Optimization of Downstream Oil Supply Chain with Respect to Transport Cost Using Monte Carlo Simulation to Evaluate Disruption Scenarios

By

Malik Asad Hayat Awan

(Registration No. 00000328996)

Thesis Supervisor: **Dr. Afshan Naseem**

Department of Engineering Management

College of Electrical and Mechanical Engineering (CEME)

National University of Sciences and Technology (NUST)

Islamabad, Pakistan.

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THESIS ACCEPTANCE CERTIFICATE

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Signature: Afshan Naseem

Name of Supervisor: Dr. Afshan Naseem

Dated: 28 Nov 2023

Signature: Yasir

Name of HOD: Dr. Yasir Ahmad

Dated: 28 Nov 2023

Signature: Rashid

Name of Dean: Dr. Nasir Rashid

Dated: 28 NOV 2023

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Dedication

"I would like to dedicate my research to my beloved parents."

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First of all, I am grateful to Allah Almighty for His countless blessings, knowledge, strength and good health that were necessary to complete this research and without His will nothing is possible.

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Malik Asad Hayat Awan

Abstract

This research explores the effects of random and anticipated disruptions on the transport costs associated with the volume flows between different stages of a downstream oil supply chain. How do the volume flows change when a refined oil supply chain's operations get disturbed due to disruptions of various nature? The purpose of the study was to develop a Multi Integer Linear Programming model that would simulate a multi-echelon, multi-modal, and multi-product refined oil supply chain. The researchers reviewed literature pertaining to the design of the supply chain to understand the disruptions that can create operational difficulties. Designing the model includes the refining and import facilities, storage depots and customer demand nodes while disruptions are used to influence the product flows between these entities. The study is divided into two parts, with a deterministic model and a Monte Carlo simulation. The deterministic model is used to achieve a baseline of the supply chain performance without any disruptions. Monte Carlo sampling is used to generate scenarios with disruptions in refined oil supply, increased demand, increase in transport costs, and interruption in pipeline services. The same model is used to simulate an optimized flow of products under all generated scenarios. The results showed an overall increase in the transport cost of the supply chain with drastic changes in flows between entities. There was an increase in the import of refined oil products to make up for the local production shortage, along with an increase in the use of bulk cargo modes to reduce costs wherever possible. Particularly road transport was more used to cover up the pipeline flows. The implication of this study is that random and anticipated disruptions in the supply chain greatly increase overall transport costs. More refined fuel has to be imported to fulfil the high demand and low local production. Other modes have to be utilized in areas where pipelines are not operational. The limitations of this study are that the supply chain is restricted to just one company and only considers the transport cost and disruptions in limited capacities are considered. Future research should examine the need for inventory management and alternate pipeline route development so that the robustness of a supply chain can be measured under disruption scenarios.

Keywords: Downstream Oil; Supply Chain Optimization; Multi Integer Linear Programming; Monte Carlo simulation

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List of Abbreviations

PMG	Premier Motor Gasoline
HSD	High-Speed Diesel
LPG	Liquefied petroleum gas
MILP	Multi Integer Linear Programming
WOP	White Oil Pipeline
OPEC	Organization of the Petroleum Exporting Countries
OCAC	Oil Companies Advisory Council
MT	Metric Tons
IPP	Independent Power Producer

CHAPTER 1: INTRODUCTION

1.1 Background

The oil industry dates back to thousands of years with ancient Greeks using natural asphalt in the construction of their towers and walls. Some of the streets of ancient Baghdad were also paved with tar, derived from crude oil that became accessible from natural oil fields in the region. The chemists of Persia and Arabia were able to distil crude oil to extract flammable compounds to be used in military weapons and kerosene lamps. The science of distillation spread across Europe during the Muslim conquest of Spain which led to the separation of crude oil into its many useful components that paved the way for the future industrial revolutions (Forbes, 1936).

