# Planning Lateral Transshipment with Transport Mode Selection in Refinery Networks

by

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A Thesis Submitted to the
Graduate School of Sciences and Engineering
in Partial Fulfillment of the Requirements for
the Degree of

Master of Science
in
Industrial Engineering

Koç University

September 2016

Koç University

Graduate School of Sciences and Engineering

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Date: 02 September 2016

# ABSTRACT

Petroleum refining is a low-margin and very competitive industry. For multi-refinery operating companies, orchestrating the operations in different refineries is beneficial to improve the effectiveness of the entire enterprise while minimizing the operational costs. Thus for the multiple refinery operating companies, inter-refinery transportation of semi-products are vital for maximum utilization. In this study, a multi-period transportation service design problem is addressed for hazardous liquid commodities transportation between two refineries in Turkey, small one near the drilling site and complex one for meeting required product specifications. Developed MILP model deals with optimal use of available infrastructure by selecting the transportation modes, assigning ordering capacities, and planning the routes and frequency of shipment for the semi-products and the final products of two geographically dispersed refineries under fluctuating demands. Transportation modes are railroad tankers, road haulage and blending the products into crude oil pipeline. It is a real industrial case of Turkish Petroleum Refineries Corp.

The problem is modeled in GAMS environment and solved using CPLEX solver with branch & cut algorithm. Exact optimal solutions for different time horizons are achieved. Several cutting plane algorithms are tested on the MILP model and solution times are investigated with the usage of different cutting planes. The results shows that MIR cuts are necessary to solve the given problem. With real and simulated data from two refineries, the cost advantage of transportation planning is determined. The optimization model is applied to the performed operations in 2015 and 2.1% decrease in the total transportation cost is achieved. Sensitivity analysis considering network upgrade by investment on vehicle cleaning, extended working hours for loading/unloading and contract changes are studied. The computational study on different scenarios shows that an effective planning can yield as much as 22.9% savings on total transportation costs with necessary investments and contract changes.

# ÖZET

Petrol rafinericiliği rekabetin yoğun olduğu ve kar marjının düşük olduğu bir sektördür. Birden fazla rafineri işleten şirketler için, farklı rafinerilerdeki operasyonların entegrasyonunun, kapasite kullanım oranlarını arttırma yönünde bir etkisi vardır. Bu sebeple rafineriler arası ara ürün taşımacılığı verimliliğin arttırılmasında ve işletme maliyetlerinin düşürülmesinde kilit rol oynamaktadır. Bu çalışmada, gerçek veriler kullanılarak, iki rafineri arasında karşılıklı akaryakıt ürünleri taşımacılığı için çok-zamanlı bir nakliye servisi tasarlanmıştır. Rafinerilerden biri petrol kuyularına yakın bir noktada konumlanmıştır ve basit bir yapısı vardır, diğeri ise daha kompleks bir rafineri olup, nihai ürün üretimi yapabilecek seviyedir. Bu çalışma kapsamında geliştirilen karmaşık tam-sayılı doğrusal programlama modeli, mevcut altyapı üzerinde taşıma kiplerine, taşınacak ürün miktarlarına ve taşıma sıklıklarına karar vererek değişken ürün taleplerine sahip iki rafineri arasında nakliye planlaması yapma amacı taşımaktadır. Taşıma kipleri demiryolu, karayolu ve boru hattıdır. Çalışma, Türkiye Petrol Rafinerileri A.Ş.'nin endüstriyel uygulamasıdır.

Nakliye planlama modeli GAMS ortamı üzerinde modellenmiş ve CPLEX çözücüsünün dal-kesme algoritması kullanılarak çözülmüştür. Farklı zaman ufukları için optimum çözümler elde edilmiştir. Çözüm aşamasında farklı kesme düzlemleri denenmiş ve çözüm süresi üzerindeki etkileri gözlenmiştir. Tam sayıya yuvarlama yönteminin çözüme ulaşabilmek için gerekli olduğu görülmüştür. Gerçek veriler kullanılarak nakliye planlaması yapılmış ve maliyet avantajı sağlanmıştır. 2015 yılı operasyonları değerlendirildiğinde %2,1'lik potansiyel bir maliyet avantajı söz konusudur. Araç temizleme, çalışma saatleri ve kontrat değişiklikleri konusunda duyarlılık analizi yapılmıştır, yatırım gerektiren farklı senaryolarda %22,9'luk bir maliyet avantajı elde edilebileceği gösterilmiştir.

## ACKNOWLEDGEMENTS

I would like to express my respect and gratitude to Prof. Dr. Metin TÜRKAY for his guidance, encouraging support and patience during the most challenging period of my life, graduate study and thesis period concurrent with my role as a Process Development Supervisor at Turkish Petroleum Refineries Corporation (Tüpraş).

Furthermore, I would like to thank my committee members, Emre Alper Yıldırım and Uğur Kaplan for their times and insightful comments. I also wish to thank all the professors of the Department of Industrial Engineering at Koç University for sharing their valuable knowledge.

I would like to thank TÜPRAŞ R&D Department and Batman Refinery, my friends Nergiz Haytural, Elif Mete and Fırat Uzman.

Last but not least, I would like to thank my wife Renin, who spent sleepless nights with me, for her understanding and love. Her support and encouragement was in the end what made this dissertation possible. My parents and brother receive my deepest gratitude and love for their dedication and many years of support that provided the foundation for this work.

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## NOMENCLATURE

| | |
|---|---|
| A | Number of block trains allowed in a specific period of time |
| $B_{g,v}$ | Frequency of wagon transported in g of company v (1/month) |
| $C_{fixed,k,v,u}$ | Fixed cost of transportation per vehicle of mode k (TL) |
| $C_{loss,i}$ | Unit cost of the product i per mass (TL/ton) |
| $C_{pipe}$ | Unit cost of pipeline transportation per mass (TL/ton) |
| $C_{process}$ | Unit cost of reprocessing the blended products in pipeline (TL/ton) |
| $C_{rail}$ | Unit cost of railroad transportation per mass (TL/ton) |
| $C_{road,i,j}$ | Unit cost of road transportation for products i and j reciprocally per mass (TL/ton) |
| $C_{wash,k}$ | Fixed washing cost per one vehicle (TL) |
| d | Direction of transportation |
| $D_{max,h}$ | Maximum pulling capacity of locomotice type h (tons) |
| $D_{min,h}$ | Minimum mass of block train allowed for locomotice type h (tons) |
| $E_{i,k}$ | Eligibility of product p can be transported by mode k |
| $F_u$ | Mass of a railroad wagon of status u (tons) |
| g | Block train status of a wagon |
| h | Locomotive type of a block train |
| i | Outgoing products from the first node to the second node |
| j | Incoming products from the second node to the first node |
| k | Mode of transportation |
| $M_{max}$ | Maximum flow allowed for pipeline in a specific period of time (tons/month) |

| | |
|---|---|
| $M_{min}$ | Minimum flow allowed for pipeline in a specific period of time (tons/month) |
| $n_{i,j,k}$ | Number of vehicles assigned for transporting products i and j reciprocally with transportation mode k |
| $N_{max,k,v}$ | Maximum number of vehicles for mode k for company v |
| $N_{min,k,v}$ | Minimum number of vehicles for mode k for company v |
| $Q_{max,k}$ | Maximum volumetric vehicle capacity of transportation mode |
| $Q_{min,k}$ | Minimum required volume for vehicles of transportation mode |
| $R_k$ | Loss ratio of products in the transportation mode k due to leakage |
| $S_{i,d}$ | Demand of product p for transportation in a specific period of time (tons/month) |
| $T_k$ | Maximum number of vehicle tour in a period of time (1/month) |
| u | Load status of a wagon |
| v | Company of the wagon owner |
| $W_{i,j}$ | Washing requirement of wagons during service change from product i to j |
| $x_{i,d,k}$ | Amount of the product i transported within the direction d with transportation mode k |
| $y_{d,v,g,u}$ | Number of railroad wagon in direction d with type v, with block train status g, and load status u |
| $z_h$ | Number of block train locomotives in the service |
| $\rho_i$ | Density value of product i (kg/m$^3$) |
| $P_{max}$ | Maximum density allowed for pipeline transportation (kg/m3) |
| $P_{min}$ | Minimum density allowed for pipeline transportation (kg/m3) |

## ABBREVIATIONS

| | |
|---|---|
| 3PL | Third-party logistic provider |
| ADR | European Agreement concerning the International Carriage of Dangerous Goods by Road |
| API | American Petroleum Institute |
| B&B | Branch and Bound Algorithm |
| B&C | Branch and Cut Algorithm |
| B&P | Branch and Price Algorithm |
| BAT | Batman Refinery |
| BOTAS | Turkish Petroleum Pipeline Corporation |
| CCR | Continuous Catalytic Reforming |
| GFC | Gomory Fractional Cut |
| HD | Untreated Heavy Diesel |
| HN | Untreated Heavy Naphtha |
| HSRN | Heavy Straight Run Naphtha |
| JETA1 | Jet-A1 type Kerosene |
| KB95 | 95 Octane Gasoline |
| KERO | Untreated Kerosene |
| KGM | General Directorate of Highways |
| KRK | Kırıkkale Refinery |
| LB | Lower bound |
| LP | Linear Programming |

| | |
|---|---|
| LPC | Lift and Project Cut |
| LPG | Liquefied Petroleum Gas |
| LSRN | Light Straight Run Naphtha |
| MILP | Mixed Integer Linear Programming |
| MINLP | Mixed Integer Nonlinear Programming |
| MIR | Mixed Integer Rounding Cut |
| NLP | Nonlinear Programming |
| RO-RO | Roll on Roll off vessels |
| TCDD | Turkish State Railways |
| TRB | Transportation Research Board |
| TSP | Travelling Salesman Problem |
| TUPRAS | Turkish Petroleum Refineries Corporation |
| UB | Upper bound |
| YKM | Untreated Diesel |
| ZHC | Zero – Half Cut |

# Chapter 1

## INTRODUCTION

The oil industry is one of the world's major industries and plays a specific part in the modern global economy. Petroleum products are essential to many other industries, and significant for upholding industrial civilization in its existing structure. While the sector generates a large stream of revenue, it also has significant costs for being the key source of energy. Corporations in the sector operate in complex and dynamic settings, experiencing continuous challenges, specifically in terms of supply and demand. Only very few industries can benefit from increasing supply-chain effectiveness more than the oil industry.

The industry is mainly divided into three categories: drilling, refining and distribution. Sahebi, Nickel [1] describes the segmentation as upstream, midstream and downstream segments, where the upstream part refers to exploration, drilling and transportation of crude oil, midstream part includes the refineries and petrochemical complexes, and the downstream part includes the storage and distribution of final products. Petroleum refining is a significant connection in the oil supply chain. Petroleum refineries convert crude oil into semi-products by distilling crude oil into fractions and then process these semi-products further into end-products, through an assembly of chemical and physical transformations. Refineries have unique configurations and economics. They are mainly classified by their complexity, location, market requirements, product quality specifications they can reach and year of construction. The refineries are mainly located domestically.

Refining companies desire to increase their production capacities to take advantage of the economies of scale in their operations while minimizing large investment costs significantly. For multi-refinery operating companies, orchestrating the operations in different refineries is beneficial to improve the effectiveness of the entire enterprise while minimizing the operational costs in a very competitive environment with low margins. Because of the complexity of the supply chain of oil industry, the decision making process is a very problematic task, which contains many elements from drilling, refining and distribution. In addition, the demand for refined oil products shows seasonal variations for which these variations are even higher in diverse geographies. Thus, for the operational planning of multi-refinery operating companies, inter-refinery transportation of semi-products and final products are vital for maximum utilization of the system under fluctuating demand.

The study is about planning inter-refinery transportation of semi-products and final products of two geographically dispersed refineries under fluctuating demands. Inter-facility transshipment plays an important role in the operational efficiency of multi-refinery operating companies because refineries differ from each other in terms of configuration and capacity. Transshipment operations require careful design and planning of the transportation system. Transport planning is significant in terms of selection of transportation modes for the products as well as the transportation quantities. Different modes of transportation, such as sea, railroad, road and pipeline, have different costs and capacities Therefore, deciding on the appropriate transportation mode(s) is important in minimizing the total transportation cost. The objective in the transport planning problem is to satisfy the demand and capacity constraints in the entire system with the minimum cost over the planning horizon.

The contribution of the study is tactical level multi-commodity transportation planning from the perspective of a multi-refinery operating company. A multi-period service design problem is addressed using a real world data set for hazardous liquid commodities transportation between two nodes. It is a real industrial case of Turkish Petroleum Refineries Corp. A deterministic mathematical model is developed dealing with optimal use of available infrastructure by selecting the transportation modes, assigning ordering capacities, and planning the routes and frequency of shipment. A MILP model is utilized with the purpose of minimizing overall transportation cost. Strong valid linear inequalities are developed and used to strengthen the MILP bound of the model by fixing variables on capacity restrictions. Preprocessing is applied to adjust the cost structure due to different policies applied to different type of modes and carriers. Exact optimal solutions for different time horizons are achieved using branch and cut solution algorithm. The effects of cutting planes algorithms on the solution times are evaluated. With real and simulated data from two refineries, the cost advantage of transportation planning is determined. The computational study shows that an effective planning can yield as much as 2.1% savings on total transportation costs. Sensitivity analysis considering network upgrade by investment on vehicle cleaning, flexible and extended working hours for loading/unloading and specific gravity of the products transported via the pipeline are also studied. Developed model is being utilized iteratively with the commercial multi-refinery production planning software.

In Chapter 2, a review of the refining industry, transportation modes and modeling methods used in similar problems are presented. The problem description and the mathematical model are given in Chapter 3 including the objective and the constraints. Theoretical background and solution algorithms are given in Chapter 4. The results of several case studies and solution algorithms are discussed in Chapter 5 and a brief conclusion is given in Chapter 6.

# Chapter 2

# LITERATURE REVIEW

## 2.1 Freight Transportation

Crainic [2] states that the primary purpose of freight transportation is to enable successful and time-efficient movement of the resources. These can be either raw materials or consumable products. Freight transportation is, consequently, one of the primary aspects of the supply chains. A more precise definition of 'transportation' by APICS [3] is as follows: "The function of planning, scheduling, and controlling activities related to mode, vendor, and movement of inventories into and out of an organization." Essentially, freight transportation is in control of transporting resources from one geographical location to the journey's end for those materials [4]. This movement is a central element of logistics as it enables the consumer to receive a product at a numerous amount of places. Moreover, transportation is a critical component of the global economy and plays a main role in supporting spatial relations between locations. Ross [5] proposes that, the accessibility of effective and low-cost transportation systems triggers financial development. Transportation generates valuable connections between different geographical districts and economic activities.

Transportation has four core components, which are the modes, infrastructures, networks and flows [6]. *Modes* represent the conveyances, mostly the vehicles supporting the movement of passengers or freight. Some modes are designed to carry only passengers or freight, while others can transport both. Secondly, Rodrigue, Comtois [6] states that *infrastructures* are the routes which enable the methods to transport the people or freight. Few primary infrastructures are: roads, railways, port and airports and tracks.

The governments are generally responsible for the infrastructures which the freight transportations utilize. Thirdly, the *networks* are the connections between geographical areas which are utilized to organize the guided routes for the transportation. The network systems and routes notify how the geographical locations are linked and how they are maintained as there are a number across the system. Lastly, Rodrigue, Comtois [6] defines *flows* as the currents of the people, freight and data through the systems of networks. These flows have a primary source, transitional geographical locations and a destination. The transitional area is mainly necessitated when a vehicle must stop at a destination before reaching the destination – this often occurs when the vehicles must stop to refuel [6].

There are three essential aspects of transportation as explained by Ross [5] which are understood most clearly after analyzing the key elements which establish the transportation as a process. First aspect is *economy of scale* which can be exemplified with the inverse correlation between transportation volume and the unit cost of transportation. Ross states that the secondary aspect, *economy of distance*, is referring to the understanding that the transportation price per mass is lowered as the length of the journey is increased. This direct correlation is defined as the 'tapering' principle [5]. Ultimately, the further the cargo is transported, the costs of the journey are spread thinner across the mileage which makes the total cost considerably cheaper. Lastly, the notion that the *economy of speed* is understood by stating that if the velocity of the travelling is increases, the price of the conveyance necessities is considerably higher. Bowersox and Closs [7] suggest these necessities can include: fuels, equipment, management and tracking.

