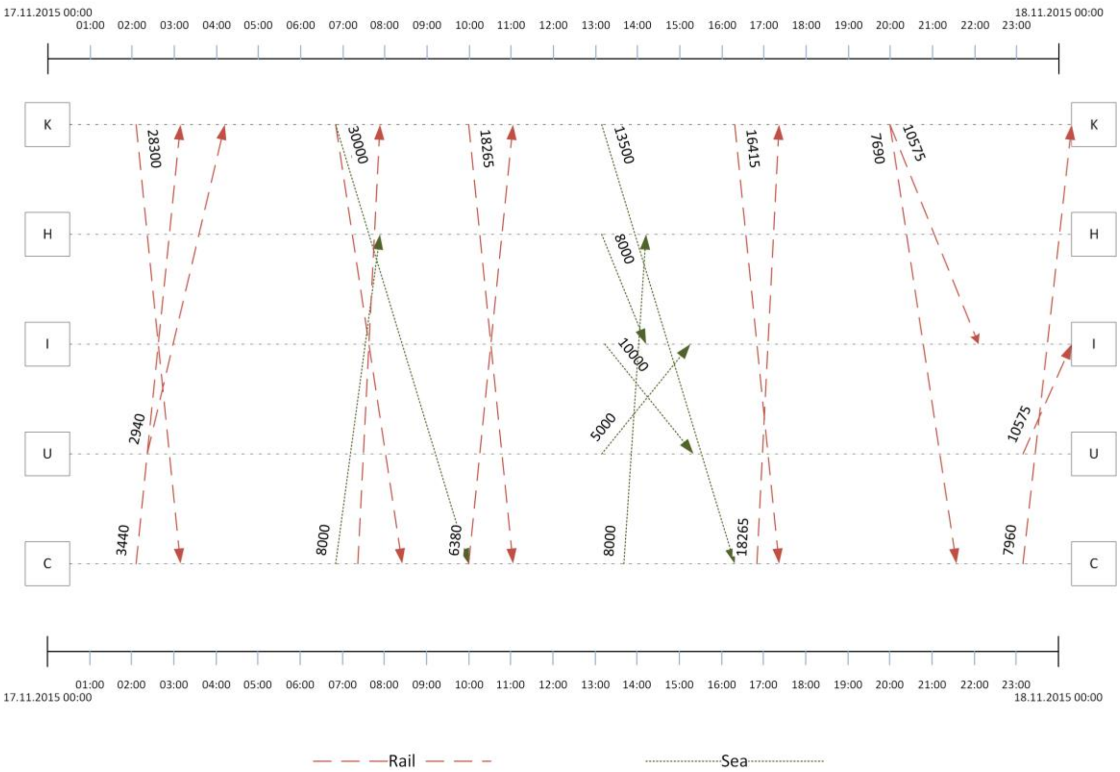

Figure 22: Amount of cargos (ton) carried by Rail and Sea Transportation in a day

In our illustrative case, we assumed that there are two different disruptions during the operations. One of them is the cancellation of the ships due to the bad weather conditions and this information is given into the system around 12:00 AM. As it is seen from the Figure 22, there are a high number of sea transportation movements around 1:00 PM under the normal conditions. After getting this weather forecast, system cancels all of the sea transportation links and the expected cargo movement should be made by either road or rail transportation. Therefore, the new network design after this revision is given and updated rail and road transportation movements are shown in Figure 23.