The production of goods by hand dominated the global economy up to the middle of the eighteenth century. But in order to meet market needs, production levels had to be raised, which necessitated a switch from manual labour to steam-powered machines. This marked the start of a new era in world history known as the First Industrial Revolution, which occurred in Britain and mostly relied on coal as an energy source. Even though coal is still utilized today, mostly in China, it is no longer the primary source of energy as more energy-dense sources have been found. Thus, oil exploration started in the late nineteenth century, during the Second Industrial Revolution. Edwin Drake was successful at drilling the first modern oil well in Pennsylvania, and modern refinery plants were constructed to separate kerosene from a mix of crude oil, to be used as fuel for heating and lighting. At the start of the 20th century, the emergence of automotive industry necessitated the extraction of gasoline, which was initially an undesired by-product of crude oil.

With advances in extraction and refining fossil fuel techniques and demand in energy needs grew during the industrial revolution in Europe, refined fuel became a very sought after energy resource. Through the 19th century, United States of America was the leading oil producer in the world, and with the discovery of oil in the Middel East in the mid-20th century, countries like Saudia Arabia, Iraq and UAE also became net exporters of oil and gas (Etemad et al., 1998).

A lot of countries' economies became reliant on the export of oil and gas in the late 20th century. To protect their resources and interests which would benefit the wealth of the oil industry, these countries forced many companies to negotiate trade agreements with them to continue their operations of extracting crude oil. After WW II, a profit-sharing system at fifty-fifty was established, but soon after, nations that exported oil started nationalising businesses to gain more control over revenue. Several energy crises and panics occurred at the latter end of the century as a result of political conflicts upsetting the delicate equilibrium between oil supply and prices, globally (Sampson, 1975).

With an objective to coordinate and unify petroleum prices among petroleum exporting countries, and to ensure stable and fair prices for its members, the Organization of the Petroleum Exporting Countries (OPEC) was established in September 1960. Acting as an intergovernmental organization, the original members were Kuwait, Iran, Iraq, Saudi Arabia and Venezuela. Currently, the organization has grown to 13 countries (OPEC: Brief History).

Currently, the oil industry has one of the most advanced and complex supply chains of any industry globally. In 2022, the world consumed 52,969 TWh equivalent of oil for its energy needs (Energy Institue, 2022). It can be said that the most valuable commodity of the 21st century is oil. The modern petroleum sector can be described as a typical supply chain, having a complex network of supply facilities connected with manufacturing centres, to satisfy the end consumer. The POSC is integrated vertically, covering all segments from exploration and refining, all the way to distribution at fuel stations. The entire supply chain can be separated into three parts namely upstream, midstream and downstream.

All of the exploration activities and production of crude oil are included in the upstream sector. According to distance, type of product, and demand volumes, the midstream section comprises facilities and modes used to carry crude oil by road, pipeline, or rail to various refineries and storage facilities. Finally, the downstream sector consists of processes involved in refining, transportation to storage facilities, distribution and marketing of petroleum-based products. A visual representation of the entire supply chain is given in **Figure 1**.

The petroleum supply chain represented in **Figure 1** shows the different stages involved. The crude oil is extracted from deep wells located above oil deposits. The extraction is done on onshore and offshore oil rigs that pump out crude oil. This crude oil is separated from water and other gases dissolved in the oil and gets transported to storage facilities via pipelines, trains, roads and oil carriers for far-off refineries. The crude oil is later sent to refineries using multiple transport modes where it gets distilled into its constituent parts. Lighter fuels get processed to regulatory standards and stored in finished product storage facilities. The heavier components are sent off to other petrol chemical processors that further refine and convert them into useful products. Some of the liquid fuels such as furnace oil and kerosene are sent to power plants to operate furnaces and turbines to generate electricity. The high demand products such as Premier Motor Gasoline, High-Speed Diesel, Jet fuel and Liquified Petroleum Gas are sent to retail storage facilities where in turn they are sent to individual customer fuel stations, airports and industrial users.

The foremost objective of the entire supply chain is to deliver crude oil and refined products in a safe, economical and efficient manner to all stages which are involved. With ever-increasing demand for energy worldwide, the rising cost of freight, uncertainty in market prices and availability and geopolitical crises, the challenge for the petroleum industry is to develop comprehensive policies to ensure efficient supply chains that meet the varied global customer demands while simultaneously reducing costs for desirable profit margins.