Taking all these factors into consideration, the overall cost of transportation is determined by seven primary aspects. Bowersox, Closs [8] states that, although they are not all essential aspects of transportation, each aspect is a fundamental aspect of the cost of travel. The primary aspects are: *distance, volume, mass, stowability, handling, liability*, and *economic market*.

Bowersox, Closs [8] states that, a principle element of the transportation cost which is inherently linked to the unpredictability of how much labor, fuel and the maintenance will cost is, distance. Secondly, the next central aspect is load volume as logistical systems such as transportation are focused heavily on how scale directly relates to economic factors. Thirdly, another key element of transportation is the mass of the cargo. The mass of the cargo is crucially significant as the price of the transportation is mainly focused on the units of weight which the vehicle must carry. The next factor, how well the goods fit into the dimensions, is important as if there is a lot of wasted space due to obscure shaped cargo or parcels, this valuable space is being wasted. It should be acknowledged that, while an item may have the same mass, the shape of the object may differ considerably. The management of how cargo is unloaded and re-loaded is a crucial element of transport and this handling must always be carried out safely and efficiently. It is also important that the items of cargo have been stowed away correctly, in order for the management of handling to be able to unload and re-load without wasting time or money. Furthermore, the cargo carriers must ensure they are insured for the contents of the vehicle or, if not, must be able to accept responsibility for any impairment which may occur to the cargo. Lastly, the economic market is a significant aspect of transportation as this refers to the unpredictability of the price of transportation, such as: the connections between the start and the final geographical locations. It must be acknowledged that the vehicles and the person driving the vehicle will have to return back to the start and, therefore, they have to get a haul load or, if not, the vehicle is returned or removed unfilled. The best result of this kind of movement is that a two-way system can be founded where the contents in the vehicle is the same both ways of the journey. Although, Bowersox and Closs [7] highlights that this two-way system is extremely unlikely as the unpredictability of the market demand and development of products is extremely high.

Among these criteria the distance between the manufacturers and the customer is the main factor which determines the need for freight transportation. The manufacturers of items necessitate transportation to transport raw materials, intermediate products and completed items at specific times to ensure they are keeping up with the needs of the consumer. This emphasizes the direct relationship between the manufacturers of the items and the need for transportation to take place. Ross [5] states that the need for freight transportation is founded from the infrastructure and organizations which move the items and these are referred to as carriers.

The freight transporters, carriers, are responsible for the vehicles which provide the actual movement of goods for the manufactures. Further, other crucial key elements of the freight transportation are those responsible for the specific organization and application of the detailed processors: the logistic providers. These are referred to as 3PLs (third-party logistic providers) and these corporations are responsible for observing and controlling the key logistics roles which were traditionally the responsibility of the manufacturers [4]. Finally, Ross [5] states that the governments and officials also carefully observe the transportation of high-risk goods and, also, tax the transportation organizations.

### 2.1.1 Transportation Modes

A fundamental aspect of the transport systems are the modes of transportation as, ultimately, they are the vehicles which support the mobility. Each of these transportation modes can be categorized into three main groups by geography scholars [5]. These groups are focused on the medium which is utilized in order for the transportation mode to function, they are: water, land and air. Every specific medium has essential criteria which must be met and changed in order to supply the correct factors for the people or cargo the mode of transportation will be carrying. These specifications emphasize that in each country the differing needs are varying and there has been a development towards combining the transportation modes by ‘inter-modality’ and connecting these transportation modes considerably further in order to bring manufacturing and delivering even closer together. Although, with this considered, Rodrigue, Comtois [6] proposes that the difference in what the transportation mode is carrying – whether freight or people – is becoming significantly more detached.

The road, railroads, air transport, marine and, lastly, pipeline are the five fundamental transportation modes which are accessible for delivering freight through the supply chain. Each different mode has its own specific strengths and weaknesses. Ross [5] emphasizes that these modes are not always categorically singular and there are examples where the modes overlap and become multimodal. However, containerized multimodal (intermodal) transportation and air transportation are not in the scope of this study.

#### 2.1.1.1 Road Transportation

The most prominent and widespread worldwide mode of transportation is the road. Fundamentally, the movement of the cargo for this specific mode happens on the road systems and networks and a variety of different automobiles, trucks and wagons are able to transport a huge variety of different types of cargo. A strength of this mode is that, dissimilar to the railways, the roads allow vehicles to transport goods free of charge. Rodrigue, Comtois [6] stresses that the distance which roads allow for transportation is phenomenal especially since there has been a huge development of road infrastructures being constructed. Ross [5] states that the road is the mode which has most considerably grown, for the transportation of freight and people, throughout the last half a decade.

While road infrastructures do cover large areas of land and they have low amounts of physical limitations between the modes of transportation, there are significant geographical restrictions in relation to the varying costs of building the roads [7]. The vehicles are able to carry people and a variety of freight. However, the nature of this mode of transportation means that the vehicles are unable to travel on anything but the road. Further, the vehicles and infrastructure have high maintenance costs. The corporations which use road transportation generally require quick movements of freight in small amounts. Rodrigue, Comtois [6] states that with the rising containerization, road transport is developing into a fundamental link in cargo delivery.

Road transport is exceptionally quick for short distances, flexible and the overall price of vehicle transport is suited to the current economic market which demands fast responses from corporations and quick consumer service [5]. These factors have all contributed to the vast development of road transportation. Further, a great benefit of road transportation is that they are able to gain direct access from supply-point-to-delivery-point as almost all geographical locations are available by road vehicle. Unlike other forms of transportation, road vehicles do not necessitate terminals, ports or switching yards and, therefore, can easily compete with planes, ships and trains in regard to speed. Another great benefit of road travel is that the variability of the vehicles allows them to deliver items of any amount or heaviness at competitive prices. Unlike railway transportation, the percentages of lost or broken items carried by road transportation are considerably lower. Lastly, the costing system of road transportation is extremely cost-effective as, while the fixed price of the road transportation equipment is substantial, up to 90% of overall road transport costs are made up of variable factors such as: labor, fuel, tolls, licenses, insurances and other expenses [5].

For new industries searching for a simple mode of transportation to become involved with, vehicles are the most appealing as the financial resources required for buying them is moderately priced and, therefore, this ensures that the cost of new machinery and improvements are able to disperse relatively fast throughout the organization. Therefore, this guarantees that the trucking companies are an extremely popular choice [8]. Furthermore, the flexibility and options provided to the vehicles by the networks regarding the course of their journey is hugely varied and this allows the vehicles to, on the whole, be able to take cargo or passengers directly from door to door [6]. These benefits have ensured that road vehicles are dominating the market for short distance journeys. However, road transportation is considerably restricted by the speed limits which are officially instated and must be followed. A second issue which troubles road transportation is that it is triggering traffic congestion in cities across the world. There is also the problematic factor of the dangerous gasses which road vehicles are continuously omitting and how far they contribute to damaging the environment. Rodrigue, Comtois [6] states that these concerns are progressing into key worldwide debates in jurisdiction.

#### 2.1.1.2 Railroad Transportation

Railroad transportation's primary purpose is carrying low-cost freight and raw resources over long-distance journeys. For example, timber, coal, oil, chemicals, minerals, food and farm products. Ross [5] suggests that, as a result of the scale and weight of this freight, they are generally transported in huge amounts in order to make the transportation cost-effective. Ross [5] identifies a benefit of railroad transportation as that it is not vulnerable to circumstances relating to weather, therefore, it is a generally safe option for industries to choose. Rail transportation was first founded during the industrial revolution and was a huge factor in the progression of Western Europe's, Japan's and North America's financial markets as this mode was relied on majorly for the transportation of cargo [7]. Rodrigue, Comtois [6] states that this development embodied a significant evolution in the transportation of passengers and freight but, most significantly, it has transformed the field of transportation on land.

Railways have a regular amount of physical restrictions associated with the models of trains and the minimal incline which is also necessitated, especially for carrying cargo. Railways are structured on a traced pathway onto which the locomotives are attached. While shipping containers has increased the availability of railway transportation as it connects them with the roads and docks, it still remains that heavy industries are conventionally associated with rain transportation [7]. Rail is the mode of transportation which boasts the biggest capacity [6]. The biggest positive aspect of railroad travel is that they are able to carry great volumes of freight over long journeys while ensuring that the cost remains relatively low in comparison to other land modes of transportation. However, like all modes of transportation, there are some major negative factors. Firstly, in comparison to the flexibility of road transportation, trains are only able to run at specific scheduled times, they are required to stop several times during the journey, they must allow time to couple and de-couple the cars in the switching yard, there are severely strict speed limitations and, lastly, train travel is only able to travel from terminal-to-terminal. While road transportation can deliver door-to-door service, the locomotives must be unloaded and reloaded using other vehicles prior to reaching the final stocking point [5].

There are three principle services which railroad transportation offer. Firstly, TRB [4] states that unit trains are used to transport mass amounts of cargo for corporations who are able to fill a whole locomotive – generally 100 cars or over – in a singular go. Secondly, railroad transportation also offers intermodal services. This service is occupied with putting containers and trailers onto the locomotive’s cars and this service is generally chosen by corporations who are shipping more expensive items. Intermodal services, in comparison to road transportation, are able to decrease the cost of shipping for journeys over a long period of time. Finally, railroad transportation also offers carload services. This option is usually chosen by corporations who only have sufficient cargo to load a couple of cars each time and, consequently, are willing to accept slower delivery times in negotiation for cheaper costs. TRB [4] states that with shipping containers, railroad transportation is able to offer an economically competitive price, unlike road transportation which is unable to gain from this type of benefit. For road travel, there is an inherent relationship between the number of containers and the increase in price, however, for rail travel, the price decreases in relation to the number of containers which are added to the train until it reaches its maximum. Similarly, while it is more cost-effective for trains to have a higher number of passengers on board, for road vehicles, an increase in passengers generally requires an increase in number of vehicles and, therefore, cost. Moreover, bulk cargo shipments, agricultural and industrial raw materials are the principal masses of freight transportation. Rodrigue, Comtois [6] states that rail transportation is extremely economically friendly or a ‘green inland mode’. This is because its energy usage per unit load per km is considerably minor in comparison to road transportation [7].

### 2.1.1.3 Marine Transportation

The initial mode of mass transportation was via water [7]. It was founded on the necessity to move masses of large, weighty and low-value-per unit cargo and, still in this day, is used for those exact means. This type of cargo can be packed and unpacked onto ships effectively and at a low-cost by using machinery. Resources and materials which are generally transported via ships are: building resources, coal, iron ore, grains and, lastly, fuels. All this cargo is similar in that, it does not necessitate fast shipment and are not generally targeted for theft or easily broken. Ross [5] states that, due to the natural buoyancy and fluidity of water, transporting via the sea is efficient for great masses of cargo which must be shipped over long distances. The principle ship journeys are conducted on: oceans, seas, lakes, rivers, coats and channels. As ports are incredibly expensive to construct, maintain and develop, maritime transportation is considered to have the biggest terminal upkeep costs. Rodrigue, Comtois [6] proposes that sea transportation is connected most considerably to heavy industries which are primarily focused on the shipment of steels and petrochemical facilities next to port sites.

The category of waterway to be navigated and the type of cargo to be carried, are the factors which directly influence which type of equipment will be utilized. For example, huge vessels are used when the journey must be made via the ocean. These vessels are specially constructed to ship large quantities of cargos such as: metals, grains, ores and tankers which are used for oil & gas industry, large containers which are used for packed commodities, food-supplies and lastly, RO-RO (roll-on-roll off) which is used for automobiles [8]. However, like all modes of transport, there are substantial downfalls to marine transport. Marine travel is substantially slower in comparison to other modes of travel, such as, train and road vehicles as marine travel must work around varying factors such as: the ports, water terminals and infrequency in movement. However, a great advantage of marine travel, excluding pipelines, is that it is the most cost-effective [5].

#### 2.1.1.4 Pipeline Transportation

Fluid materials are transported economically and efficiently by pipelines. Pipeline's primary purpose is transporting great quantities of oil derivatives across huge expanses. Pipelines are inherently different from all other modes of transport as they do not rely on railways or roads and are made up of pipes, storage tanks, dispersal facilities and pumping stations which means that they are, on the whole, not noticeable to people [7]. Pipelines are able to transport huge quantities of products, do not require labor as in other modes. Due to the infrastructure of pipelines, they do not need motor vehicles, upkeep and backhaul problems do not exist. Further, the pipeline mode of transport is mainly automatic and the flow of fluids throughout the entire pipeline network is monitored and well-ordered via computers in pumping locations which are often located miles from the pipelines they may be controlling. Ross [5] suggests that pipelines are the most cost-effective mode of transportation as they are the smallest price per capita ton mile of any method of transport and, therefore, it generates the highest rates of revenue. Moreover pipelines are not vulnerable to the variability of weather.

There are three primary products which are transported by pipelines: natural gas, oil and slurry [5]. Generally, to transport these produces, the pipelines are situated on top of or underneath the earth. Products such as: water, chemicals, natural gasses, petroleum products and crude oil are all well-suited to be transported by pipelines [8]. For example, amongst oil corporations, the mode of pipelines are utilized to collect crude oils from the drilling sites and, following this, it streams through the pipes to the processing plant. The product lines then deliver the finalized produce from the processing plants to the areas of consumption. Furthermore, another product which is naturally suited to being transported by pipelines is slurry. In order to be fully prepared for transportation via pipelines, the solid produces are crushed and mixed with water. Coal, for instance, is concentrated into a powdery consistency, water is added and, following this, it is able to be transported through the pipelines and transitioned back into a solid state at the final destination by eliminating the water which was added. Ross [5] states that, slurry products constitutes a very low amount of the overall pipeline usage. Pipelines are considerably and inherently restricted to the types of produce which they can deliver, they are fixed and immobile, relatively slow in comparison to other travel methods and, lastly, they necessitate the introduction of other vehicles in order to ensure the products reach their final destination, whether it be shops or customers [5].

The price of manufacturing pipelines is directly affected by the size of the pipes and the viscidness of the produce which must be pumped throughout the pipelines. However, the observation and operation system prices are considerably cheap and the pipelines are a crucial element to the movement of important gasses and liquids [4]. However, pipelines are inherently fixed and, therefore, once they have been created, it is very difficult to adapt or expand them. Further, there is exact limitations to the volume of liquids or gasses which are able to be pumped throughout the pipes. Therefore, if there is variability in the amount of products required, this will be directly interconnected to the profits which the pipelines will produce. Moreover, if there is a change or development in the geographical location which the pipelines must cater for, it is almost impossible to move the pipelines so new ones would have to be produced [6].

Pipelines are predominantly used for effective and efficient transportation of great amounts of products which have no other alternative mode of transportation, for instance, water. They are always constructed with an exact purpose in mind and, therefore, generally, are only able to transport one specific product through the pipeline. They require a large amount of investment, usually by private companies, as they must be put into action prior to any profits being returned by the industry [7]. Pipeline networks are most commonly used to connect geographically inaccessible locations with the main refining and manufacturing areas when considering oil and the highly populated locations, when referring to natural gas [6].

### 2.1.2 Transportation Mode Selection

A corporation, when choosing suitable mode of transportation, should take into consideration the following factors: speed, dependability completeness, capability, frequency and cost related to the performance value of each transport mode. Each specific mode of transport has different characteristics. As a result of international influences on business, the traditional road transportation is simply unable to meet the necessary requirements and, consequently, a mixture of modes must be used. The modes previously discussed can be evaluated in many different methods and Ross [5] positions how successful the modes of transports are in relation to the principles as in Table 2.1.

Table 2.1. Transportation mode characteristics [5]

| Attribute | Motor | Rail | Air | Water | Pipeline |
|---|---|---|---|---|---|
| Speed/transit time | Fast | Slow | Very fast | Slow | Slow |
| Cost | High | Low | Very high | Low | Low |
| Accessibility | Very high | High | Limited | Poor | Very poor |
| Reliability of service | Very high | High | Variable | Moderate | Very high |
| Safety | Poor | Moderate | Very high | High | Very high |
| Security | Poor | High | Very high | Moderate | Very high |
| Bulk transport | Moderate | Very high | Very poor | Very high | Poor |
| Small package delivery | High | Poor | Very high | Poor | Poor |
| Intermodal capability | Very high | Very high | High | Very high | Poor |

Road transportation is quick and flexible for manufacturers and transporters but it is considerably more expensive than the rail transport mode. Air transportation mode is categorized as the highest costing but it is, also, classed as the quickest. The cheapest transportation modes are pipeline and marine in relation to cost per capita mile, however, they are considerably slower and are unable to provide a flexible cargo shipment service. The type of cargo which must be shipped is what directly determines the mode of transport which is required by the transporters. Those industries which have expensive or unpreserved freight, are more likely to choose a motor vehicle or a plane in order to minimize the shipment time and ensure the items are in a mode of transport which is dependable. First-class parcels or perishable items such as flowers are generally transported via airplane as it is crucial that this specific cargo arrives within a few hours of their departure. Motor vehicles, particularly wagons, are able to transport a variety of goods, however, it is more likely that their goods will be of a considerably higher worth, for example: items for customers, technological goods or equipment and, lastly, pharmaceuticals [6].