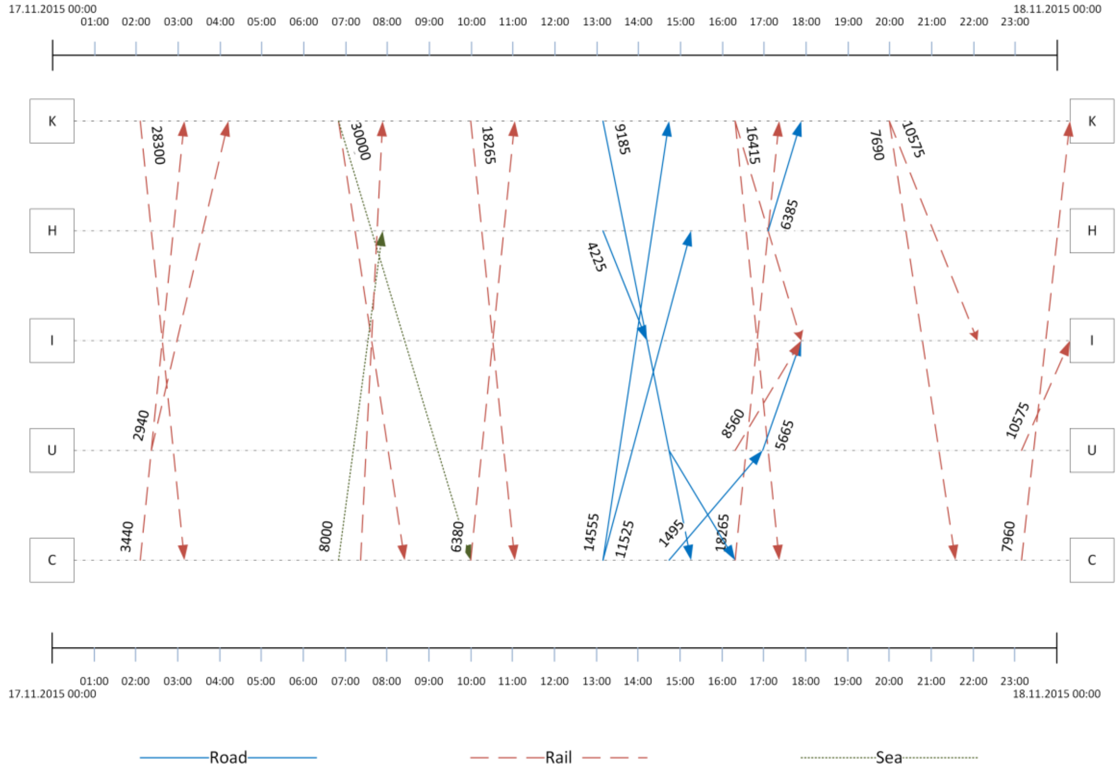

Figure 23: Updated network after first disruption

Second disruptive case is the train accident. We assumed that the train departed from Node K to Node I at 08:00 PM has a traffic accident around 08:30 PM and the cargo on this train should be taken to the other vehicles and moved to the final destination. Taking urgent actions on the unexpected events is one of the very important characteristics of the Synchromodal transportation. In this case, we assumed that all of the cargo on the train will be carried by road transportation because there is no opportunity to carry that much cargo by sea transportation at that time period. Therefore, transfer of the containers or trailers to the trucks will take some time and operation will continue after waiting this transfer time which is assumed as approximately 45 minutes. The new planning scheme after the second disruption (in addition to the first one) is given in Figure 24.

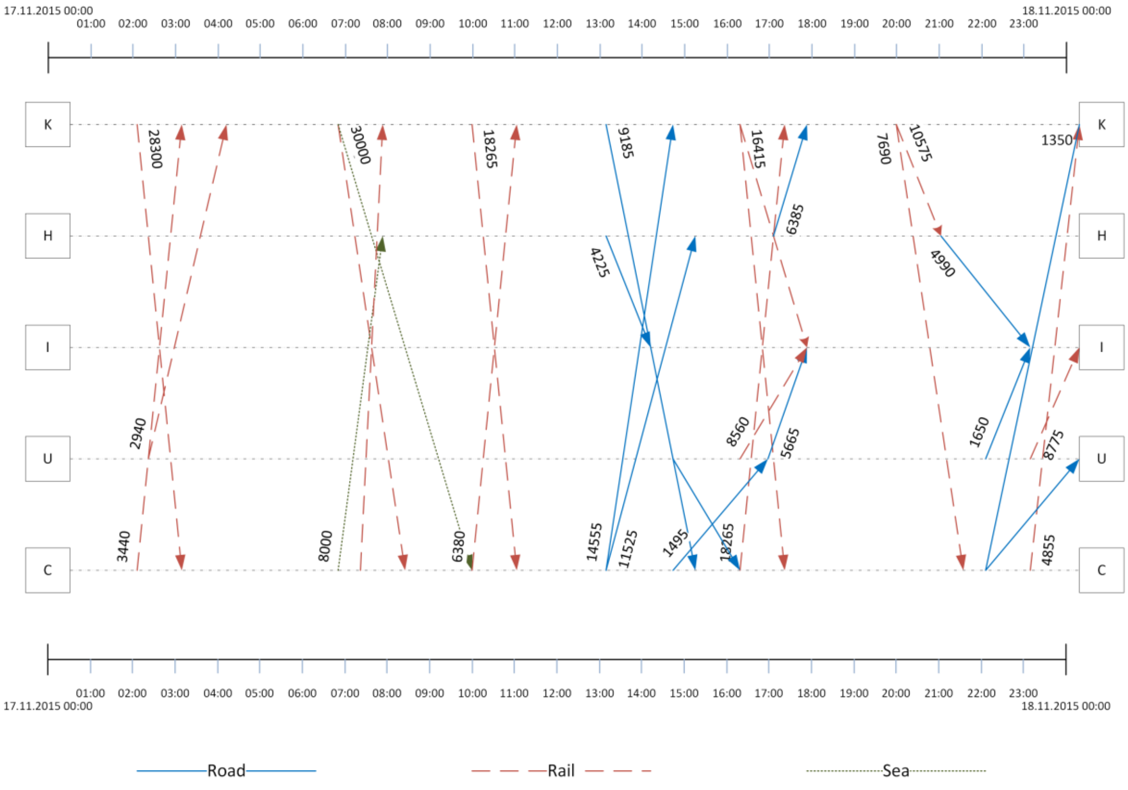

Figure 24: Updated network design after first and second disruptions

This problem with two disruptions is solved with non-linear and linear models separately and 100 different Pareto solutions are found for three different objective functions (cost, time and carbon emission) for both linear and non-linear models and given in Figure 25.

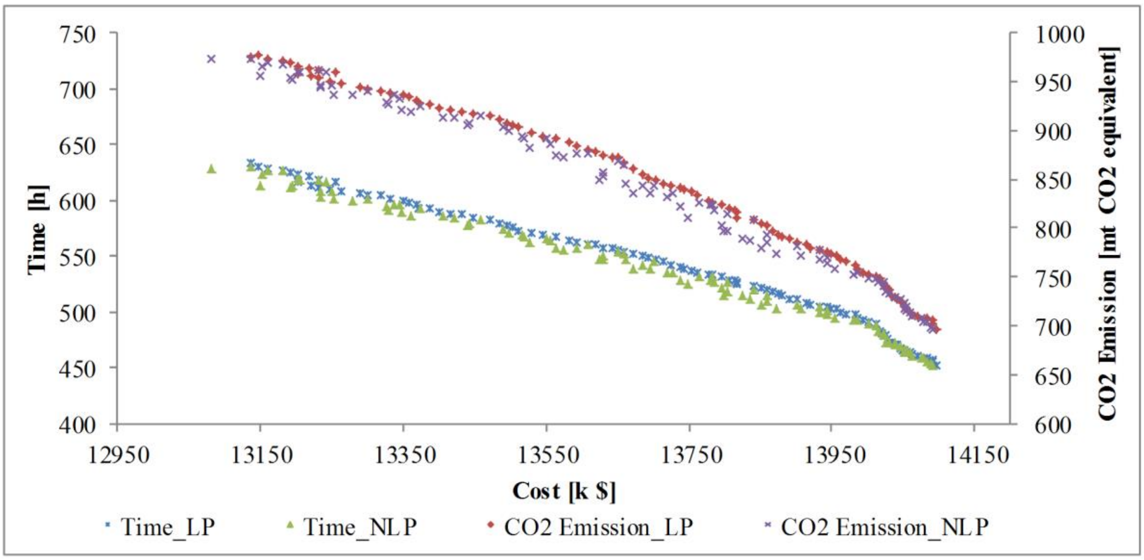

Figure 25: 100 Pareto Solutions for 5-Node Network

After finding the Pareto solutions, pre-processing constraints are included into the models and some sensitivity analyses are made in terms of average computational efforts by using the several combinations of these additional constraints. The results for this case are given in Table 10.