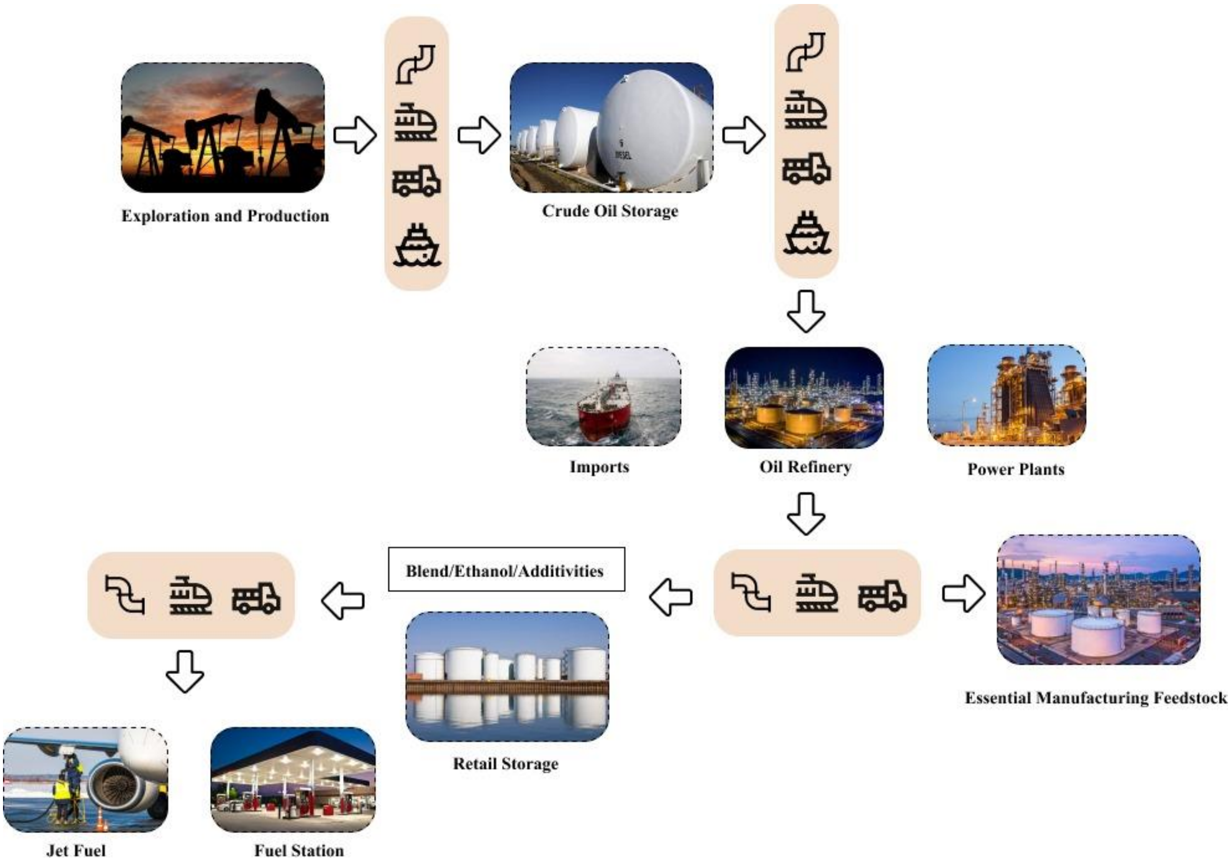

Figure 1. Downstream Oil Supply Chain Overview

1.2 The Downstream Section of Petroleum Supply Chain

Storage depots, wholesale markets, and retail markets are the main facilities. Storage facilities are owned by refineries and oil marketing companies, primarily used to keep inventory and transshipment points between distant markets. The wholesale segment is made up of power plants, petrochemicals, and large fuel consumers, whereas the retail segment is made up of small fuel users. Refined oil products are marketed in bulk to large consumers such as petrochemical companies, heavy industry manufacturers, independent power producers, and aviation industries. Consumer segments include in transportation, retailers such as stores, marketplaces, and gas stations.