Trains on the railways are most likely to carry cheaper freight, for example: grain and coal. However, they do occasionally transport cargo which is of a higher value, for example: motor vehicles and parts. Marine transportation usually transports inexpensive cargo on mass which does not need to arrive at the destination particularly quickly. Further, pipelines are specifically used for natural gases and petroleum produces. In general, the transportation modes which are considerably higher costs are usually used by the manufacturers who require a greater awareness of the progress of the delivery and when it has successfully arrived to its destination. The amount of time transportation takes is a crucial element of the choices suppliers must make. Air shipments, marine and trains, on the whole, are slower than the other modes of transport. Therefore, road vehicles are able to get the small distance cargo transportations [6].

Cargo deliveries, on the whole, tend to utilize a variety of transportation methods. For example, road vehicles connect the shipments to the marine transportation, the railways or, often, it takes the cargo the last few miles to the final destination. This type of joint methods of transportation is referred to as "intermodal" and, particularly, refers to shipment containers which are able to be shifted between motor vehicles, vessels and railways [5]. "Intermodal" transportation allows distributers to avoid the high prices of using a series of different transportation methods [6].

### 2.1.3 Multimodal Freight Transportation

In multimodal freight transportation the materials are needed to be transported by at least two different transportation modes under a single contract [9]. The transportation component can be a vessel, a road truck or a railroad car. Stahlbock and Voß [13] overviews the multimodal transportation and operational planning of terminals, which is not in the context of this study. Christiansen, Fagerholt [10], Crainic and Bektas [11] and SteadieSeifi, Dellaert [12] are the most recent reviewers of transport planning problems with multimodality.

### 2.1.4 Intermodal Freight Transportation

Intermodal freight transportation is similar to multimodal transportation, with the only difference being the freight to be transported from the beginning point to the end point in a single intermodal transportation unit such as containers. In other words, intermodal freight transportation is a multimodal sequence of container conveyance. This sequence frequently connects the original shipper to the end consignee of the container. The problems in the literature are the multi-commodity location problems with balancing requirements [14] and multi-commodity production distribution problems [15, 16]. Most of them concentrate on seaport container terminal operations. Crainic and Kim [17] gives a detailed overview about intermodal freight transportation discussing previously developed models aiming cost minimization for intermodal containerized freight transportation networks.

## 2.2 Transportation Planning

Items passing throughout the supply chain from manufacturing to the final location of delivery is the primary aim of the transportation modes. Transportation industries are constantly aiming to increase the speed of their transportation systems by shortening material handling, using modal transportation, optimizing routing and, lastly, overall minimization of the price of the transportation services [5]. In order to ensure transportation capabilities are kept high, the mode of transports must optimize transportation capacities. By following these guidelines, the transportation industries are operating the most suitable material handling equipment, vehicles and laborers in order to ensure their service is cost-effective and efficient. If a large quantity of cargo is divided over a series of vehicles, this maximizes the cost and negatively impacts the shipping's efficiency. Therefore, a vehicle should grow according to the size of the cargo. This core principle is founded on these two primary considerations. Firstly, the cost of services like, handling of the goods, route planning, delivery and shipment documentation, are able to stay the same irrespective of the volume of goods. Secondly, the operational costs of the transportation vehicle are independent of the load volume [5].

The utilization of transportation factors is directly impacted by the type of vehicle, the geographical routing, scheduling and operative tasks. The term 'utilization' in transportation is used to define the proportion of materials, employees and time that is being used at one specific time [8]. Therefore, the primary aim of the transportation administration is to minimize the utilization unevenness which is generated due to uncontrollable factors, such as: the time of year, hauling the cargo back to the original location while the vehicle is empty, disorganized planning and, lastly, filling and emptying the vehicles. In order to successfully organize transportation plans, one must have a detailed and systematic awareness of these core aspects in transportation. The principle priority is to plan the transportation while capitalizing profits and diminishing the transporter modes. When the payload and the deadweight of the transportation vehicle are added together and the shipping containers and handling materials, the price of gas for the vehicle can be worked out. In general, if the transportation vehicle is big, the ratio of payload to total weight will be more satisfactory. Further, by using light resources and vehicles, the transportation management are able to minimize the deadweight of the containers and, consequently, the vehicles of transportation too [5].

### 2.2.1 Decision Levels

In a supply chain, generally, decisions come under three main categorized groups: strategic, tactical and operational levels. The categorization amongst the groups is based on their planning horizon. The strategic level involves stages may take up to 5-20 years in supply chains like oil, the tactical level has planning stages of around 6-24 months and, lastly, and the operational level involves weekly and/or daily basis decisions [1]. However, there is no official contract or arrangement for the process of making decisions.

It has been identified that the strategic planning process groups classify a number of areas where units are to be constructed, for example: ‘facility location’ or ‘technology selection’ where technologies should be practiced at every facility [18]. This perspective suggests that the planning processes are what truly constructs the supply chain and, consequently, configures a system of networks whereby strategic and planning groups can be carried out. Huang, Lau [19] carry out further decision making, for example: the distribution of facilities and subcontracting. Further, Melo, Nickel [20] undertake a complete and all-inclusive data collection study concerning the organization and facility positions of supply chains. It is proposed that as great investments have been put into the planning and strategical aspects, ensuring these are kept stable is crucially important. However, in some situations, the opportunity of introducing subtle changes in the volumes of the facilities and the organization of the supply chains is something vital to comprehend. A direct effect of these studies is that the facility rearrangement issues are also comprehended as planning and strategical choices that involve the facility completely changing, the facility relocating and, lastly, the volume increasing [21].

Chopra and Meindl [22] suggest that the strategical planning issues deal with the commencement of the infrastructure of the supply chain in order to coordinate the strategic aims of the corporations amongst the network of systems. Whilst considering the area of strategic planning problems, the effective models help to support the systems of making choices throughout the system of networks in order to advance the revenue margins which are found when the harmony is reached in relation to: obtaining, manufacturing, inventory and conveyance charging, while always maintaining a high level of customer services [23]. Consequently, the primary choices which must be made are directly linked to the facility positioning, sizing, technological equipment, modes of transportation, outsourcing, and investments and so forth [1]. The choices which are made will have a long and important influence for many years after they are implemented throughout the supply chain because of the huge financial venture which is required to apply these assets and facilities.

In order to fulfil strategical planning aims, tactical planning of every ‘medium-term’ activities are necessitated. Unpredictable elements, such as: cost, market demand, current political environment, currency exchange rates and so on, are able to become more precise at the tactical stage due to the prearranged strategical choices which have been implemented. It has been proposed that manufacturing and shipping strategical planning are routine tactical choices [19]. By selecting systems, transportation vehicles, utilizing the known and understood infrastructure, correctly assigning cargo volumes on shipments and, lastly, organizing their routes and regularity are the principle objectives and roles of the tactical planning level. Further, SteadieSeifi, Dellaert [12] proposes that choices associated with manufacturing, shipping, raw resources organization, listing overseeing and organization strategies are the choices which, in relation to the decisions already made at the strategic level, can be bettered and developed further.

The period of time spent on tactical organization and planning is, generally, several months or up to a year. Barbosa-Póvoa [23] proposes that, if the strategical and tactical choices concerning the network design issues are dealt with simultaneously, the results will be considerably better. Moreover, it has been suggested that if the greatest aspects of the strategic planning and tactical planning are combined, it is easier to establish the ideal infrastructure network and the ultimate utilization of manufacturing, shipping and, even, stowage options, in attempts to meet the requirements of the market whilst remaining relatively cheap [24]. There are two subgroups which can be established to define the previous studies on tactical planning studies in networks, they are: Network Flow Planning and Service Network Design [12]. Firstly, Network Flow Planning is organization choices which relate to the flow of supplies amongst the network systems. Secondly, Service Network Design is concerned with the source, destination, transitional terminals, the route and mode of transportation and, lastly, the capacity decisions [12].

Lastly, real-time planning of shipments, reaction and adaptation to unforeseeable issues such as: collisions, weather changes or equipment breakdowns are all problems which are dealt with at the operational level. Most of the aspects stated above are variable and, therefore, are not able to be pre-determined and expected. The operational level choices, unlike the prior levels, must be made on the specific information on the day and the short approximation for the future. The primary objectives are to heighten the dependability of the system networks whilst still ensuring the price remains low. Aspects which are not issues at the tactical and strategic levels are choices which have an unplanned probability and, therefore, must be quickly analyzed as much as possible but cannot be dealt with precisely. SteadieSeifi, Dellaert [12] proposes that constructing precise and quick procedures is fundamental, as the operation level is dealing with organizational issues which are significantly more complicated.

### 2.2.2 Modeling Approaches

There are different approaches to model tactical level deterministic transport planning problems including arc-based and path-based and cycle-based. Croxton, Gendron [16] propose an arc-based network flow problem with variable disaggregation and piecewise linear cost. Cohn, Davey [25] deal with a network design and flow problem with cross-arc costs including road and air transportation. Bektaş, Chouman [26] give a comparison flow-based and arc-based and decomposition algorithms in solving small sizes of non-linear multi-commodity network design problem with penalty of capacity violation. They show that arc decomposition solution algorithm takes more time compared to flow-based decomposition, but the arc decomposition has a better convergence. Meng and Wang [27] propose a path-based service network design with empty container repositioning. Verma, Verter [28] propose a bi-objective model for planning rail-truck intermodal hazardous materials transportation.

Besides the generalized commodity transportation models, De Matta and Miller [29] propose a mixed integer linear programming (MILP) model for both production processes and inter-facility transshipment planning including three different transportation modes. Ayar and Yaman [30] propose an intermodal multi commodity service design using a real world data set with 34 nodes and 167 services, and generate a random network of 66 nodes and 1200 arcs, and test them for 1000 commodities. They combine road and marine transportation and fixing variables on capacity restrictions using branch & cut algorithm. Zeng, Hu [31] propose a multimodal transportation model in automotive logistics with transportation mode distribution including railway, waterway and road transportation. Sitek and Wikarek [32] deal with a supply chain optimization problem from the perspective of a multimodal logistics provider. Their work includes a MILP model aiming multilevel cost optimization.

Lei, Zhu [33] propose by combining particle swarm optimization algorithm and ant colony algorithm to solve the combinatorial optimization problem of multimodal transportation scheme decision effectively combining the advantages of particle swarm optimization algorithm and ant colony algorithm. Resat and Turkay [34] propose a multi-objective model for the design and operation of an intermodal transportation network with different transportation modes in a specific geographical region. They deal with minimization of transportation cost and total transportation time simultaneously.

### 2.2.3 Solution Methodologies

Solving network flow planning and service network design problems for multimodal transportation is difficult due to their complexity and large set of variables and constraints. A number of solution methodologies have been applied supply chain management models. Goetschalckx [35] explains the methodologies as following; exact mathematical optimization, hierarchical decomposition, stochastic simulation, ad hoc heuristics and constraint programming. Melo, Nickel [20] suggest a similar classification dividing the solution methods into general solver and specific algorithm.

Heuristic and metaheuristic approaches, especially tabu search, are the most popular algorithms for solving these kind of tactical planning problems and is used by Crainic, Li [36] and Verma, Verter [28]. Beside these approaches, there are also exact solution methodologies applied to similar problems in the literature. These methodologies are mainly based on branch & bound, branch & cut and branch & price algorithms. Using branch & bound algorithm Lin and Chen [37] solved their deterministic model for minimizing transshipment via scheduling road and air transportation with allowing empty flows,. Gelareh and Pisinger [38] proposes a network design and hub location of liner shipping companies using branch & cut algorithm. They deduct transshipment costs from the revenue in their objective function. Andersen, Christiansen [39] proposes branch &

price algorithm integrating two column generation sub problems for integer cycle design and continuous flow-path variables using a combination of branching strategies, a tool to vigorously add resilient linear cuts for relaxation, and an acceleration technique based on depth-first search to speed up finding integer solutions.

The other exact solution methodologies used are, decomposition and relaxation. Bektaş, Chouman [26] formulate and compare flow-based and arc-based decomposition methods in solving their non-linear multi-commodity network design problem. Verma and Verter [40] use an iterative decomposition based solution methodology for their bi-objective optimization model to plan and manage intermodal shipments. Meng, Wang [41] solve their problem about short term planning of liner ship fleet with participating the average approximation including Lagrangian relaxation and dual decomposition method. Chen and Miller-Hooks [42] use Benders' decomposition, column generation, and Monte Carlo simulation. Miller-Hooks, Zhang [43] formulate an integer L-shaped method and uses Monte Carlo simulation to solve their problem.

## 2.3 Refinery Operations

Petroleum refineries are industrial process plants where crude oil is processed and refined into more useful products such as LPG, gasoline, diesel, jet fuel, fuel oil and bitumen as described by Gary and Handwerk [44]. Petroleum refineries convert crude oil into semi-products by distilling crude oil into fractions and then process these semi-products further into end-products, through an assembly of chemical and physical transformations. Process flow diagram of a complex refinery is illustrated in Figure 2.1. The finished products of refinery are used as fuel or raw materials for petrochemicals industry. The configuration and operating characteristics at each oil refinery are unique. They are mainly classified by their complexity, location, market requirements, product quality specifications they can reach and year of construction. The refineries are mainly located domestically [45].

Currently in 115 countries, there are more than 650 refineries. Total production amount of refined products is more than 90 million barrels per day [46]. Turkey has a refining capacity of 550.000 barrels per day which is around 0.6 percent of world production. [47].

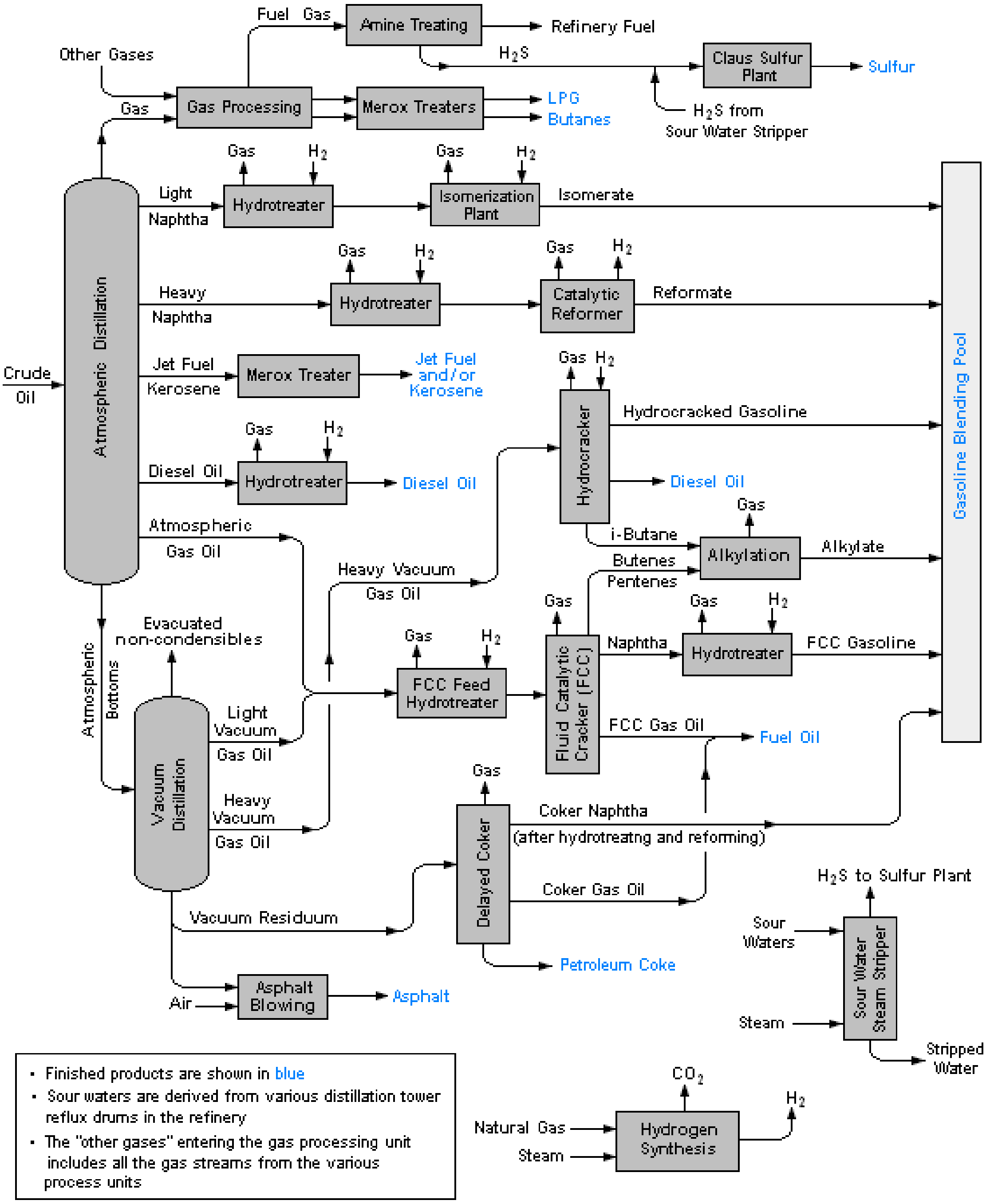


Figure 2.1. Flow diagram of a typical petroleum refinery [48]

The refineries are divided into four main categories: top-ping, hydro-skimming, conversion and deep conversion refineries [49]. Topping and hydro-skimming refineries are classified as simple, whereas the conversion refineries are classified as complex refineries. The refinery complexity comparison is shown in Figure 2.2. Complex refineries include a combination of interrelated processes to produce a broader range of refined petroleum products. Nelson Complexity value is used to quantify the complexity of the refineries [45]. The simplest refineries execute only the distillation process, whereas more complex refineries have operations in extra functions. The transformation of the hydrocarbon fractions distillied in the crude oil separation process to other more valuable products (hydrocracking, decoking, etc.) and the further treatment of semi-products in order to obtain higher-value products (hydro-treating, reforming, isomerization, alkylation, desulphurization, etc.) Refineries having a large transformation and desulphurization capacity can realize higher returns from the refined products. The first reason is the economies of scale and the second is they can process cheaper and higher sulphur ratio crude oil than the refineries with poorer transformation and desulphurization capacities. In addition, environmental regulations and market conditions force refining companies to maximize their higher-value oil products.