Table 10: The Computational Results of Different Combinations in Case 1

Additional Constraints	**Non-Linear Model**	**Linear Model**
	Avg. CPU (sec.)	**Avg. CPU (sec.)**
None	112	105
Eq. (37)-(38)	107	102
Eq. (39)-(40)	108	103

Eq. (37)-(40)	103	99
Eq. (37)-(43)	97	94

10-Node Case

This illustrative example consists of ten different nodes in the network with different transportation modes and network model is given in Figure 26. The transportation mode connections, distances and operational information (opening, closing times, etc.) are obtained from the studies of DTM (2010), KGM (2011) and TCDD (2010).

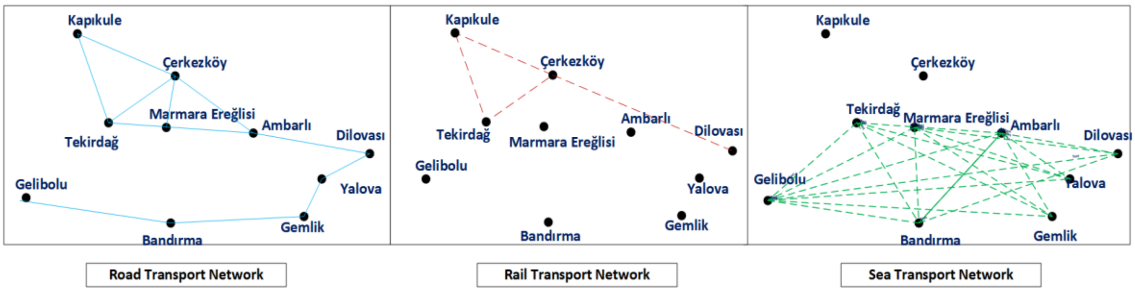

Figure 26: Network design of the 10-node case for different transportation modes

In this case, we again considered the same disruptions shared in 5-Node case, bad weather conditions around 1:00 PM and train accident around 8:00 PM, and problem with two disruptions is solved with non-linear and linear models separately and 100 different Pareto solutions are found for three different objective functions (cost, time and carbon emission) for linear and non-linear models and given in Figure 27.

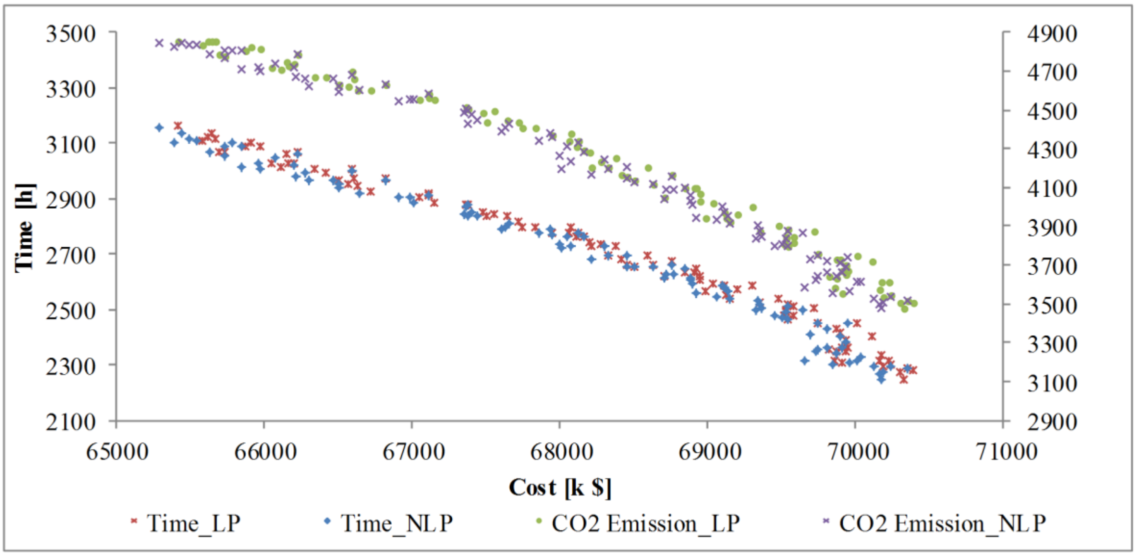

Figure 27: 100 Pareto solutions for trade-off between three objectives

After finding the Pareto solutions, pre-processing constraints are included into the models and some sensitivity analyses are made for the computational efforts by using the several combinations of these additional constraints. The results of this case are given in Table 11.

Table 11: The Computational Results of Different Combinations in Case 2

Additional Constraints	Non-Linear Model Avg. CPU (sec.)	Linear Model Avg. CPU (sec.)
None	921	873
Eq. (37)-(38)	901	858
Eq. (39)-(40)	903	861
Eq. (37)-(40)	882	834
Eq. (37)-(43)	842	817

25-Node Case

This illustrative example consists of twenty-five different nodes in the network with different transportation modes and network model is given in Figure 28. The transportation mode connections, distances and operational information (opening, closing times, etc.) are obtained from the studies of DTM (2010), KGM (2011) and TCDD (2010).