The distribution of goods between downstream facilities is separated into two categories: primary distribution and secondary distribution. The primary is responsible for distributing oil products across refineries, petrochemical plants, and depots in the wholesale segment. It originates in the refineries and ends at transshipment points. The principal distribution modes are pipeline (pipelines), marine (ships), railroad (train wagons), and road (tank trucks). The secondary transportation starts in storage depots and moves oil products from domestic, international, and regional petrochemical plants and refineries to the end consumers in the retail sector or exports them abroad. Tank trucks and occasionally railway wagons are the transportation methods that are most frequently utilized in secondary distribution. Pipelines, however, are employed in specific circumstances, such as the delivery of jet fuel to air ports (Lima et al., 2016).

Although it demands a significant financial commitment, shipping oil products through pipelines is the most cost-effective and dependable way to move them across great distances. Pipelines can be used to transmit large quantities of distinctive refined products with little product contamination. Marine transportation is the most cost-effective option when it comes to moving big quantities of goods over the sea without the use of pipelines. Train wagons are the most reliable and cost-effective onshore transportation option. Trucks convey the oil derivatives, nevertheless, when these three modes of transportation are unavailable or the demand in the final destination does not call for vast quantities of the goods. Another characteristic regarding transportation modes is the product flow that is continuous only in pipelines and discrete in ships, wagons and trucks (Mirhassani, 2008).

Additionally, there are a few peculiarities in the downstream sector that can affect how complex the supply chain can be designed. First off, petroleum (and subsequently its products) is viewed as a commodity since it is fungible and carries a value. As a result, numerous buy-and-sell transactions can take place before petroleum is consumed. Oil products are non-discrete, meaning they cannot be identified individually and are not packed, which is another significant characteristic that also adds to their complexity. Other characteristics, though, also reduce complexity. First off, demand in particular markets is very steady; previous data can be used to predict future demand, and changes in customer preferences or product modernization have little impact on it. Moreover, there are fewer products to track in comparison to other industries and the mixture of products is static and stable (Lima et al., 2016).

1.3 Overview of the Petroleum Supply Chain in Pakistan

According to Trade Development Authority of Pakistan (2021), the demand for petroleum-based products in Pakistan was 19 million tons (MT) in 2021. The locally produced crude oil along with imported crude oil for domestic refineries satisfies almost half of the needs. The sectors that depend heavily on petroleum products are transportation (59%), electricity use (32%) and industry (8%). The problem with importing crude oil and refined products from other countries is the relative cost compared to local production. However, due low crude oil reserves and unfavorable balance of trade, Pakistan often buys petroleum products from oil rich countries that either have a relaxed government to government trade relations or offer a deferred payment scheme. Low production capacities of local refineries also contribute to this issue, with most operating at an average of 60% of total capacity.

In 2020, International Trade Center reported that petroleum-based oils and oils obtained from bituminous minerals, other than crude along with petroleum-based oils and oils obtained from bituminous minerals, crude; imported into Pakistan were worth $6.462 billion, accounting for 14% of the country's combined imports. Mineral fuels, mineral oils and products of their distillation; bituminous substances; mineral waxes; that were imported were around $10.13 billion, about 22% of Pakistan import bill. Pakistan mainly imported crude oil from the United Arab Emirates (56%) Saudi Arabia (34%), and Kuwait (4%). The report also suggested that it would be cheaper for Pakistan to buy refined petroleum products from KSA and Malaysia instead of UAE, while for crude oil, Indonesia and KSA are the best markets for countries like Pakistan as they offer lowest prices.

According to Pakistan Oil Report, (OCAC, 2021), the post COVID-19 demand of petroleum products was better than expected with 20.35 million MT of products consumed in 2020-2021 as compared to 17.6 million MT in 2019-2020. The major contributions were from increase in Motor Gasoline (+12%), HSD (+17.5%) and Furnace Oil (+37%), due to economic recovery resulting from good performance of the agriculture and industrial sectors. The bulk of these products (energy and non-energy) were sold in the province of Punjab (12.5 million MT), then Sindh (5.6 million MT) followed by KPK (1.9 million MT) and Baluchistan (0.4 million MT). Azad Kashmir (0.2 million MT) and Gilgit Baltistan (0.1 million MT) had very minimal sales. **Table 1** shows the distribution of petroleum products (energy) sales at a commercial level across the country.