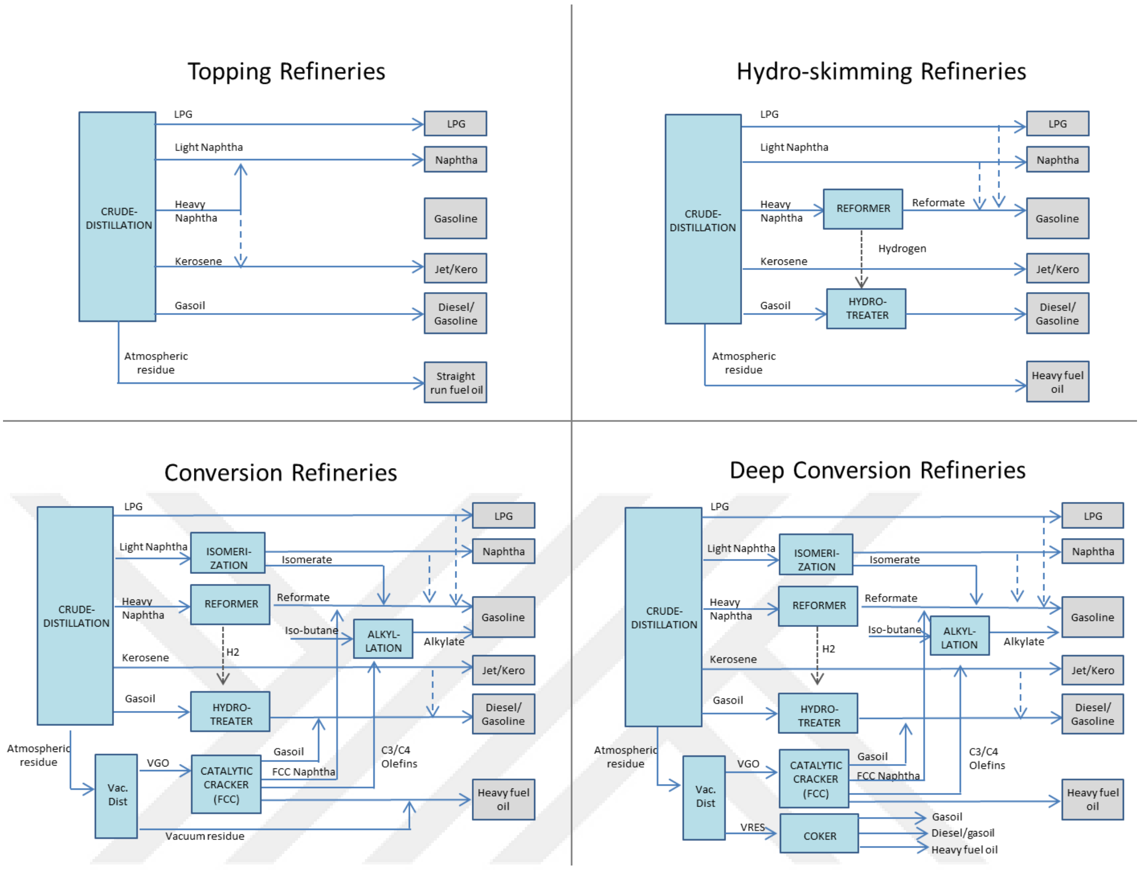


Figure 2.2. Refinery complexity comparison

## 2.4 Refinery Logistics Planning

The movement of oil and oil products are the key elements in refinery logistics. Supply chain in the oil industry is composed of oil suppliers, refineries with interconnections of product flows, terminals and distribution centers. Value chain in oil industry is illustrated in Figure 2.3.

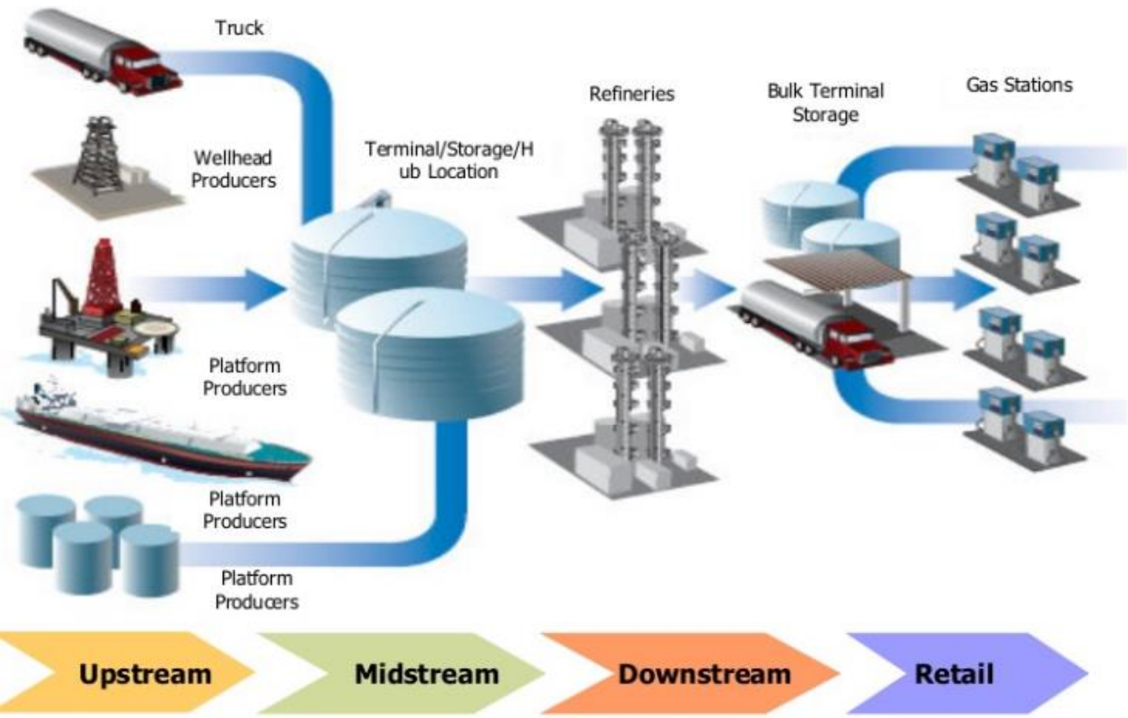


Figure 2.3. Petroleum value chain [50]

Hall [51] indicates that reliability, delivery time and cost are the most important expectations of the companies in the chain. He also notes that these factors are the elements of strong competition between the companies in the industry. Furthermore, the market is very volatile due to some unpredictable factors. These factors can be explained as frequent political strategy changes and frequent oil price fluctuations. Ribas, Leiras [52] note that these uncertainties makes the oil supply chain more vulnerable and need to be handled with an unique supply chain management approach.

Transportation planning models developed for the oil industry in the literature mostly include production planning or crude oil supply. Most recent reviewers of oil supply chain management problems are Sahebi, Nickel [1] and Lima, Relvas [21]. First detailed network flow planning model related to oil supply chain in the literature belongs to Sear [53] and he addresses downstream segment distribution problem in the petroleum supply chain. He developed a LP model and dealt with three product classes: light, middle and heavy distillates. He formulated the distribution cost based on the supposition that distribution includes vehicle routing. His study suggests flows for the oil products on a given network structure. Maturana and Contesse [54] proposes a MILP model for optimizing the complete logistic system of sulfuric acid at strategic level. In their model, several transportation modes were involved such as rail, truck and pipeline.

Neiro and Pinto [55] solved a large-scale problem for operational planning of petroleum supply chains using a mixed integer nonlinear programming (MINLP) model of processing units, terminals and pipeline networks. Their model is applied to a real-world corporation with 4 refineries, 5 terminals, a pipeline network for crude oil supply and a product distribution network for 32 different products. MirHassani [56] developed a stochastic model for planning of the distribution of oil products in uncertain demand for 9 refineries, 90 depots, 70 pump stations, 221 markets and 4 transportation modes. Decision variables suggest the volumes transported by each transportation mode and the volumes of lack and excess of each product. Kim, Yun [57] developed a model to integrate service network design and tactical production planning for oil products at the downstream level for multi-site refineries including 3 refineries, 46 depots and 124 markets.

Kuo and Chang [58] developed an integrated MINLP model for the whole oil supply chain system including purchasing and transportation of crude oil, refining operations and distribution for planning the network of 3 refineries, 7 terminals, 3 transportation modes, 8 local customers and overseas customers. Guyonnet, Grant [59] extended the model developed by Neiro and Pinto [55]. They added the scheduling of crude oil transportation and distribution of the final products. Their problem consists 1 refinery, 1 depot, 8 markets and 3 transportation modes. They solved their integrated MINLP model by using branch & cut algorithm. Tong, Feng [60] formulates a two stage stochastic MILP model for tactical and operational planning. The model is applied to an oil refining operation problem, under product demand and product yield uncertainties. The problem includes 1 refinery, 3 depots, 3 oil suppliers, customers and 4 different transportation modes. Their model is based on conditional vale-at-risk framework in which they can come with risks and uncertainties simultaneously.

Leiras, Ribas [61] formulates a two stage stochastic MILP model integrating tactical and operational planning of multisite refining networks. The network contains 3 refineries, 6 terminals, 2 distribution bases and 4 transportation modes. The uncertainties around market prices and product demand are addressed in the upper level model and the uncertainties around processing capacities and crude oil supply are addressed in the lower level model. There is an iterative approach and information flow between the two models.

## 2.5 Contributions

The contributions of this study include the modeling multi-commodity transportation service design using the real world data set with two nodes for hazardous liquid commodities with the objective of minimizing the overall transportation cost. A tactical level multi-modal, multi-period transportation planning problem is addressed from the perspective of a multi-refinery operating company. It is a real industrial case of Turkish Petroleum Refineries Corp. Transportation modes are railroad tankers, road haulage and blending the products into crude oil pipeline. A deterministic mathematical model for cost optimization is developed dealing with optimal use of available infrastructure by selecting the transportation modes, assigning ordering capacities, and planning the routes and frequency of shipment for the semi-products and the final products of two geographically dispersed refineries under fluctuating demands. Strong valid linear inequalities are developed and used to strengthen the MILP bound of the model by fixing variables on capacity restrictions. Moreover, preprocessing is applied to adjust the cost structure due to different policies applied to different type of modes and carriers (empty returns, insurance, maneuvers, hazardous good surcharges, transshipment leakages and reprocessing). A brief comparison with the similar work in the literature is given in Table 2.2.

Table 2.2. Literature comparison & Contributions

| | Decision Level | Model | Uncertainity | Real Case | Objective | Products | Time Periods | Nodes | Commodity Flow | Transportation Stages | Transportation Modes |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Pinto et al. (2000) | Operational | MINLP | Deterministic | √ | Profit Max. | 2 | 3 days, 2-hour cycles | 1 refinery, 4 terminals | Single | Single stage | 2 |
| Neiro and Pinto (2004) | Tactical & Operational | MINLP | Deterministic | √ | Profit Max. | 32 | 2 time periods | 4 refineries, 5 terminals | Single | 2 stages | 1 |
| Al-Othman et al. (2008) | Tactical & Operational | MILP | Stochastic | - | Cost Min. | 12 | 12 months, monthly cycles | 10 oil sites, 3 refineries, 17 markets | Single | 2 stages | 1 |
| Kuo and Chang (2008) | Tactical & Operational | MILP | Deterministic | - | Profit Max. | 4 | 3 time periods | 3 refineries, 3 terminals | Single | Single stage | 3 |
| Alabi and Castro (2009) | Tactical & Operational | MILP | Deterministic | √ | Profit Max. | 5 | 3 time periods | 4 refineries, 60 depots | Multi | 2 stages | 1 |
| Guyonnet et al. (2009) | Tactical & Operational | MINLP | Deterministic | √ | Profit Max. | 8 | 3 months, daily cycles | 1 refinery, 8 markets | Single | Single stage | 1 |
| Tong et al. (2011) | Tactical & Operational | MILP | Stochastic | - | Cost Min. | 4 | 10 time periods | 1 refinery, 3 depots | Single | 2 stages | 4 |
| Guajardo et al. (2013) | Strategic & Tactical & Operational | MINLP | Deterministic | - | Profit Max. | 4 | 12 time periods | 2 refineries, 3 terminals, 6 markets | Single | Single stage | 1 |
| Leiras et al. (2013) | Tactical & Operational | MILP | Stochastic | √ | Profit Max. | 10 | 6 months, montly cycles | 3 refineries, 6 terminals | Single | Single stage | 4 |
| Tong et al. (2014) | Strategic & Tactical | MILP | Stochastic | √ | Cost Min. | 2 | Single Period | 40 oil sites, 2 refineries, 39 markets | Single | 2 stages | 1 |
| Fernandes et al. (2015) | Strategic & Tactical | MILP | Deterministic | √ | Cost Min. | 8 | 12 years, 4 year cycles | 2 refineries, 18 markets | Single | Single stage | 4 |
| This study | Tactical | MILP | Deterministic | √ | Cost Min. | 9 | Single Period | 2 refineries | Multi | Single stage | 3 |

The major difference with the literature is the combination of different transportation modes with multi-directional commodity flows. Moreover, the model is developed to serve tactical level decisions with the objective of cost minimization. Mixed Integer Linear Programming is utilized and exact optimal transportation planning is obtained with branch & cut algorithm. The effects of cutting planes algorithms on the solution times are compared. The results shows that MIR cuts are necessary to solve the given problem. With real and simulated data from a refinery, the cost advantage of transportation planning is determined. The computational study shows that an effective planning can yield as much as 2.1% savings on total transportation costs. Generated model is being used iteratively with the commercial multi-refinery production planning solver. Sensitivity analysis considering network upgrade by investment on vehicle cleaning, flexible and extended working hours for loading/unloading and specific gravity of the products transported via the pipeline are studied. The computational study on different scenarios shows that an effective planning can yield as much as 22.9% savings on total transportation costs with necessary investments and contract changes.