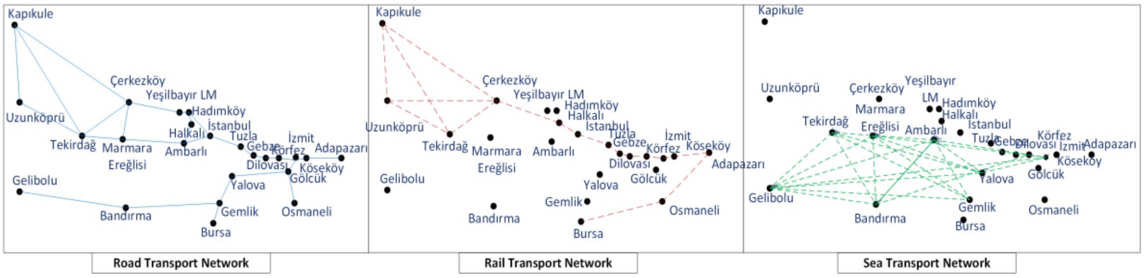

Figure 28: Network design of the 25-node case for different transportation modes

Problem with two disruptions is solved with non-linear and linear models separately and 100 different Pareto solutions are found for three different objective functions (cost, time and carbon emission) for linear and non-linear models and given in Figure 29.

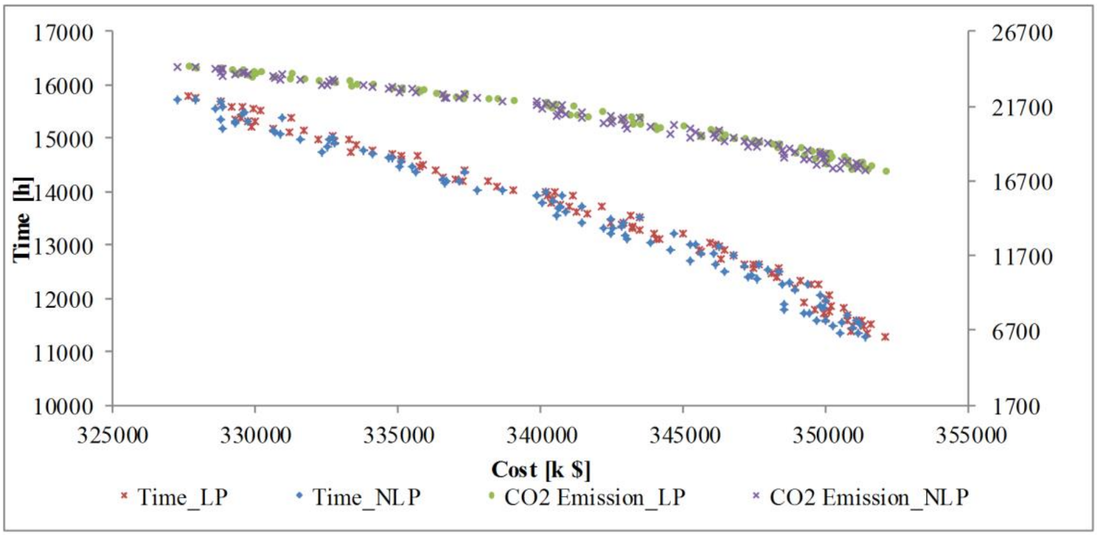

Figure 29: 100 Pareto solutions for trade-off between three objectives

After finding the Pareto solutions, pre-processing constraints are included into the models and some sensitivity analyses are made over the computational efforts by using the several combinations of these additional constraints. The results of this case are given in Table 12.

Table 12: The Computational Results of Different Combinations in Case 3

Additional Constraints	**Non-Linear Model**	**Linear Model**
	Avg. CPU (sec.)	**Avg. CPU (sec.)**
None	4,625	3,452
Eq. (37)-(38)	4,485	3,407
Eq. (39)-(40)	4,605	3,394
Eq. (37)-(40)	4,481	3,318
Eq. (37)-(43)	4,259	3,254

Sensitivity Analysis

We solved three illustrative cases by using both mixed-integer linear and non-linear programming models and optimization of such large problems to get Pareto solutions requires serious computational efforts, therefore there are some pre-processing constraints are inserted into the problem and effects of these constraints are assessed in different combinations and obtained average CPU (computational performance unit) times are given in Figure 30. According to the results given in Table 10-11-12, if the problem is converted from non-linear form to linear one, the average computational performance unit time decreases around 5%, 7% and 33% for 5, 10 and 25-Node cases respectively. Also, the effect of each pre-processing constraint set is reduction of the CPU efforts approximately 3%, 5%, 2% for 5,10 and 25-Node cases respectively, however if all of the additional constraints are inserted into the models then average CPU times reduce around 7-15% for different cases and this reduction in computational efforts increases by the complexity of the problem.

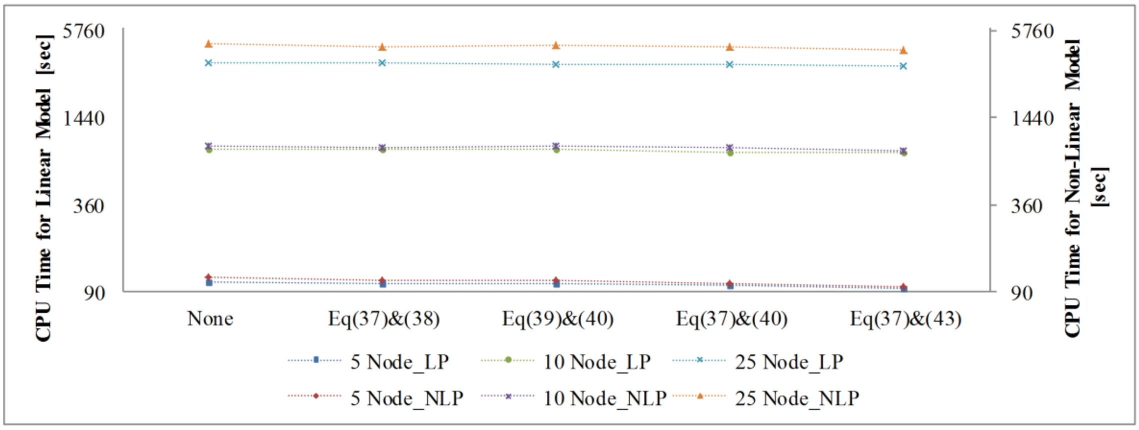

Figure 30: Computational Times for Linear and Non-Linear Models with different Constraints