Product wise the consumption of energy and non-energy products of 2020-2021 is given in **Figure 2**. As expected, 40% is MS, mostly used in all types of vehicles for transportation. HSD is relatively less at 37 %, which is used mostly for heavy load vehicles that are used for bulk cargo shipments, trains and buses, and the generation of electricity by diesel generators. FO (16%) is used by IPPs for power generation. JP-1 (2%) is sold to commercial airlines while JP-8 (0.8%) is used in military aircrafts. HOBC (1%) is used by high-end passenger cars but due to a higher price, it is not preferred by customers. Both Naphtha (1%) and Kerosene (0.3%) are used in various industries either for heating or as base for other petro-chemical products. Lubricants and other industrial fluids (2%) are accounted for in the non-energy category.

Table 1. Distribution of Petroleum Product Sales across Pakistan (OCAC, 2021).

Region	Sales (million MT)	Retail Outlets	Market Share %
Punjab	12.5	6047	60.3
Sindh	5.6	2040	26.9
KPK	1.9	956	9.3
Baluchistan	0.4	312	1.8
Azad Kashmir	0.2	159	1.1
Gilgit Baltistan	0.1	91	0.6
Country Total	20.7		

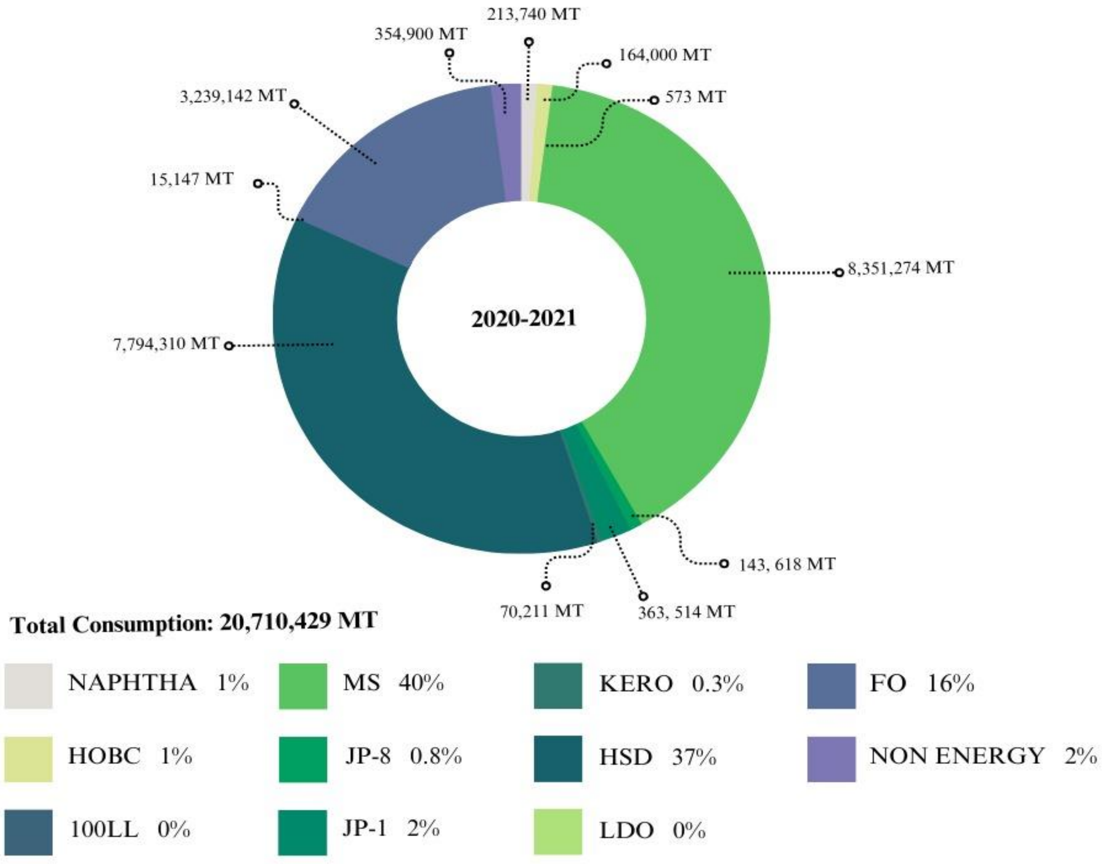

Figure 2. Refined Oil Product Consumption in Pakistan (OCAC, 2021).