# Chapter 3

# PROBLEM STATEMENT

## 3.1 Problem Description

The problem is centered on a simple refinery “Batman” near the drilling site abbreviated as “BAT”, selling only bitumen as a final product and sending rest of the semi-products to the other refinery “Kırıkkale” abbreviated as “KRK” for further processing. “BAT” uses single type of petroleum drilled nearby and refinery production plan is done according to bitumen demand from the region. The other semi-products, Light Naphtha, Heavy Naphtha, Light Kerosene, Heavy Kerosene, Light Diesel, and Heavy Diesel are sent to “KRK”. Production amounts of these semi-products are dependent on bitumen production. After being further processed in “KRK”, some of the Gasoline, Jet Fuel and Diesel are sent back to “BAT” which is also used as a distribution terminal. Transportation modes are pipeline and maritime combination, railroad tank car and road tanker haulage. Pipelines are operated by BOTAS Petroleum Pipeline Corporation, railroad is operated by TCCD Turkish State Railways. The operations in all of the transportation modes are regulated by government, and managed by yearly contracts. Thus it is important to plan the operations in advance to assign and allocate necessary vehicles, etc. The transportation network is illustrated in the Figure 3.1.

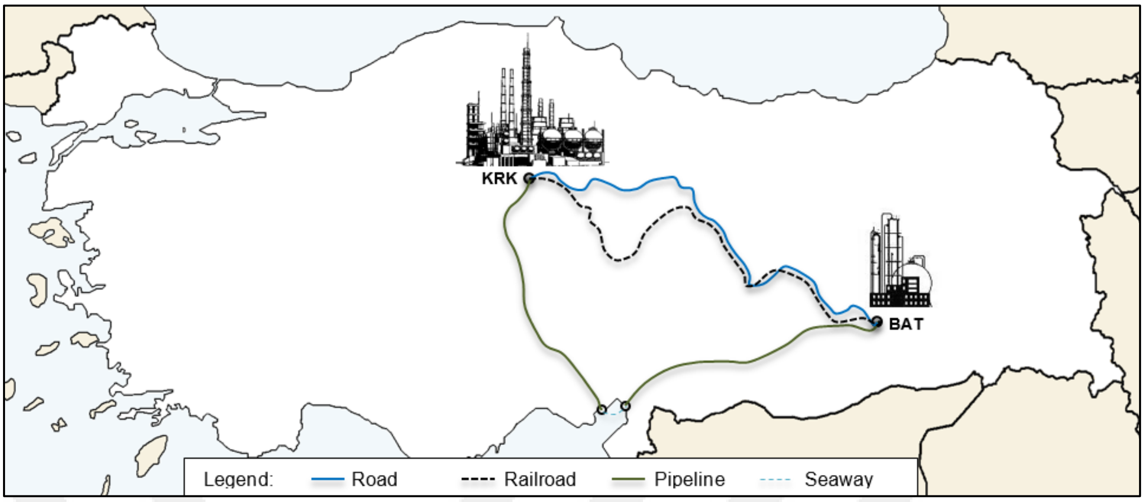


Figure 3.1. Refinery transportation network

The lateral and reciprocal shipment with a variety of transportation modes is the main consideration in this problem. The product flows between the refineries are illustrated in Figure 3.2.

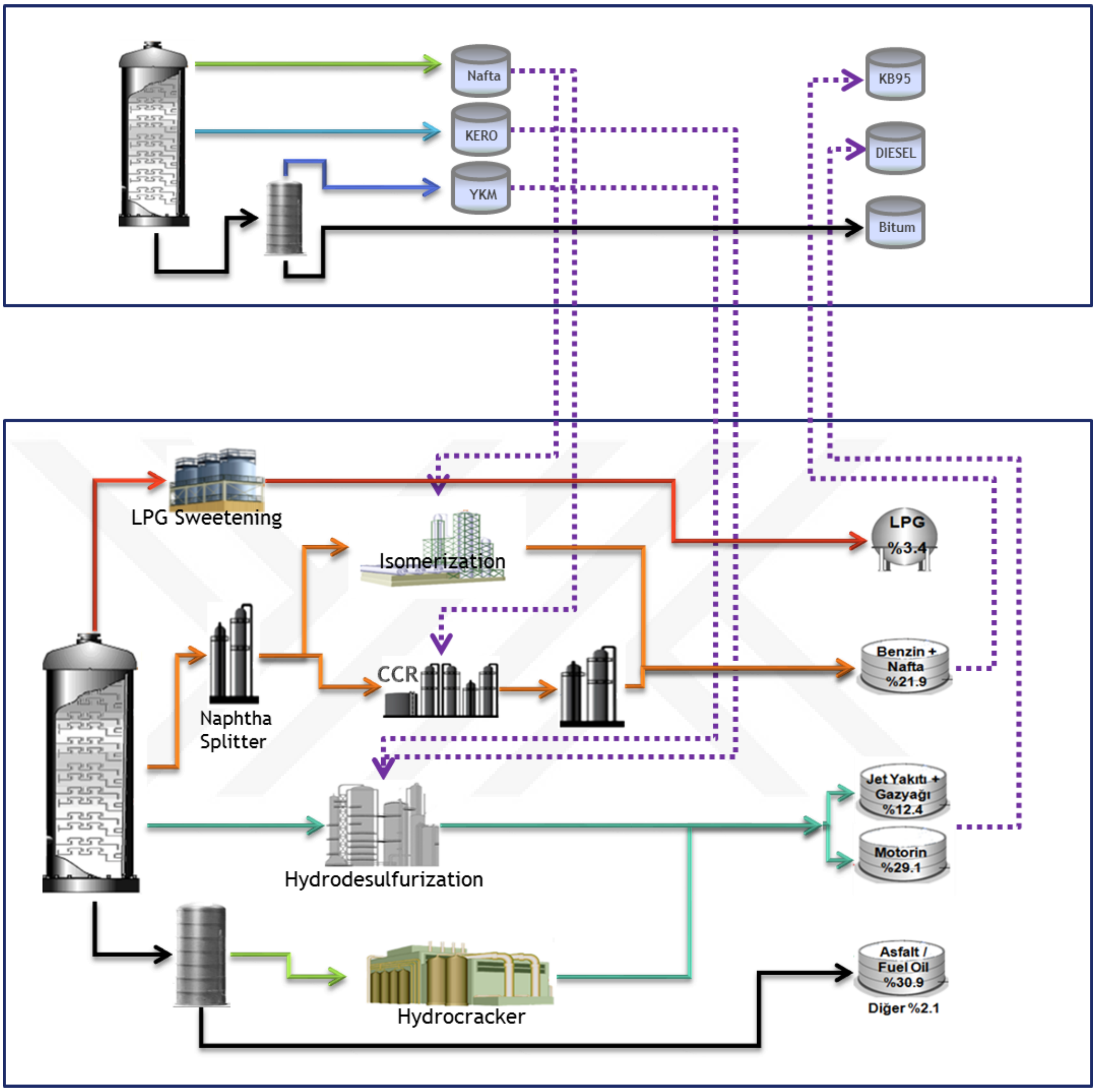


Figure 3.2. Product flow between two refineries

### 3.1.1 Pipeline & Maritime Combination

Pipelines provide an economical transportation mode for liquids, especially when large amounts of petroleum derivatives have to be pumped over long distances. One of the transportation modes from BAT to the KRK is blending the semi-products back in to crude oil to transport the products to the nearest harbor, then transport other refinery via marine transportation. The schematic representation of pipeline network is shown in Figure 3.3.

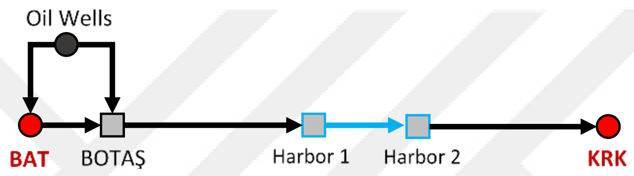


Figure 3.3. Product flow via pipeline & maritime transportation

The black lines represent the pipelines whereas the blue lines represent maritime transportation. Multimodal structure of this method makes the unit price of transportation higher in contrast to traditional pipeline transportation. Both of the pipelines are operated by BOTAS (Turkish National Petroleum Pipeline Corporation) [62, 63]. The pipeline operations are done according to a prearranged contract, which is usually signed at the beginning of each year. Total length from BAT to Harbor 1 is 448 km and from Harbor 2 to KRK is 511 km adding up to 959 km in total with 7 different pumping stations [62, 63]. The distance between the two harbors is 20 kilometers.

The pipeline has a maximum pumping capacity and minimum density constraint to avoid cavitation within pumping stations. The density constraint limits the ratio of lighter products in the blend. Leakage in the pipelines is also an important factor to consider since the value of lost products due to leakage is different for each mixture. Another disadvantage of this transportation mode in this case is the necessity of re-distillation of the blended products in receiving refineries, adding a reprocessing cost.

### 3.1.2 Railroad Transportation

Road transportation is usually the most expensive method among the modes considered in this study. However, due to safety regulations, only the semi-products, Light Diesel, and Heavy Diesel, and as final products, Jet Fuel and Desulfurized Diesel can be transported in this mode. The rest of the products cannot be transported with this mode due to their flammable and highly volatile characteristics.

The railroad connection between the refineries is not very efficient due to old infrastructure. There are two operation modes of railroad wagons: Block trains or single railroad car transshipment. In block train mode, the public contractor, TCDD, allocates a number of locomotives with different capacities and expects the locomotive to be used bilaterally and at full capacity for each direction. The capacity limit differs at each direction due to elevation differences between the origin and destination. A full tour of a block train takes approximately one week and planned block train operations must be arranged from the previous month. There is no capacity limit for the single tank car case, but tour times of wagons double in case of not using block trains [64].

There are three different railroad tank car designs, one of which is owned by the refinery and other companies own the remaining two tank types which must be arranged one month prior to the operations. The three designs differ in terms of fixed and unit prices and costs are preset in order to adjust cost structure including empty returns, insurance, maneuver, and hazardous good surcharge for different designs. If a service change occurs for a railroad tank car, the tank car should be washed at a fixed cost involving investment. This can happen only in “KRK”. Without washing, the tank cars return to the origin empty. Railroad tank car haulage has several constraints such as vehicle capacity, transportation time, number of railroad cars, and availability of washing and cleaning service when transporting specific products. The average capacity of a wagon is approximately 58 $m^3$ and the distance between two refineries is 1057 km [64].

### 3.1.3 Road Transportation

Road transportation is the most expensive among others. However, due to safety regulations, some of the light products must be carried within a pressurized vessel that is only available in road tankers. The products are carried out in compliance with ADR [65] (the European Agreement concerning the International Carriage of Dangerous Goods by Road) between the refineries [66]. A private contractor handles the operations and trucks can carry products in both directions. The selected type of product for each direction determines the cost per unit weight. The average capacity of a tanker truck is approximately 32.5 $m^3$ and the distance between two refineries is 927 km [67].

### 3.1.4 The Cost Structure

Costs associated with pipeline are transportation cost ($c_{pipe}$), product losses due to leakage ($c_{loss}$) and re-processing costs ($c_{process}$). All of these costs are variable costs and same for all of the products. Transportation costs are associated with the separate two parts of pipeline and the seaway in-between. Road transportation cost matrix has two dimensions representing the variable costs associated to the products in both directions. Railroad transportation cost structure includes variable ($c_{rail}$) and fixed ($c_{fixed}$) costs.

For empty returning wagons;

**Variable cost:** Unit Cost * (1 + Safety Premium – Discount)

**Fixed Cost:** 2 * Maneuver + Insurance + Empty Return Surcharge

For full returning wagons;

**Variable cost:** Unit Cost * (1 + Safety Premium + Full Return Premium)

**Fixed Cost:** Maneuver + Insurance

Variable cost is per tons of products transported fixed cost is per vehicle. Unit cost is declared by TCDD annually, safety premium is %0.2, discount is %45 and only valid for the wagons owned by TUPRAS, maneuver cost and insurance and empty return surcharge is fixed in both directions and declared annually and full return premium is %5.

## 3.2 Mathematical Modeling

The main decision variables in the model are the amounts of the product transported with pipeline transportation, road haulage and railroad transportation, the number of vehicles assigned to a specific service the number of wagons to be washed and the amount of total needed locomotives.

**Indices**

| | |
|---|---|
| d | direction of the transportation (d=1,2) |
| g | block train status of wagon (1:belongs to a block train, 2:not) |
| h | locomotive type of the block train (h=1,2,3) |
| i | outgoing products from the first node to the second node (i=1,…,I) |
| j | arriving products from the second node to the first node (j=1,…,J) |
| k | mode of transportation (1:pipeline, 2:road, 3:railroad) |
| u | status of wagon (1:full, 2:empty) |
| v | company of the wagon owner (v=1,2,3) |

**Variables**

| | |
|---|---|
| $n_{i,j,k}$ | number of vehicles assigned for transporting products i and j reciprocally with transportation mode k (integer and valid for k=2,3) |
| $x_{i,d,k}$ | amount of the product i transported within the direction d with transportation mode k |
| $y_{d,v,g,u}$ | number of railroad wagon in direction d with wagon type v with block train type g, transporting products i and j with status u (integer) |
| $z_h$ | number of block train locomotives in the service (integer) |

**Parameters**

| | |
|---|---|
| $A$ | number of block trains allowed in a specific period of time |
| $B_{g,v}$ | time constant of wagon transported in g of company v |
| $C_{fixed,k,v,u}$ | fixed cost of transportation per vehicle of mode k |
| $C_{loss,i}$ | unit cost of the product i per mass |
| $C_{pipe}$ | unit cost of pipeline transportation per mass |
| $C_{process}$ | unit cost of reprocessing the blended products in pipeline |
| $C_{road,i,j}$ | unit cost of road transportation for products i and j reciprocally per mass |
| $C_{rail}$ | unit cost of railroad transportation per mass |
| $C_{wash,k}$ | fixed washing cost per one vehicle |
| $D_{max,h}$ | maximum pulling capacity of locomotice type h |
| $D_{min,h}$ | minimum mass of block train allowed for locomotice type h |
| $E_{i,k}$ | 1 if product p can be transported by mode k<br>0 else |
| $F_u$ | mass of a railroad wagon of status u |
| $M_{max}$ | maximum flow allowed for pipeline in a specific period of time |
| $M_{min}$ | minimum flow allowed for pipeline in a specific period of time |
| $N_{max,k,v}$ | maximum number of vehicles for mode k for company v (k=2,3) |
| $N_{min,k,v}$ | minimum number of vehicles for mode k for company v (k=2,3) |
| $P_{max}$ | maximum density allowed for pipeline transportation |
| $P_{min}$ | minimum density allowed for pipeline transportation |
| $\rho_i$ | density value of product i in $kg/m^3$ |
| $Q_{max,k}$ | maximum volumetric vehicle capacity of transportation mode k (k=2,3) |
| $Q_{min,k}$ | minimum required volume for vehicles of transportation mode k (k=2,3) |
| $R_k$ | loss ratio of products in the transportation mode k due to leakage |
| $S_{i,d}$ | demand of product p for transportation in a specific period of time |
| $T_k$ | maximum number of vehicle tour in a period of time (k=2,3) |
| $W_{i,j}$ | 1 if wagon is to be washed after service change from product i to j<br>0 else |