5.5 Conclusions

In this study, we tried to make some theoretical analysis and contributions over the logistics industry. In the most of developed countries, there are serious negotiations over the quality, reliability and efficiency of the transportation systems and these important challenges are tried to be improved by some researches and regulations. Considering the increasing transportation activities and demand in this sector, there are some new ideas and concepts have occurred and synchromodal transportation is one of this new challenging areas. The main purpose of this study is to define what synchromodality is and how it can be used and implemented into the real life case. Therefore, the design and operation of synchromodal transportation is investigated in this paper and linear and non-linear mathematical models are developed and implemented into the different cases to indicate the characteristics of the synchromodal transportation. Performance evaluation of these models are obtained and analyzed and comparison tables are given within the study. Due to need of extensive computational efforts and memory, we just made our pilot studies in some illustrative cases, however our main objective for the future studies is to increase our complexity in our test networks and use data for a real life case in Europe.

Chapter 6

CONCLUSION AND FUTURE WORK

In this thesis, we tried to make some theoretical analysis and contributions over the logistics industry. In the most of developed countries, there are serious negotiations over the quality, reliability and efficiency of the transportation systems and these important challenges are tried to be improved by some researches and regulations. Especially, governments are willing to convert their transportation systems more sustainable, cost and environmental friendly formats and also considering the congestion, emissions, intermodal transport integration, the need for new infrastructure development and maintenance of existing infrastructures in their transportation systems.

In our first study, the definition of the sustainability in transportation activities are defined and main indicators for economic, environmental and social factors of sustainability of logistics sector are indicated and also theoretical studies and methodologies are investigated for decision makers and stakeholders from different areas to assess the current situation of the sector. After that, we analyzed one of the most promising ways of reducing the economic and environmental effects of the transportation industry, Intermodal Transportation. There are many studies which indicate and give some aspects of intermodal transportation and results of some illustrative cases but we designed a mixed-integer linear programming model for intermodal transportation by considering the traffic congestion and time dependency and implemented into both illustrative and real cases in our study. The obtained Pareto results of the problems give opportunity the decision makers to assess the operational efficiency and sustainability. After that, considering the increasing transportation activities and demand in this sector, there are some new ideas and concepts have occurred and synchromodal transportation is one of this new challenging areas. The main purpose of this thesis is to define what synchromodality is and how it can be used and implemented into the real life case. Therefore, design and operation of synchromodal transportation is investigated in our study and linear and non-linear mathematical models are developed and implemented into the different cases to indicate the characteristics of the synchromodal transportation. Performance evaluation of these models are obtained and analyzed and comparison tables are given within the study. Due to need of extensive computational efforts and memories, we just made our pilot studies in some small illustrative cases, however our main objective for the future studies is to increase our complexity in our test networks and use data for a real life case within Europe.

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VITA

Mr. Giray Resat, is a research and teaching assistant in Industrial Engineering Department, Koc University. He specialized in sustainable manufacturing and transportation solutions for industrial clusters. He received bachelor degree in Chemical Engineering from Bogazici University. He developed multi-period and multi-scale optimization models and bi-objective optimization algorithms for multi-modal transportation systems. He is also involved in the analysis of cluster efficiency in mobility and transportation systems in the light of sustainability concept. He participated in 3 FP7 projects: InTraRegio, Log4Green and MapDriver.

COMPUTER SKILLS

- MS Office Applications (Very Good)
- C programming / C# (Good)
- AutoCAD (fairly good)
- SAP (Good)
- MATLAB
- GAMS

PUBLISHED PAPERS

Resat, H. Giray and M. Turkay, Design and Operation of Intermodal Transportation Network in the Marmara Region of Turkey, the *Transportation Research Part E, vol 83, pg 16-33, 2015*.

PAPERS UNDER REVIEW

Resat, H. Giray and M. Turkay, Regional Comparative Cluster Analysis of Logistics Sector in Five European Regions.

Resat, H. Giray and M. Turkay, Design and Analysis of Green Vehicle Routing Problem by using both Conventional and Electric Vehicles.

Resat, H. Giray and M. Turkay, A Bi-Objective Model for Design and Analysis of Intermodal Transportation Systems: A Case Study of Turkey (Submitted to the *Transportation Research Part E*)

Resat, H. Giray and M. Turkay, A Discrete-Continuous Approach for the Design and Operation of Synchromodal Transportation Networks (PhD Thesis) (Submitted to the *Transportation Research Part E*)

PEER REVIEWED CONFERENCE PROCEEDINGS

Resat, H. Giray and M. Turkay, Time Dependant Intermodal Transportation in Marmara Region, A European Research Strategy for Intermodal Transport, Canary Islands, April 2013

BOOKS / BOOK CHAPTERS

Resat, H. Giray and M. Turkay, Sustainability of Products, Processes and Supply Chains: Theory and Applications, *Computer-Aided Chemical Engineering*, 36, Elsevier, April 2015.