In **Table 2**, it is shown that the downstream oil sector of Pakistan with the different companies operating and their market shares as of June, 2021. The majority of the market (45.7%) belongs to the state-owned enterprise of Pakistan State Oil Company Limited. The next four have very similar market shares with TPPL (9.4%), APL (9.4%), SPL (7.8%) and GO (7.4%). It is fair to say that the structure of downstream oil is very much cornered by one company which also has the highest sales percentage in the energy products. There are around 33 companies actively functioning as OMCs in the country. The industry holds a strategic importance in the country's economy by contributing around 9% to the national Gross Domestic Product (GDP). The sector's performance is influenced by demand patterns and pricing for petroleum products (POL). Recently, due to the decline in international oil prices brought on by COVID-19 and the decline in demand for POL products, the OMCs' performances have been negatively harmed. The cycle is reversing, though, since the lockdown limits have been released and oil prices on the global market have become more stable in performance, therefore anticipated to get better moving forward.

Table 2. Distribution of Market Share of Major OMCs (OCAC, 2021).

S. No	OMCs	Market Share (%) Sales Volume	No. of Retail Outlets	% of Retail Outlets
1	PSOCL	45.7	3,501	36
2	TPPL	9.4	820	9
3	APL	9.4	739	8
4	SPL	7.8	754	8
5	GO	7.4	812	8
6	BPPL (MKTG)	5.7	415	4
7	HPL	4.0	622	6
8	BE ENERGY	2.9	381	4
9	PARCO (PEARL)	1.7	-	-
10	PUMA	1.4	542	6

The refining capacity of the entire country is presented in **Table 3**. PARCO is the country's second largest refinery located in the centre of the country near Multan, with a refining capacity of 5.3 million tons per annum of crude oil. BPPL, located in Hub, Baluchistan, is the largest refinery with 7.2 million tons of processing capacity. ARL, in Rawalpindi, is the northern most refinery with 2.4 million tons of capacity. The other refineries are located in Karachi; NRL having 3.1, PRL with 2.1, and ENAR-I and ENAR-II with 0.1 and 0.2 million tons per annum respectively. The geographical locations of all refineries in Pakistan are given in **Figure 3**.

Table 3. Operating Output of Refineries in Pakistan (OCAC, 2021).

S. No	Name of Refinery	Location	Province	M. Tons / Annum	Barrels / Day
1	Pak-Arab Refinery Limited (PARCO)	Mehmood Kot	Punjab	5.3	120,000
2	Attock Refinery Limited (ARL)	Rawalpindi	Punjab	2.4	53,400
3	National Refinery Limited (NRL)	Karachi	Sindh	3.1	70,000
4	Pakistan Refinery Limited (PRL)	Karachi	Sindh	2.1	47,110
5	Enar Petroleum Refining Facility (ENAR-I)	Karachi	Sindh	0.1	2,500
6	Enar Petroleum Refining Facility (ENAR-II)	Karachi	Sindh	0.2	5,000
7	Byco Petroleum Pakistan Limited (BPPL)	HUB	Baluchistan	7.2	155,000
	Total Country Installed Oil Refining Capacity			20.4	453,010

Compared to the mentioned annual 20 million ton of refining capacity, currently actual capacity utilization is at around 11 million. The reason for the low production of refined products is the decreasing FO demand in the country because of the alternation in the sources of energy generation for the power sector. The refineries cannot produce HSD and PMG without FO and other low demand products. Therefore, as the FO demand diminishes, refiners have no choice but to reduce outputs so that they can keep operating at optimal levels.

Geographically, the distribution of refineries is not uniform across the country as the trend follows the population density. All are located in the industrial hubs instead of near oil fields. Since, three major refineries are located in the south of the country, they have to compete with each other for the local market. Furthermore, the import terminals are also located close to these refineries which makes it easier for them to import crude oil. The mid country refinery is connected by a crude oil pipeline that starts at the ports in Karachi. The north most refinery is mostly supplied by the crude oil fields located in the north west of the country.