**Model**

$$\begin{aligned}
& min\sum_{i\in I}\sum_{d\in D} x_{i,d,1} * \left(C_{pipe} + C_{process} + R_1 * C_{loss,i}\right) \\
& + \sum_{i\in I}\sum_{j\in J} n_{i,j,2} * C_{road,i,j} * \rho_i * Q_{max,2} \\
& + \sum_{i\in I}\sum_{j\in J} n_{i,j,3} * C_{rail} * \rho_i * Q_{max,3} \\
& + \sum_{d\in D}\sum_{v\in V}\sum_{g\in G}\sum_{u\in U} y_{d,v,g,u} * c_{fixed,3,v,u} \\
& + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} n_{i,j,k} * W_{i,j} * C_{wash,k}
\end{aligned} \tag{1}$$

$$S_{i,d} = \sum_{k\in K} E_{i,k} * x_{i,d,k} \qquad \forall i \in I,\ \forall d \in D \tag{2}$$

$$\sum_{i\in I} x_{i,1,1} \geq M_{min} \tag{3}$$

$$\sum_{i\in I} x_{i,1,1} \leq M_{max} \tag{4}$$

$$x_{i,2,1} = 0 \qquad \forall i \in I \tag{5}$$

$$\sum_{i\in I} x_{i,1,1} \leq P_{max} * \sum_{i\in I} \frac{x_{i,1,1}}{\rho_i} \tag{6}$$

$$\sum_{i\in I} x_{i,1,1} \geq P_{\min} * \sum_{i\in I} \frac{x_{i,1,1}}{\rho_i} \tag{7}$$

$$x_{i,d,k} \leq \sum_{j\in J} n_{i,j,k} * \rho_i * Q_{max,k} \qquad \forall i \in I \quad \forall d \in D \quad \forall k \in K, k \neq 1 \tag{8}$$

$$x_{i,d,k} \geq \sum_{j\in J} n_{i,j,k} * \rho_i * Q_{min,k} \qquad \forall i \in I \quad \forall d \in D \quad \forall k \in K, k \neq 1 \tag{9}$$

$$\sum_{i\in I}\sum_{j\in J} n_{i,j,k} \leq \sum_{v\in V} n_{max,k,v} * T_k \qquad \forall k \in K, k \neq 1 \tag{10}$$

$$\sum_{i\in I}\sum_{j\in J} n_{i,j,k} \geq \sum_{v\in V} n_{min,k,v} * T_k \quad \forall k \in K, k \neq 1 \tag{11}$$

$$\sum_{i\in I}\sum_{j\in J} n_{i,j,k} = \sum_{j\in J}\sum_{i\in I} n_{j,i,k} \quad \forall k \in K, k \neq 1 \tag{12}$$

$$\sum_{i\in I}\sum_{j\in J} n_{i,j,3} = \sum_{d\in D}\sum_{v\in V}\sum_{g\in G} y_{d,v,g,1} \tag{13}$$

$$\sum_{j\in J}\sum_{i\in I} n_{j,i,3} = \sum_{d\in D}\sum_{v\in V}\sum_{g\in G} y_{d,v,g,2} \tag{14}$$

$$\sum_{h\in H} z_h * D_h = \sum_{d\in D}\sum_{v\in V} y_{d,v,1,1} * F_1 + \sum_{d\in D}\sum_{v\in V} y_{d,v,1,2} * F_2 \tag{15}$$

$$\sum_{h\in H} z_h \leq A \tag{16}$$

$$T_3 * N_{max,3,v} \geq \sum_{d\in D}\sum_{g\in G}\sum_{u\in U} B_{g,v} * y_{d,v,g,u} \quad \forall v \in V \tag{17}$$

The objective function given in Eq. (1) is the minimization of total transportation cost of all modes and washing/cleaning cost of the rail cars. Pipeline cost includes pipeline transportation, losses due to leakage and reprocessing costs, plus the quantity of the leaked multiplied by the product price. We assume that leakage only occurs in pipeline transportation, since it is negligible in the other modes. Road transportation cost includes the number of vehicles times the reciprocal product dependent cost times the vehicle capacity. Regardless of the capacity used, the price is calculated as if the vehicle is fully loaded. Although there is no fixed cost in road transportation, both variable and fixed costs are applied for railroad transportation. Variable cost is similar to the road transportation regardless of the returning product. Fixed cost depends on the owner company of the rail car multiplied by the number of cars used. The last term of the objective function is the washing cost of the vehicles that is calculated by multiplying washing cost per unit vehicle and number of vehicles assigned for transporting products *i* and *j* reciprocally to be washed if service changes from product *i* to *j*.

The supply amounts are to be satisfied in both directions in specified period of time. Eq. (2) indicates that the products transported from the first node to the second node and from second node to the first node must be higher than the total demand as shown. There is a specific contract with the local authority that specifies the minimum flow rate in the pipeline shown in Eq. (3). It is because of the minimum pumping specifications of the pumping stations. Same contract applies for the maximum flow rate in the pipeline shown in Eq. (4). It is both because of the allocation of the pipeline and the pumping capacities. Pipeline can only be used in single direction, due to the configuration of the pumping stations. The product flow in the reverse direction is zero as shown in Eq. (5). The density of the products blended in the pipeline has to be greater than the minimum allowed density due to the pumping constraints of the pipeline authority as shown in Eq. (6). Similarly, density of the blended products has to be lower than the maximum allowed density due to the viscosity constraints as shown in Eq. (7). The density of the products in the pipeline is calculated via volumetric average of the blended products, the total mass is divided by the volume.

There is a maximum volumetric capacity of each transportation vehicle and the mass capacity depends on the density of the products transported. It is calculated by multiplying the volumetric capacity of the vehicle and the density of the product as shown in Eq. (8). Although there are some design variations for the tankers, the average volume is assumed to be valid for all vehicles in the fleet for simplicity. According to the dangerous goods transportation regulations, it is advised to fill the tankers more than a specific amount, in order to increase the road handling and avoid any liquid movement within the tanker. Eq. (9) gives the minimum loading capacity of the tankers. Eq. (10) indicates the maximum number of vehicles in the fleet that can be used; this quantity does not dependent on the direction of transportation of the products. Eq. (11) indicates the minimum number of tanker vehicles in the fleet that has to be used. This is valid when a specific contract is made with a third party logistics provider. The constraints given by Eq. (12) ensure that accumulation of vehicles is not allowed in one location. Every single vehicle has to return either full or empty. The total number of vehicles travelling at each direction is equal.

Eq. (13) and Eq. (14) are the constraints about distribution of the rail cars to the different companies and usage about block train locomotives. Eq. (15) ensures the total pulling capacity of a block train locomotive is equal to the weight of the attached wagons in railroad mode. The number of locomotives is determined by this equation. Eq. (16) is ensures only limited numbers of block trains that can be loaded or unloaded within a specific period of time. Block trains have some advantages over single wagons; if a rail car set is prepared as a block train with a dedicated locomotive, it will complete its route faster than normal single cars. Besides the number of rail cars is limited for different companies that are expressed in Eq. (17).

The problem is modeled deterministically with the assumption that there is no interruption of the transportation processes such as transportation time between the two nodes are fixed and does not depend on the weather condition etc. and the products prices are fixed in the given planning horizon. Besides these properties, optimization is applied at a fixed point in time (static) and all of the constraints are continuous and differentiable.

# Chapter 4

# SOLUTION APPROACH

The mathematical modeling of transportation networks requires the use of both linear and discrete components. There are two types of decision variables in the given problem, first type is the amount of the products to be transported for the selected mode, and second type is the number of vehicles required to perform the transportation. The problem includes several modes of arc-based transportation such as road haulage, railroad and pipeline transportation. The amount of product transportation is limited by the integer number of vehicles. Therefore Mixed-Integer Programming (MILP) is used to model the given optimization problem. The problem is modeled in GAMS environment and solved using CPLEX solver with branch & cut algorithm.

## 4.1 Mixed Integer Linear Programming

MILP is an optimization method that combines continuous and discrete variables. It is a problem with linear objective function, linear equalities and inequalities, and restrictions on some decision variables to have integer values. A MILP can be formulated as;

$$\begin{aligned} &\min c^T x + d^T y \\ &Ax + By \leq b \\ &x \in Z^n \\ &y \in R^m \end{aligned} \tag{18}$$

where $n$ and $m$ are positive integers, $Z$ is the set of integers, $x$ is an integer variable, $y$ is an continuous variable, $c^T$ and $d^T$ are column vectors constants of the objective function, $A$ and $B$ are matrix constants of the constraints and $b$ is column vector of upper bounds [68].

If a set of $(x, y) \in Z^n \times R^m$ is found such that it satisfies all constraints, it is described as a feasible solution. Between all feasible solution, if $(\hat{x}, \hat{y})$ can give the minimum value of the objective function, it is called global optimal solution.

## 4.2 Branch & Bound Algorithm

Branch and Bound (B&B) is a method that explores all of the possible solutions to a MILP problem. The technique divides the feasible region into sub regions which are explored for reducing the problem size [68].

Branch-and-bound algorithm contains of a methodical enumeration of possible solutions by state space search. The set of possible solutions is supposed of as establishing a decision tree with the full set at the root. The method explores the branches of the tree, which are subsets of the solution set. The branch is controlled whether it is in between upper and lower bounds on the optimal solution before enumerating the possible solutions. The branch is dismissed if there is no better solution on the branch than the best one found so far. The division of the feasible region is graphically represented by a search tree. A search tree is a decision tree that has its root and branches [68]; an example of search tree for a binary variable is shown in Figure 4.1.

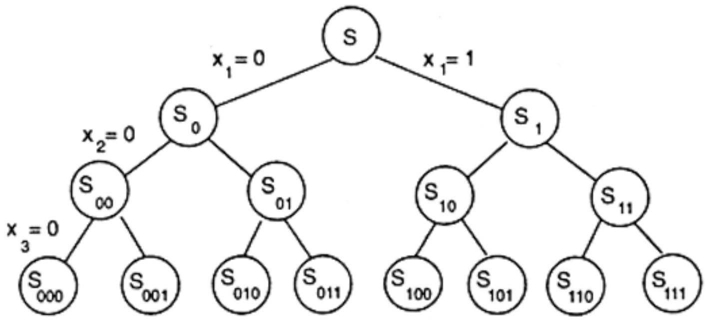


Figure 4.1. Search tree in branch and bound algorithm

## 4.3 Cutting Planes Implementation

Cutting planes iteratively refines a feasible set or objective function by means of linear inequalities. Cuts are new constraints implemented to the model in order to restrict non-integer solutions that would be solutions of the relaxation. Cutting plane algorithms for general integer programming problems are first proposed by Dantzig, Fulkerson [69] and Gomory [70]. However, they are considered to be impractical due to numerical instability, as well as ineffective because many rounds of cuts are needed to make progress towards the solution.

Branch-and-bound and cutting plane algorithms are usually combined and used together in order to decrease the solution time of the mixed integer programs. This combined method is called branch-and-cut algorithm. The logic of B&C is running a branch and bound algorithm and integrating cutting planes to tighten the LP relaxations. Geoffrion [71] proposed a successful combination of Gomory cuts with LP based branch-and-bound to solve MIPs. Especially, they used a hybrid branch & bound and cutting-plane method where the cuts applied to each node problem in order to tighten the LP bounds. The number of branches are expected to be reduced with addition of cuts. A general branch-and-cut scheme proposed by Padberg and Rinaldi [72] in the context of the Traveling Salesman Problem (TSP).

Cutting planes are classified as generic cuts and structured cuts. The generic cuts are based on mathematical arguments and can be applied to any integer programming model to apply relaxation. The structured cuts are specific to certain structures that can be found in some relaxations of the MILP problems. Binary variables and network structures are examples. Gomory fractional cuts and the mixed-integer rounding inequalities form the most important class of cutting planes. However, adding cutting planes does not always improve branch-and-bound performance. While removing integer infeasibilities, it also increases the number of constraints in each node and adds more constraints may increase the total time required to solve the model. Bixby and Rothberg [73] made a performance degradation comparison by enabling cuts. More recently, Klotz and Newman [74] examined and compared several cutting algorithms in their work. Detailed review of the common cutting planes can be found in Marchand, Martin [75].

Several cutting plane algorithms are tested on the MILP model. Combination of cutting planes with branching increases the reliability and improves the efficiency of the overall branch and bound algorithm by reducing the number of nodes. Gomory fractional cuts, mixed integer rounding cuts, lift and project cuts, flow cover cuts and zero half cuts are evaluated for this problem in order to assess their performance considering the number of branch and bound nodes examined and the decrease in the computing time that algorithm processes for each branch and bound node.

### 4.3.1 Gomory Fractional Cuts

The Gomory cutting plane method is developed by Gomory [70] and Chvátal [76] and it is used to strengthen LP-relaxations of integer and mixed integer programs. Gomory fractional cuts are introduced via integer rounding on a basic integer variable with a fractional value on the pivot row of the optimal LP tableau. The algorithm comprises solving the continuous relaxation of an MILP problem and deriving from its optimal solution one or more inequalities that are violated by the solution itself, but satisfies the feasibility of the problem. The problem is re-optimized after adding these inequalities; then, the method is applied again to the new solution. The cut generation and re-optimization of the relaxed problem continues until the optimal solution becomes integer, and therefore feasible and optimal also for the original MILP problem. Considering the set;

$$X = \left\{ \begin{matrix} (x_R,\ x_0,\ x_I) \in R^2 \times Z \times Z^p \mid x_0 + \\ a_I^T x_I + x_R^+ - x_R^- = b,\ x_R \geq 0,\ x_I \geq 0 \end{matrix} \right\}, \tag{19}$$

The Gomory fractional cut is given by the inequality;

$$\sum_{i \in I_1} f_i x_i + \sum_{i \in I_2} \frac{f_0(1-f_i)}{f_i} x_i + x_R^+ + \frac{f_0}{(1-f_0)} x_R^- \geq f_0 \tag{20}$$

is valid for *X*, where $I_1 = \{ i \in I \mid f_i \leq f_0 \}$, $I_2 = I \setminus I_1$, $f_i = a_i - \lfloor a_i \rfloor$ for $i \in I$ and $f_0 = b - \lfloor b \rfloor$ are the fractional parts of *a* and *b* [68].

### 4.3.2 Mixed Integer Rounding Cuts

Nemhauser and Wolsey [68] introduced mixed-integer rounding inequalities (also referred to as Mixed-Integer Rounding Cuts (MIR)) which are integer rounding on the coefficients of integer variables and the right-hand side of a constraint. To obtain a slight variant of the basic inequality, considering the two variable set,

$$S = \left\{ \begin{matrix} (x_1,\ x_2) \in R^1 \times Z^2 \mid x_2 \leq b + x_1, \\ x_1 \geq 0 \end{matrix} \right\} \tag{21}$$

Let $f_0 = b - \lfloor b \rfloor$, then;

$$x_2 \leq \lfloor b \rfloor + \frac{x_1}{1-f_0} \tag{22}$$

is valid for *S* by verifying it for the two cases: $x_2 \leq \lfloor b \rfloor$ and $x_2 \geq \lfloor b \rfloor + 1$ [68].

### 4.3.3 Zero Half Cuts

Zero-half cuts can be described as rounding down the right-hand side coefficients. When the left-hand side of an inequality contains integral variables and coefficients, then the right-hand side can be rounded down to generate a zero-half cut. The cuts are described as $\lambda^T Ax \leq \lfloor \lambda^T b \rfloor, \lambda_i \in \{0, 1/2\}$. Zero-half cuts are also known as 0-1/2 cuts [74].

### 4.3.4 Lift and Project Cuts

Lift and project cuts are developed by Balas, Ceria [77] and are split cuts separated by fixing the disjunction in advance. The logic behind the lift and project cuts is considering the problem in some higher dimensional space than the original space. Then, the inequalities in this higher dimensional space are projected back to the original space resulting in tighter integer programming formulations [75].

# Chapter 5

# REAL LIFE APPLICATION

In this section, the lateral transshipment planning with transport mode selection in a refinery network problem is addressed. The model results are compared with real data from TUPRAS. An overview of the results obtained from the solution of the MILP problem, analysis of the computational effort spent for solving the model and different scenario analyses are presented.  Actual amounts are hidden for confidentiality purposes.

## 5.1 Base Case

Performed operations of the year 2015 is taken as the base case. Normalized amounts of the base case are given in Figure 5.1.

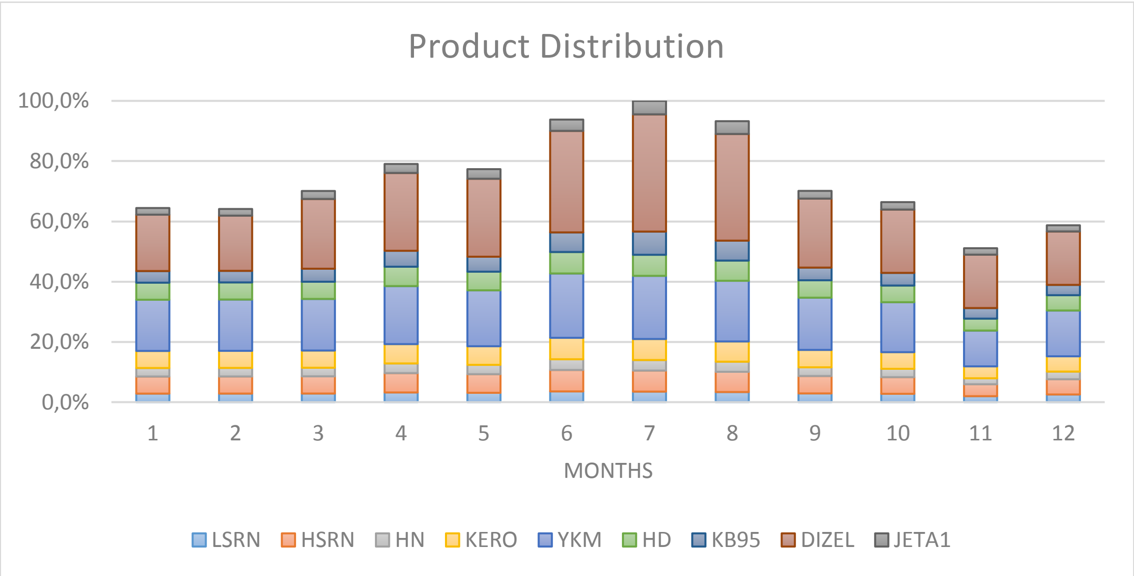


Figure 5.1. Normalized yearly product transportation distribution

## 5.2 Preprocessing

Preprocessing is done in some cost calculations to adjust cost structure since different policies apply to different type of modes and carriers (empty returns, insurance, maneuver, hazardous good surcharge for railroad and pumping, mixing, transshipment leakage and reprocessing costs for pipeline). In addition, discrete-continuous optimization problems benefit from user supplied cutting planes and integer solutions in branch and cut type algorithms. The decision variables of vehicles are assigned as starting from BAT, transporting product *i* and returning with product *j*. In order to allow empty returns both sets contains "empty" as a product. The number of vehicles travelling in both directions without any product is fixed to zero. Besides, using the road option with reciprocal transportation is much cheaper than empty return of vehicles. If the amount of KB95 and JET are higher than LSRN and HSRN, then the vehicles cannot return empty. Theoretically, it is possible to transport every single product by road but it is not practical to do so. The products given in the Table 4.1 are fixed with the associated transportation modes, "o" represents the availability in different scenario analyses.