CONFERENCE PRESENTATIONS

Resat, H. Giray and M. Turkay, Design and operation of time–dependant Synchromodal Transportation Systems, “British-France-Germany Conference on Optimization”, London, June 2015

Resat, H. Giray and M. Turkay, Design and operation of time–dependant Synchromodal Transportation Systems, “Workshop on ICT Solutions for Transportation”, Italy, July 2014

Resat, H. Giray and M. Turkay, Time Dependant Intermodal Transportation in Marmara Region, EURO 2013, Rome, July 2013

Resat, H. Giray and M. Turkay, Time Dependant Intermodal Transportation in Marmara Region, " A European Research Strategy for Intermodal Transport”, Canary Islands, April 2013

Resat, H. Giray and M. Turkay, Time Dependant Intermodal Transportation, EURO 2012, Vilnius, July 2012

SPONSORED RESEARCH PROJECTS

A. **Project Title:** InTraRegio-Towards an Intermodal Transport Network through innovative research- driven clusters in Regions of organised and competitive knowledge (286975)

Funding Source: European Commission FP7 Program THEME [REGIONS-2011-1]
Role: Research Assistant at Koc University
Budget: 104,326 €
Dates: 01.01.2012-31.12.2014

B. **Project Title:** LOG4GREEN-Transport Clusters Development and Implementation Measures of a Six-Region Strategic Joint Action Plan for Knowledge-based Regional Innovation (287091)
Funding Source: European Commission FP7 Program THEME [REGIONS-2011-1]
Role: Research Assistant at Koç University
Budget: 122,782 €
Dates: 01.01.2012-31.12.2014

C. **Project Title:** MAPDRIVER-Towards a Roadmp to boost Demand for ICT in Transport-based Regional Innovation
Funding Source: European Commission FP7 Program CIP
Role: Research Assistant at Koç University
Budget: 148,000 € (Total)
Dates: 01.02.2014-01.08.2015

APPENDIX

Table A.1: Limit Speeds of Transportation Modes (S_k)

Transportation Mode (k)	Limit Speed [km/h]
Sea	35
Rail	60
Road	90

Table A.2: Transfer Time Matrix between Transportation Modes (TrT_{kl}) [hours]

	Sea	Rail	Road
Sea	0,7	0,17	0,17
Rail	0,17	0,4	0,12
Road	0,17	0,12	0,1

Table A.3: Transfer Cost Matrix between Transportation Modes (TrC_{kl}) [USD/kg]

	Sea	Rail	Road
Sea	5	7,5	4,4
Rail	7,5	4	5
Road	4,4	5	2,5

Table A.4: Distances between the nodes for Road Transportation in Case 1(d_{ij}) [km]

	K	U	I	H	C
K	-	65	-	41	144
U	65	-	55	105	140
I	-	55	-	178	-
H	41	105	178	-	180
C	144	140	-	180	-

Table A.5: Distances between the nodes for Rail Transportation in Case 1(d_{ij}) [km]

	K	U	I	H	C
K	-	88	37	43	23
U	88	-	23	57	-
I	37	23	-	17	41
H	43	57	17	-	43
C	23	-	41	43	-

Table A.6: Distances between the nodes for Sea Transportation in Case 1(d_{ij}) [km]

	K	U	I	H	C
K	-	26	-	-	86
U	26	-	59	87	-
I	-	59	-	127	-
H	-	87	127	-	22
C	86	-	-	22	-

Table A.7: Transportation Unit Cost for Road Transportation

Filling Rate	TC_c [USD/Tone]	TC_f [USD/Tone]	TC_m [USD/Tone]	TC_{ex} [USD/Tone]	TC_{Sea} [USD/Tone]	TC_{Sea} [USD/km]
0,1	50,18	226,361	61,861	31,133	369,46	0,369
0,2	25,054	113,181	30,93	15,567	184,73	0,185
0,3	16,703	75,454	20,62	10,378	123,15	0,123
0,4	12,527	56,59	15,465	7,783	92,37	0,092
0,5	10,022	45,272	12,372	6,227	73,89	0,074
0,6	8,351	37,727	10,31	5,189	61,58	0,062
0,7	7,158	32,337	8,837	4,448	52,78	0,053
0,8	6,264	28,295	7,733	3,892	46,18	0,046
0,9	5,568	25,151	6,873	3,459	41,05	0,041
1	5,011	22,636	6,186	3,113	36,95	0,037

Table A.8: Transportation Unit Cost for Rail Transportation

Filling Rate	TC_c [USD/Tone]	TC_f [USD/Tone]	TC_m [USD/Tone]	TC_{ex} [USD/Tone]	TC_{Sea} [USD/Tone]	TC_{Sea} [USD/km]
0,1	64,464	137,612	89,966	5,671	297,71	0,298
0,2	32,232	68,806	44,938	2,836	148,86	0,149
0,3	21,488	45,871	29,989	1,89	99,24	0,099
0,4	16,116	34,403	22,492	1,418	74,43	0,074
0,5	12,893	27,522	17,993	1,134	59,54	0,06
0,6	10,744	22,935	14,994	0,945	49,62	0,05
0,7	9,209	19,659	12,852	0,81	42,53	0,043
0,8	8,058	17,202	11,246	0,709	37,21	0,037
0,9	7,163	15,29	9,996	0,63	33,08	0,033
1	6,446	13,761	8,997	0,567	29,77	0,03

Table A.9: Transportation Unit Cost for Sea Transportation

Filling Rate	TC_c [USD/Tone]	TC_f [USD/Tone]	TC_m [USD/Tone]	TC_{ex} [USD/Tone]	TC_{Sea} [USD/Tone]	TC_{Sea} [USD/km]
0,1	13,951	16,648	19,003	3,824	53,43	0,053
0,2	6,975	8,324	9,501	1,912	26,71	0,027
0,3	4,65	5,549	6,334	1,275	17,81	0,018
0,4	3,488	4,162	4,751	0,956	13,36	0,013
0,5	2,79	3,33	3,801	0,765	10,69	0,011
0,6	2,325	2,775	3,167	0,637	8,9	0,009
0,7	1,993	2,378	2,715	0,546	7,63	0,008
0,8	1,74	2,081	2,375	0,478	6,68	0,007
0,9	1,55	1,85	2,111	0,435	5,94	0,006
1	1,395	1,665	0,382	5,34	5,34	0,005