Unfortunately, the south-western parts of Baluchistan are a hot spot for smuggling fuel due to the open border between Iran and Pakistan. Low quality fuel is filled into make shift containers and transported on pick-up trucks, which is a grave safety and health hazard for all those who are involved in this trade. Furthermore, since activity does not register on any government body, no tax revenue can be created resulting in further loss to the nation. Multiple instances have been reported of vehicles involved in the smuggling of fuel igniting and resulting in the death of dozens nearby but due to criminal negligence of the authorities, no concrete measures to counter this have been implemented. The region suffers from a lack of economic activity and therefore the local populous do not have a choice but to use cheap but low-grade smuggled fuel for their personal use. The local government is also unable to counter this flow into the country; sighting repercussions which may cause further trouble (Butt, 2023).

The refining sector currently faces a multitude of problems. In the last 40 years, only 2 refineries were set up; siting the huge investment cost for the investors. Another problem is the limited availability of domestic crude supplies which results in new investors to opt for establishing oil marketing companies instead of refineries. This saves the extensive capital and technical burdens that otherwise would have been unavoidable. The old refineries are also in a state of deterioration as the majority need significant upgradation to the process equipment. The government has shown a very inconsistent intent to solve this issue as no finite policy has been created that regulates the upgradation, production and incentivization of new refineries (Petroleum Division, 2023). Over all of this the day-by-day depreciating currency crisis also forbids any equipment to be imported in to the country.

Needless to say, that the importance of investment in the refining industry cannot be taken lightly. A modern refining industry would not only encourage the growth of the upstream and related industries, but it will also result in industrial development, which is essential for economic progress. The modernization also increases production, which boosts the local economy, and benefits all the stakeholders, including the final customer.

Figure 3. Geographical Location of Refineries in Pakistan (PACRA, 2022)

The pipeline structure of Pakistan is very limited. An 870-km pipeline was commissioned in 1981, to transport crude oil from terminal in Port Qasim near Karachi to the mid country refinery PARCO in Mehmoodkot near Multan. The pipeline is owned by PARCO. Another pipeline was also commissioned by PARCO in 1997. The 362 km Mehmoodkot-Faisalabad-Machhike (MFM) pipeline, is used to transport refined products like diesel and kerosene from the MCR to Faisalabad and Machhike near Lahore which are industrial centers in the north of the country.

In 2005, another strategic asset was developed and commissioned by PARCO for the transport of refined products from the terminals in Port Qasim and Kemari in Karachi to all the way up to the high population density areas of Punjab (PACRA, 2022). The 786 km, 26" White

Oil Pipeline (WOP), connects Port Qasim, Karachi to Mehmoodkot in South Punjab, with a capacity of up to 12 million tons per annum. It is estimated that WOP has reduced the movement of about 4,000 oil carrying trucks between Karachi and South Punjab (PAPCO). WOP is operated by a PAPCO, a subsidiary of PARCO (62%), PSO (12%) and SPL (26%).

Another 22 km multi-purpose pipeline was also commissioned in 2006, that connects Korangi-Port to Port Qasim. The purpose is to transport refined fuel from the refineries in Karachi to up country via the WOP. The physical representation of these pipelines is given in **Figure 4**.

Figure 4. Geographical Representation of White Oil Pipeline. (Tracker Map - Global Energy Monitor, 2022)

There are 3 major ports in Pakistan; all in the south of the country. Karachi Port Trust has 3 Oil Piers each with a capacity of 8 million tons. Port Qasim Authority has the Fauji Oil terminal with 9 million tons. Hub, Baluchistan has the third; BYCO SPM with 12 million tons.

The import of refined fuel for the period of 2020-2021, is given in **Table 4**. KPT is a less busy terminal considering that it has three oil piers and is located closer to the city. MS cargos were dominant at KPT. Considering the pipeline connection, it has with the WOP and a less busy port which allows larger oil tankers to berth for longer time, FOTCO received more fuel cargos.