Table 5.1. Transportation mode availability for products

| | | Pipeline | Road | Railroad |
|---|---|---|---|---|
| BAT → KRK | LSRN | | ✓ | |
| | HSRN | o | ✓ | |
| | HN | ✓ | | |
| | KERO | ✓ | | |
| | YKM | ✓ | ✓ | ✓ |
| | HD | ✓ | | |
| KRK → BAT | KB95 | | ✓ | |
| | JET | | ✓ | o |
| | DIESEL | | ✓ | ✓ |
| | FOIL | | | ✓ |

In order to generate comparable cases, relying on the base case, some new cases are generated;

1- Base Case – Real data from TUPRAS
2- Product flows are increased by 10% in each direction
3- Product flows are decreased by 10% in each direction
4- Keeping the total products flow same in each direction, products are randomly distributed.
5- Product flows in Case 4 are increased by 10% in each direction
6- Product flows in Case 4 are decreased by 10% in each direction

## 5.3 Algorithm Efficiencies

Application of the model on different cases and effects of cutting planes on solution efficiency are investigated. The model is solved using CPLEX solver on GAMS platform on a PC with Intel Core I7-5600U CPU with 2.60 GHz processor, and with 8.00 GB of RAM. Model size is given in Table 5.3.

Table 5.2. Model size

| | **# of Variables** | **# of Discrete Variables** | **# of Equations** |
|---|---|---|---|
| MILP Model | 83245 | 624 | 14089 |

Solution times are investigated with the usage of different cutting planes. The results are the averages of the six cases and given in Figure 5.2. Optimality gap represents the remaining gap after 1000 seconds. The number of the cuts generated for each case is given in Figure 5.3.

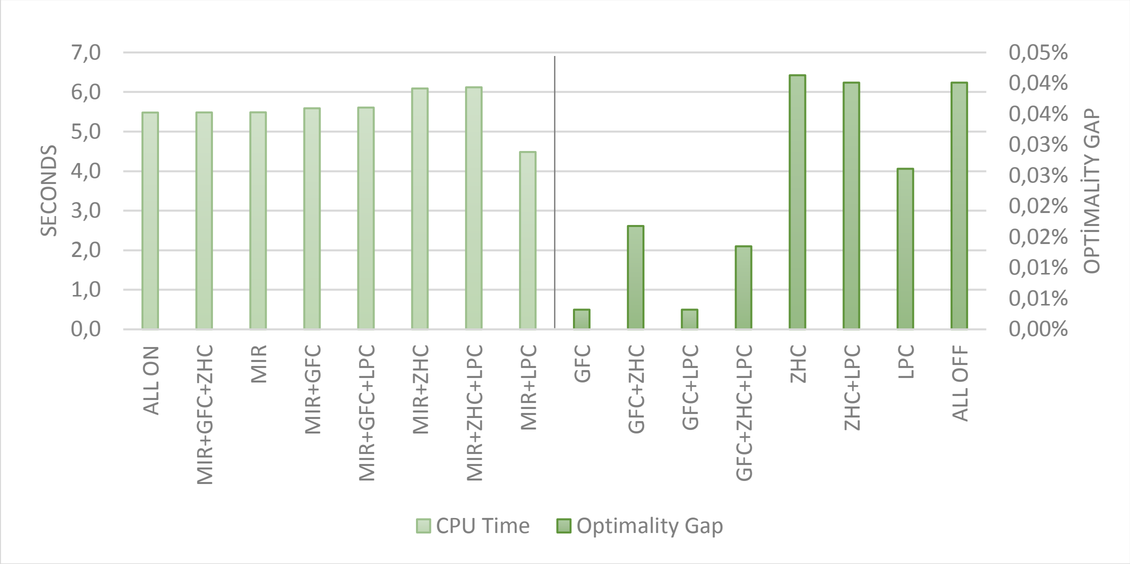


Figure 5.2. Solution times and optimality gaps with different cuts

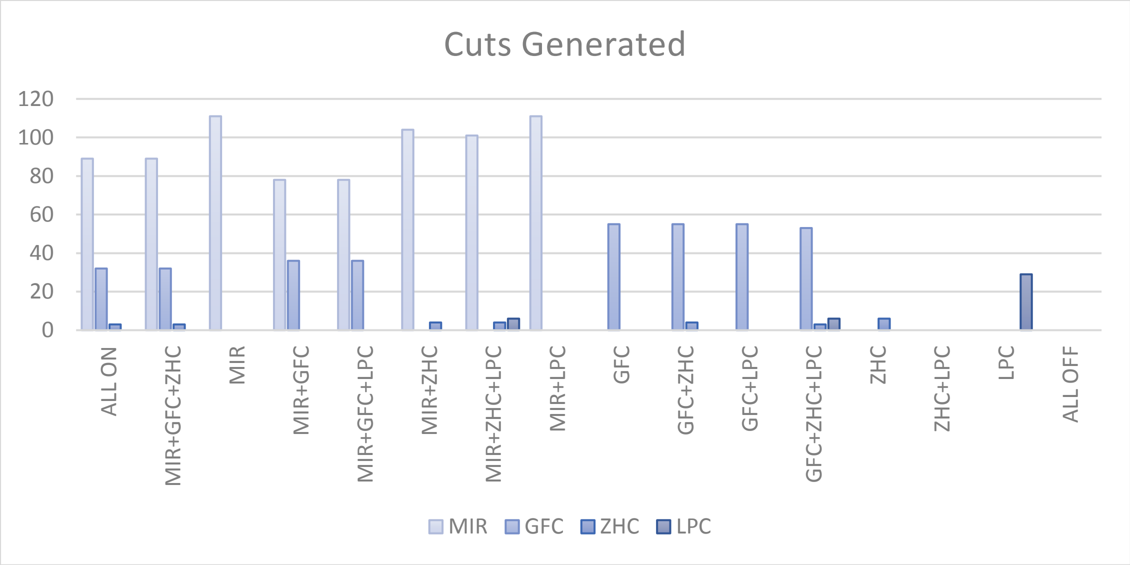


Figure 5.3. Number of cuts generated

| | Solution Statistics | | | | Cuts Generated | | | |
|---|---|---|---|---|---|---|---|---|
| | # of Nodes | # of Iterations | Optimality Gap | CPU Time | MIR | GFC | ZHC | LPC |
| ALL ON | 5930 | 45440 | 0 | 5,481 | 89 | 32 | 3 | 0 |
| MIR+GFC+ZHC | 5930 | 45440 | 0 | 5,484 | 89 | 32 | 3 | 0 |
| MIR | 6080 | 37237 | 0 | 5,487 | 111 | 0 | 0 | 0 |
| MIR+GFC | 10106 | 69071 | 0 | 5,589 | 78 | 36 | 0 | 0 |
| MIR+GFC+LPC | 10106 | 69071 | 0 | 5,607 | 78 | 36 | 0 | 0 |
| MIR+ZHC | 11807 | 64273 | 0 | 6,090 | 104 | 0 | 4 | 0 |
| MIR+ZHC+LPC | 11807 | 64273 | 0 | 6,12 | 101 | 0 | 4 | 6 |
| MIR+LPC | 6080 | 37237 | 0 | 5,484 | 111 | 0 | 0 | 0 |
| GFC | 2320583 | 12372553 | 0,003% | 1000+ | 0 | 55 | 0 | 0 |
| GFC+ZHC | 3478040 | 12899393 | 0,017% | 1000+ | 0 | 55 | 4 | 0 |
| GFC+LPC | 2861806 | 15451552 | 0,003% | 1000+ | 0 | 55 | 0 | 0 |
| GFC+ZHC+LPC | 2833843 | 13357127 | 0,014% | 1000+ | 0 | 53 | 3 | 6 |
| ZHC | 4841967 | 15409763 | 0,041% | 1000+ | 0 | 0 | 6 | 0 |
| ZHC+LPC | 4266702 | 14026879 | 0,040% | 1000+ | 0 | 0 | 0 | 0 |
| LPC | 4279693 | 12987710 | 0,026% | 1000+ | 0 | 0 | 0 | 29 |
| ALL OFF | 4266692 | 14026857 | 0,040% | 1000+ | 0 | 0 | 0 | 0 |

The results shows that MIR cuts are necessary to solve the given problem. None of the cases without MIR cuts could achieve global optimum within 1000 seconds. Integer rounding on the coefficients of integer variables and the right-hand side of a constraint have a critical impact on solution time.

Decreasing the problem size to single-period, the average improvement ratios on the solution times of the 24 different cases are given in the Table 5.3.

Table 5.3. Mean improvement in solution times

| | |
|---|---|
| **Mixed Integer Rounding Cuts** | 42,3x |
| **Gomory Fractional Cuts** | 3,84x |
| **Zero Half Cuts** | 1,29x |
| **Lift and Project Cuts** | 1,47x |

## 5.4 Optimization Results

The model is utilized with the historical data of 2015. The performed operations in 2015 are optimized and the potential decrease in total cost is illustrated in Figure 5.4. Tank car washing is not available in this scenario. An average of 2.1% decrease in the total cost is yielded.

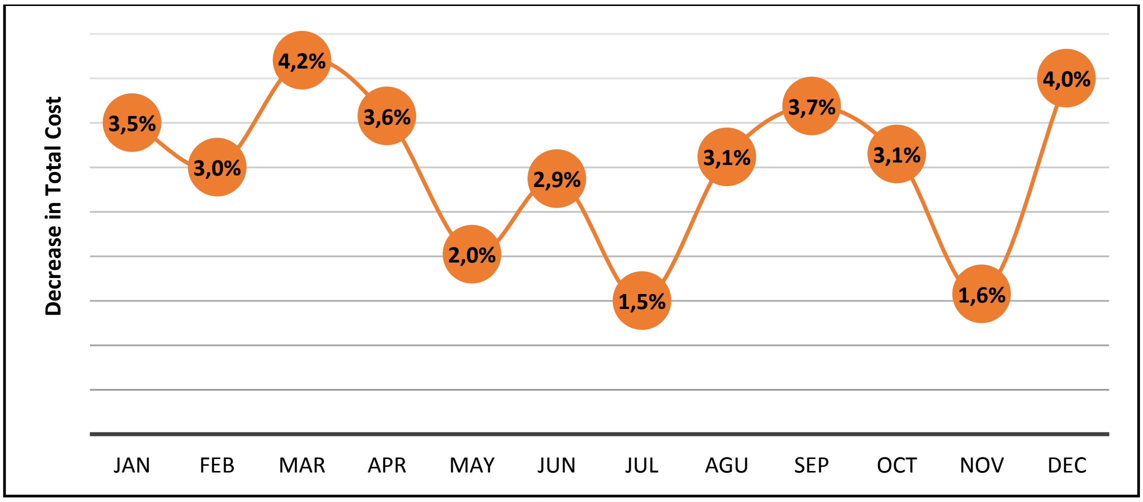


Figure 5.4. Optimization results of year 2015

The optimization model tends to select the lowest price transportation method, which is railroad. Then pipeline and road haulage comes respectively. However some constraints limit the products not to be transported by some transportation modes. Capacity restrictions also plays role in the decision. In addition railroad transportation and road haulage have some different modes in themselves. Although they have the same constraints their costs are different. TUPRAS wagons have lowest price, then comes RENT and TCDD. Their prices are not explained because of confidentiality. Same situation applies for the modes of road haulage. Figure 5.5 represents the optimum distribution of the products among the transportation modes. Figure 5.6 gives a comparison of performed and optimum operations.