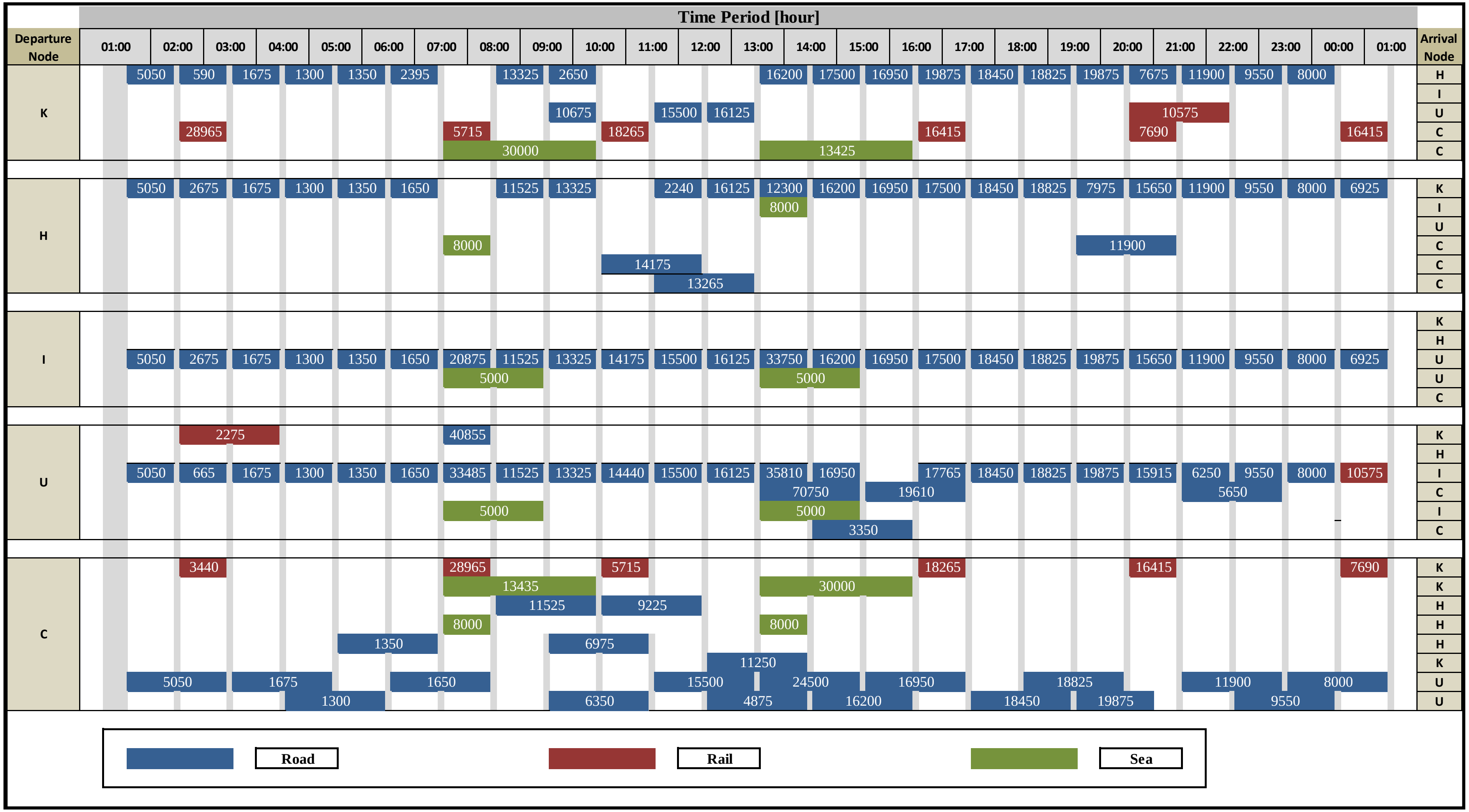

Figure A.1: Representation of the solutions for point I

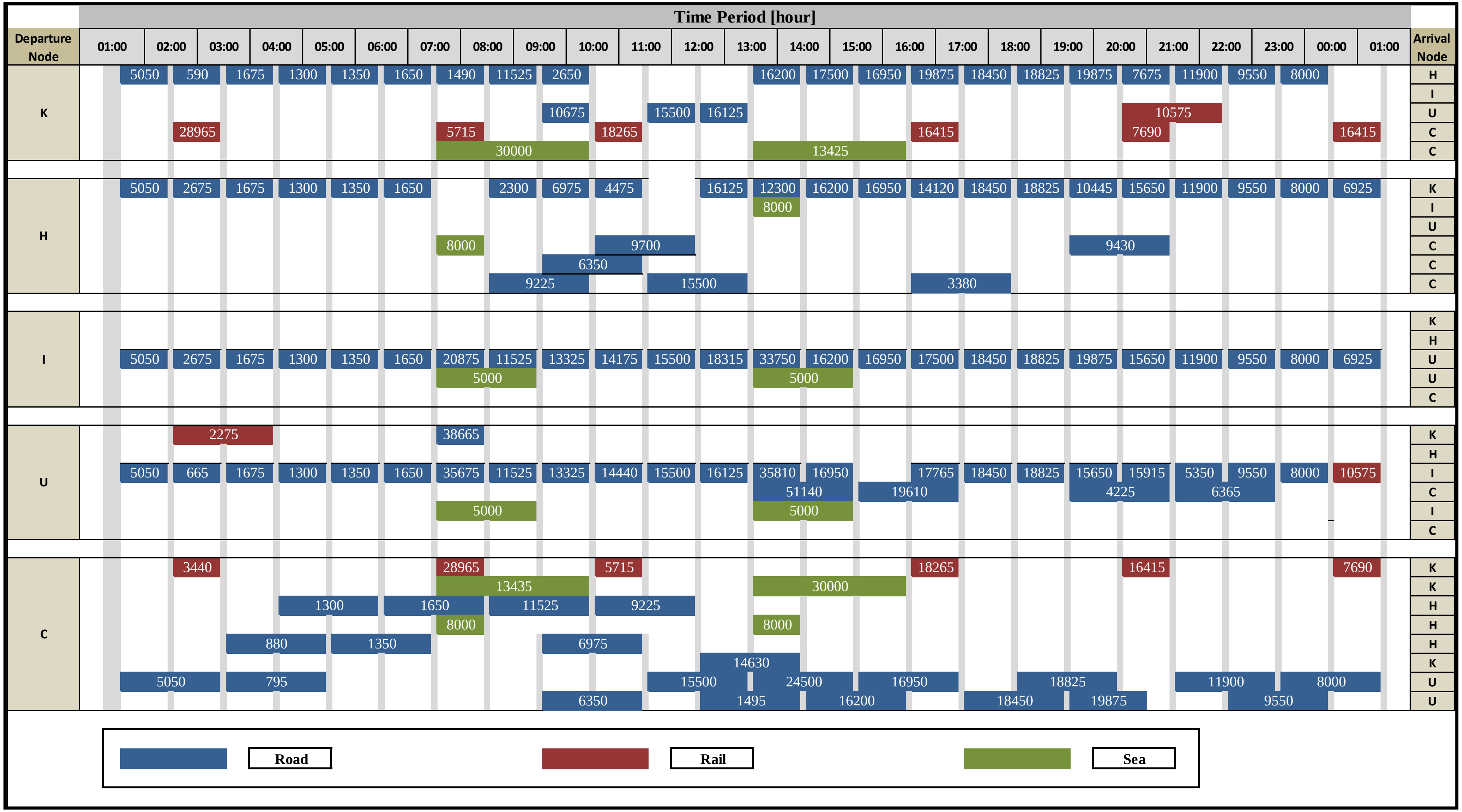

Figure A.2: Representation of the solutions for point II

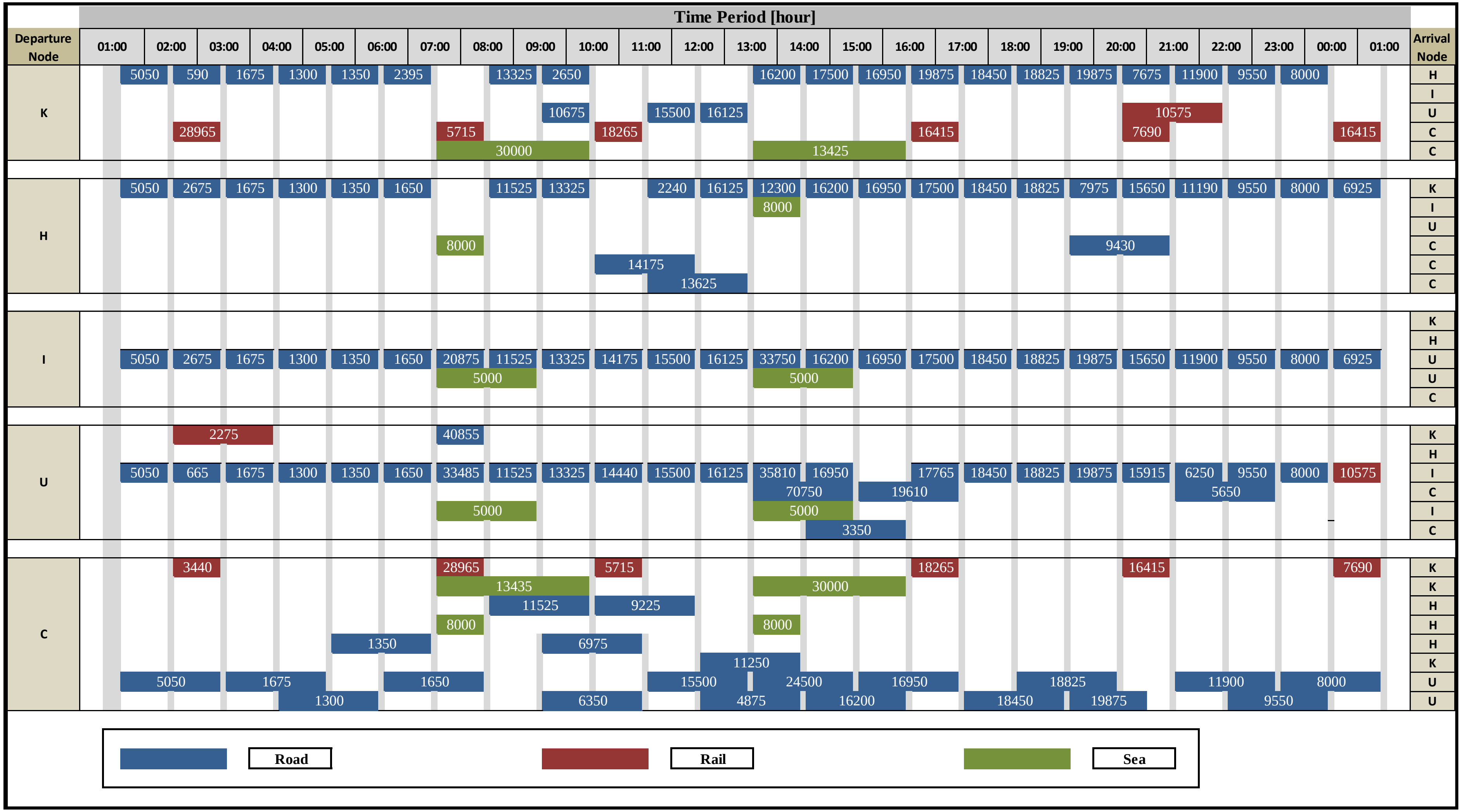

Figure A.3: Representation of the solutions for point III