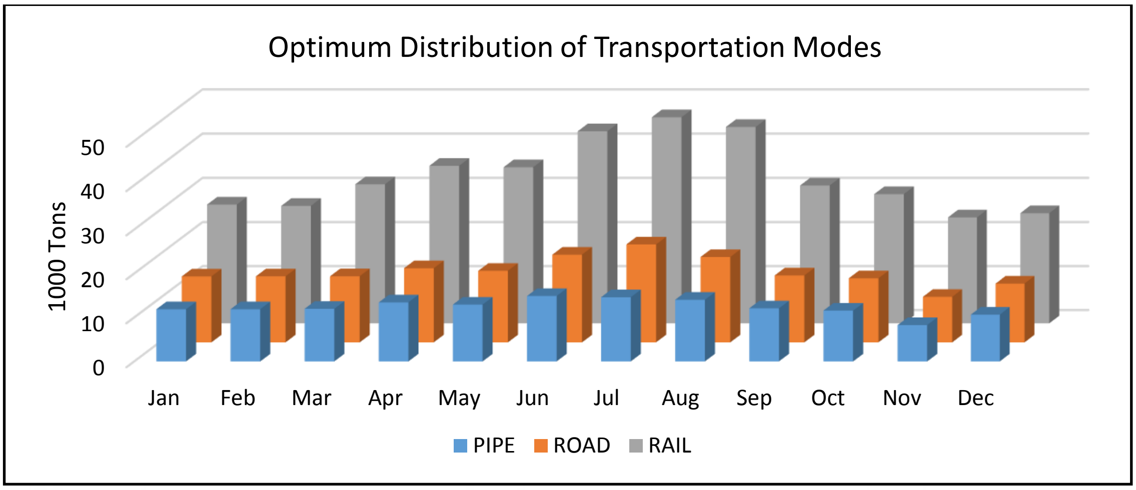


Figure 5.5. Optimum distribution of products among transportation modes

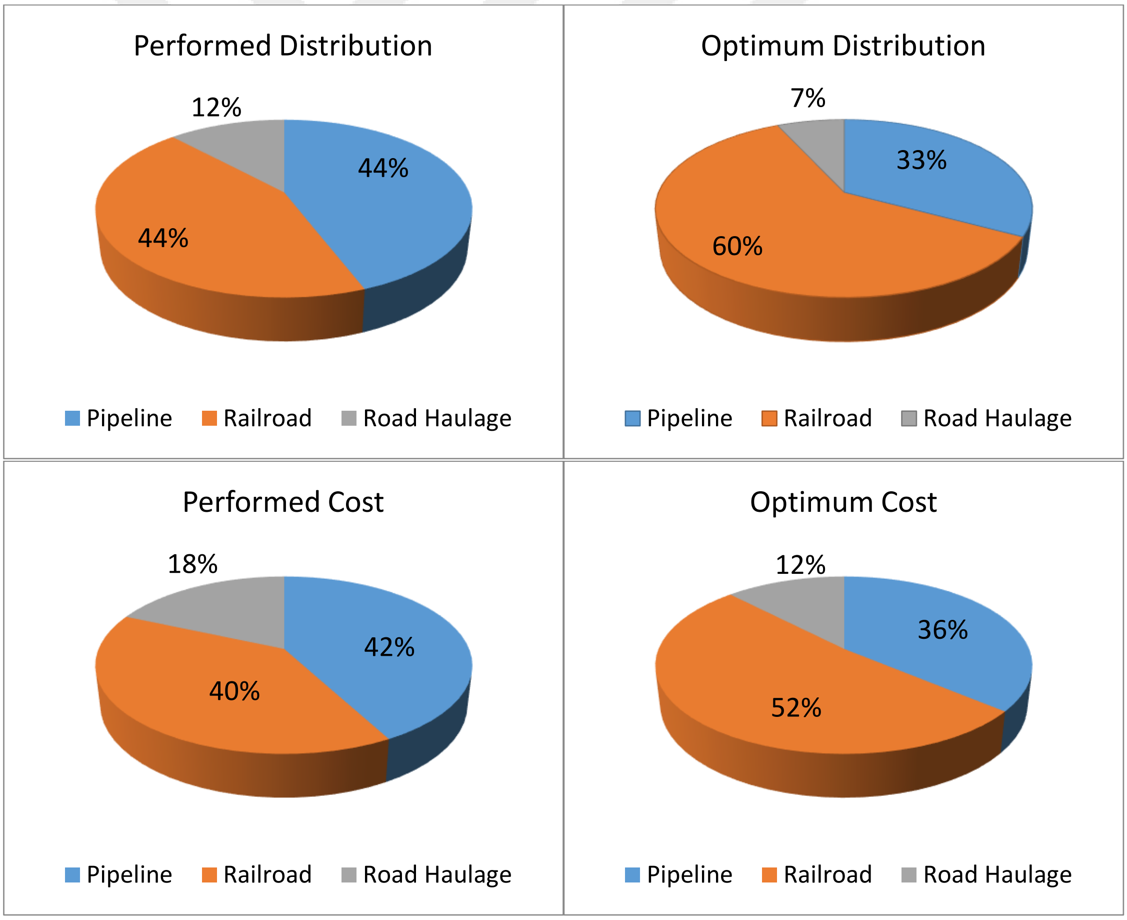


Figure 5.6. Performed vs. optimum operations comparison

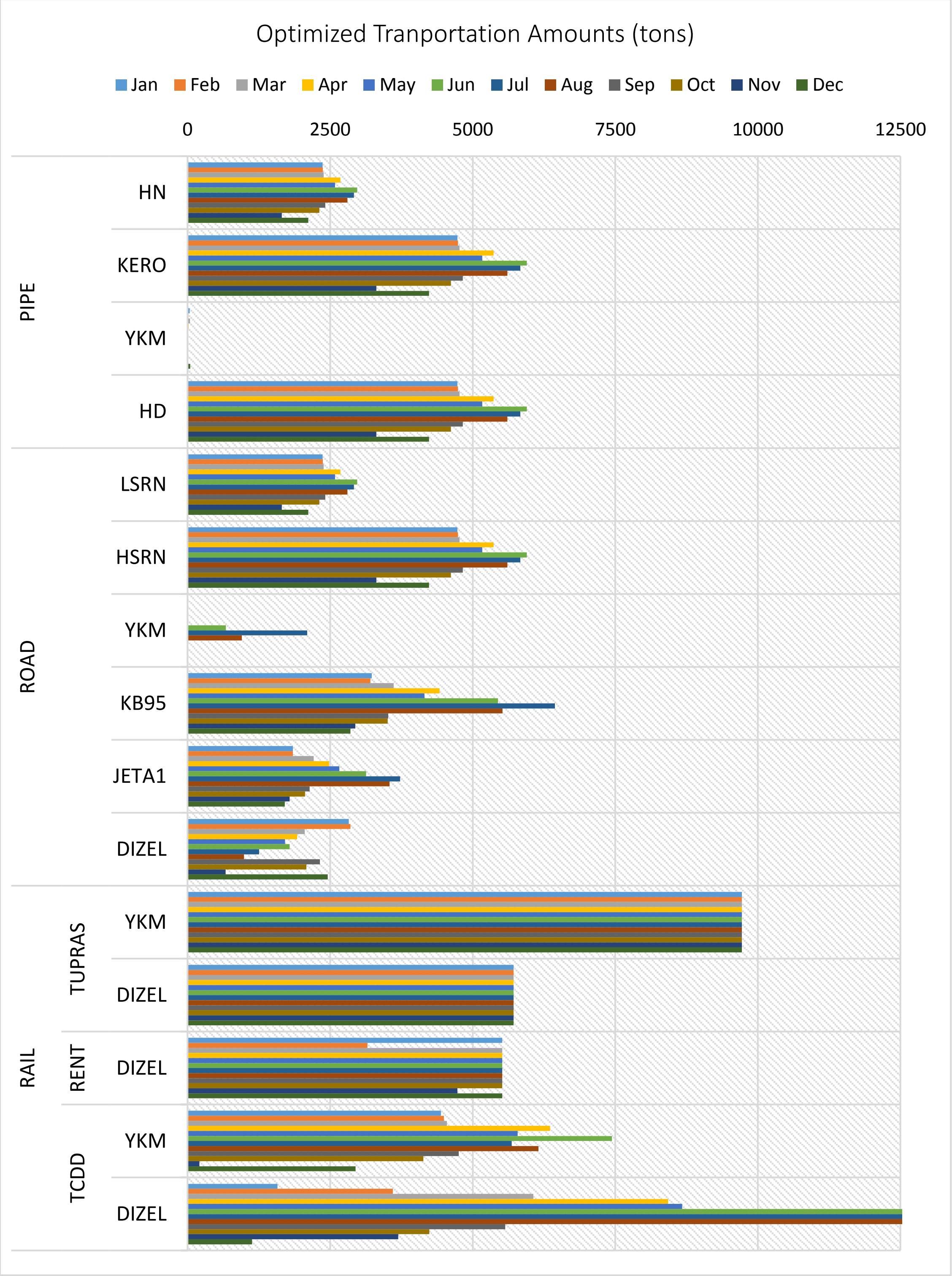


Figure 5.7. Optimized transportation amounts in detail

Railroad cars of owned by TUPRAS and rented are used at their maximum limits is clearly shown in Figure 5.7. The capacity limit of TCDD is not reached since it is a lot higher than the other two options. However TCCD is the most expensive option among others. The optimum number of railroad cars are given in Table 5.4. The necessary locomotives for the block train operations are given in Table 5.5.

Table 5.4. Optimum number of railroad cars

| | | | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TUPRAS | BLOCK | YKM | 188 | 188 | 188 | 188 | 188 | 188 | 188 | 188 | 188 | 188 | 188 | 188 |
| | | DIZEL | 116 | 116 | 116 | 116 | 116 | 116 | 116 | 116 | 116 | 116 | 116 | 116 |
| RENT | BLOCK | DIZEL | 112 | 64 | 112 | 112 | 112 | 112 | 112 | 112 | 112 | 64 | 64 | 64 |
| | SINGLE | DIZEL | 0 | 48 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 24 | 32 | 24 |
| TCDD | BLOCK | YKM | 86 | 0 | 0 | 0 | 108 | 0 | 108 | 108 | 0 | 0 | 0 | 0 |
| | | DIZEL | 66 | 0 | 324 | 324 | 0 | 324 | 0 | 0 | 324 | 0 | 0 | 0 |
| | SINGLE | YKM | 0 | 87 | 88 | 123 | 4 | 144 | 2 | 11 | 92 | 80 | 4 | 57 |
| | | DIZEL | 0 | 0 | 0 | 0 | 0 | 469 | 0 | 108 | 0 | 0 | 0 | 0 |

Table 5.5. Optimum number of locomotives

| | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DE18000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| DE22000 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| DE33000 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |

The optimum number of road trucks are given in Table 5.6. It is the single option for LSRN, HRSN and KB95 products.

Table 5.6. Optimum number of road trucks

| | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LSRN | KB95 | 100 | 100 | 100 | 100 | 100 | 100 | 90 | 93 | 100 | 100 | 77 | 99 |
| LSRN | JETA1 | 5 | 4 | 11 | 25 | 21 | 39 | 46 | 38 | 13 | 8 | 0 | 0 |
| LSRN | DIZEL | 6 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| HSRN | KB95 | 33 | 33 | 49 | 83 | 72 | 100 | 100 | 100 | 46 | 44 | 45 | 20 |
| HSRN | JETA1 | 67 | 68 | 76 | 72 | 83 | 84 | 100 | 100 | 71 | 73 | 70 | 67 |
| HSRN | DIZEL | 100 | 100 | 77 | 72 | 64 | 67 | 47 | 37 | 87 | 78 | 25 | 92 |
| YKM | KB95 | 0 | 0 | 0 | 0 | 0 | 24 | 75 | 34 | 0 | 0 | 0 | 0 |

## 5.5 Scenario Analyses

Three different scenarios throughout the year of 2015 are presented in this section. Total amount of transferred products vary monthly between 50,000 and 100,000 tons/month. Scenario 1 is the optimization of the current operation with extended working hours for loading and unloading operations. Scenario 2 is a case analysis of enabling of blending Heavy Straight Run Naphtha into pipeline products on top of Scenario 1. Scenario 3 is a case analysis of enabling railroad tank car washing on top of Scenario 2. Figure 5.8 represents the re-applied optimization on historical data of 2015. The variation between months is related with the total amount and the distribution of the products. Running the model with different scenarios in a sensitivity analysis approach for various possible transportation options, the yearly average reduction in the transportation costs are obtained as 3.7% for Scenario 1, 9.5% for Scenario 2 and 13.9% for Scenario 3. Furthermore, Figure 5.9 represents the optimal distribution of transportation costs among the modes.

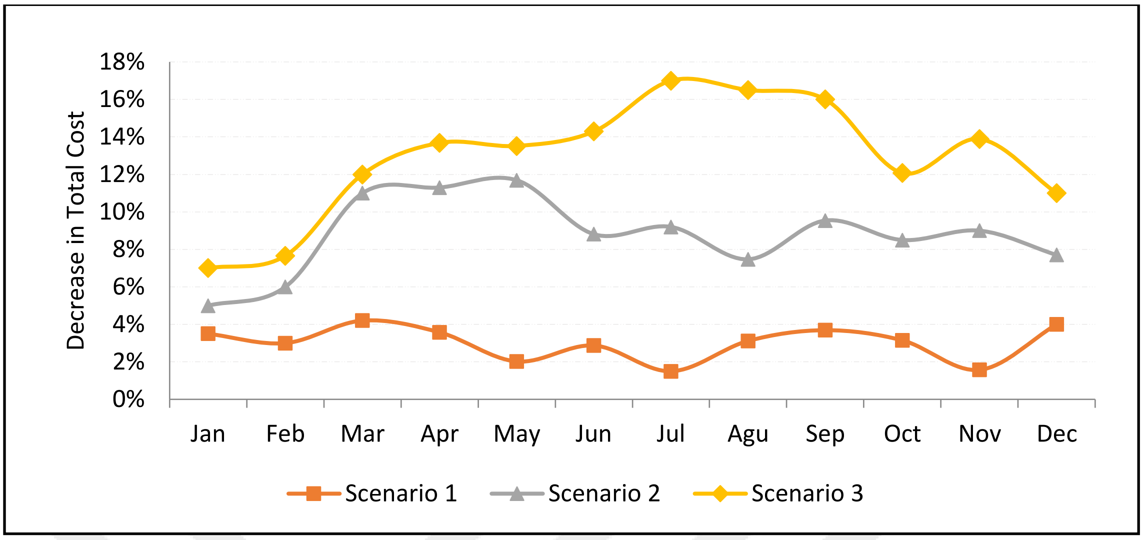


Figure 5.8. Monthly decrease in total transportation costs

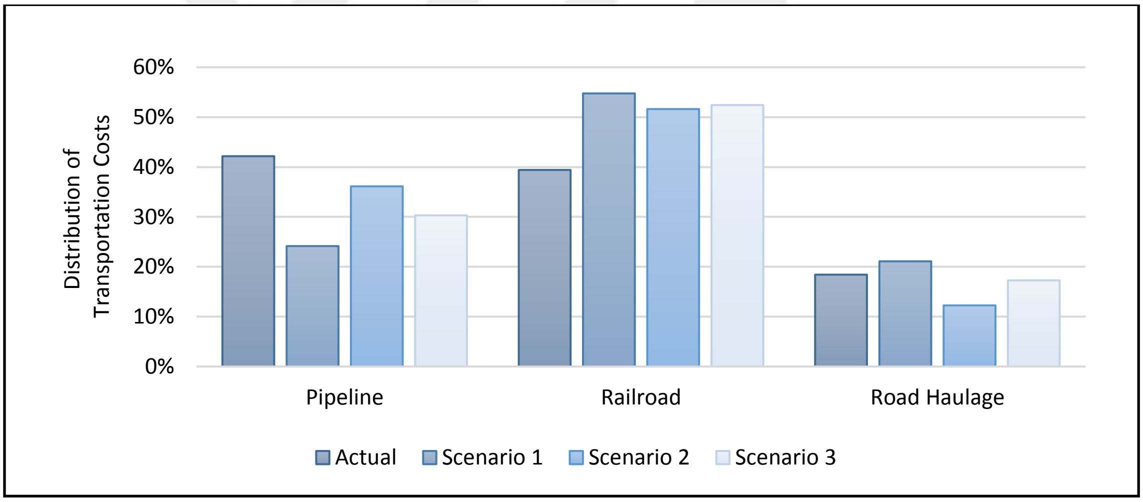


Figure 5.9. The distribution of transportation costs among modes

Some more scenarios analyses are given in Table 5.7 with explanations given in the table. It is possible to reach up to 22.9% savings with necessary investments and contract changes.

Table 5.7. More scenarios analyses

| **Scenario** | **#1** | **#2** | **#3** | **#4** | **#5** | **#6** | **#7** | **#8** | **#9** | **#10** |
|---|---|---|---|---|---|---|---|---|---|---|
| Max monthly tour in railroad | 4 | 5 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| HSRN in Pipeline | - | - | X | X | X | X | X | X | X | X |
| JETA1 in Railroad | - | - | - | - | X | - | - | - | X | X |
| Wagon washing | - | - | - | - | - | X | X | X | X | X |
| Washing cost (TL) | - | - | - | - | - | 500 | 250 | 100 | 250 | 250 |
| API Limit in Pipeline | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 42 |
| **BAT Savings** | 9,9% | 11,6% | 13,8% | 15,5% | 21,6% | 27,8% | 27,8% | 27,8% | 37,5% | 37,4% |
| **KRK Savings** | -3,2% | -1,4% | 3,9% | 5,7% | 5,9% | 12,2% | 12,5% | 12,5% | 8,6% | 17,2% |
| **Total Savings** | **2,1%** | **3,7%** | **7,8%** | **9,5%** | **12,1%** | **13,9%** | **16,2%** | **17,6%** | **17,7%** | **22,9%** |

# Chapter 6

## CONCLUSION

For multi-refinery operating companies, orchestrating the operations in different refineries is beneficial to improve the effectiveness of the entire enterprise while minimizing the operational costs in a very competitive environment. In this study, a multi-period transportation service design problem is addressed using a real world data set for hazardous liquid commodities between two nodes. It is a real industrial case of Turkish Petroleum Refineries Corp. Tactical level multi-commodity transportation planning model is developed and utilized to plan TUPRAS's inter-refinery transportation operations. The objective of the MILP model is minimizing the overall transportation cost. Developed deterministic model deals with optimal use of available infrastructure by selecting the transportation modes, assigning ordering capacities, and planning the routes and frequency of shipment for the semi-products and the final products of two geographically dispersed refineries under fluctuating demands.

The problem is modeled in GAMS environment and solved using CPLEX solver with branch & cut algorithm. Exact optimal solutions for different time horizons are achieved using branch and cut solution algorithm. Several cutting plane algorithms are tested on the MILP model and solution times are investigated with the usage of different cutting planes. Gomory fractional cuts, mixed integer rounding cuts, lift and project cuts and zero half cuts are evaluated for this problem in order to assess performance due to fewer examined nodes and the potential decrease in the rate at which the algorithm processes the nodes. The results shows that MIR cuts are necessary to solve the given problem. None of the multi-period annual planning cases without MIR cuts could achieve global optimum within 1000 seconds. Using mixed integer rounding cuts can increase the solution time by 42 times on average in single-period monthly planning cases.

The model is utilized with the historical data of 2015. Total cost occurred in the year 2015 is around 50MTL. With real and simulated data from two refineries, the cost advantage of transportation planning is determined. The performed operations in 2015 are optimized and 2.1% decrease in the total transportation is achieved with the current configuration. The optimization model tends to select the lowest price transportation method, which is railroad. Then pipeline and road haulage comes respectively. Sensitivity analysis considering network upgrade by investment on vehicle cleaning, flexible and extended working hours for loading/unloading and specific gravity of the products transported via the pipeline are also studied. The computational study on different scenario analyses shows that an effective planning can yield as much as 22.9% savings on total transportation costs with necessary investments and contract changes. Developed model currently is being used in Turkish Petroleum Refineries Corporation and utilized iteratively with the commercial multi-refinery production planning software. Future work can be studied on increasing the node size and integrating production planning which will convert the model into a MINLP.

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# VITA

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