Table 4. Terminal Capacities with respect to Products. Information taken from Pakistan Oil Report (OCAC, 2021)

PORT	MS (92 RON) Million tons per annum	HSD Million tons per annum
KPT	3,278,812	166,036
FOTCO	2,647,718	3,056,542
TOTAL	5,926,529	3,222,578

1.4 Supply Chain Disruption in the Petroleum Industry

Worldwide instability has resulted in disruptions becoming more and more unpredictable as well as more frequent in all kinds of industries. The POSC is extremely rigid as well as complex while also proving as a significant risk with a high impact on the economy of the nation. The complications lead to the formation of risk of various types that needs to be measured for when designing, developing and operating such a system (Amor et al., 2018).

Disruptions in supply chains can be explained as random events that leave a high impact on the individual functions and can potentially occur in any segment of the supply chain. The effected functions can stop partially or, depending on the severity, completely. Causes of disruption risk fall into two main segments: premediated disruptions are intentionally planned to disrupt the operations while random disruptions can occur arbitrarily at any point throughout the supply chain (Azad et al., 2013). Any kind of technical failures, emergencies, supply issues and natural disasters can be considered as random disruptions. The supply of crude oil to refineries was hindered at the start of the pandemic due to instability in the international market during COVID-19. This kind of random disruption could have been avoided by having multiple reliable sources of crude oil and better contract management. Premediated disruptions such as labour unions refusing to work, delays in maintenance jobs, and even payment issues with vendors can also bring the entire supply chain down.

Usually, businesses have designed their supply chains around common practices like just-in-time logistics, overseas production, efficient production schedules and low inventories. These work well to reduce the overall cost but become vulnerable to even disruptions in their supporting system. Modern petrochemical plants are very inter-connected and dependent on smooth operations of the entire industry. Demand issues from customers or supply issues from oil extraction companies, harm the norm refinery operations as production capacity has to be adjusted to make sure enough profitable products are produced. Therefore, it is of the utmost importance to design appropriate tactical and strategic plans that can mitigate the effects of supply chain issues.

During the COVID-19 pandemic, there was so much oil production that it was more that the already reduced demand, resulting the price of crude oil going below $0. Producers wanted to sell of their stocks as quickly as possible, sighting even less demand (Ajami, 2020). However, refineries were not buying more crude oil as they were not able to sell the refined products to OMCs. As individual customers were in lockdown and did not need fuel to power their vehicles and businesses, OMCs were unable to sell their stock. Hence creating an excess of inventory at all stages of the supply chain.

The opposite happened in 2022 as a result of the Ukraine-Russia war, as oil prices rose past the pre COVID-19 levels (Liadze et al., 2023). The reason was the sanctions put on Russia oil exports by western European countries, along with USA and its allies. The overall volume of crude oil available in the international market decreased dramatically but the demand was steadily growing as countries around the world went back to recover their economies. This resulted in sky rocketing of energy prices and inflation in all commodities.

According to a report by Maersk (2023), the Covid-19 effects and problems are still being observed globally, both indirectly and directly. World largest exporter by volume, China, keeps up its zero-COVID plan, cutting factory production and frequently delaying ocean freight with new lockdowns and strict controls. Congestion at sea ports is still creating issues in Northern Europe as a result, which result in ripple effects to affect global supply chain networks across industries. The war in Ukraine has severely impacted the global logistics, that has increased the pressure on an already over used and stressed systems, ultimately resulting in widespread disruption of services (Ngoc et al., 2022). The primary reasons are the sanctions by Western Europe along with closure of the sea route from the Black Sea into the Mediterranean, thereby restricting exports from Russia. It can be said that the most worthwhile illustration of this scenario is crop supplies.

1.5 Problem Statement

The importance of the oil industry is considered in the overall energy supply chain of the world. There is an urgent need to analyse risks and possible disruptions to the oil supply chains and develop mitigation strategies that have the interests of all stake holders. Governments, organizations and companies should focus on reforming the current practices to avoid having massive fluctuations in the prices of oil products. In this study, the focus would be on a company's country wide refined product distribution network which will include distribution centres, refineries, terminals, multimodal transport infrastructure and the end customer.

The downstream environment is characterized by the complex network of refineries, distribution centres, transport infrastructure and demands of different refined products. Designing a downstream petroleum network involves strategic as well as tactical considerations. The decisions of strategic nature may comprise of the location, capacity and network linkages of distribution centres while the tactical decisions include the quantity of flows between entities, inventory of products and choice of transport mode. To decrease the overall cost of the entire network, the company has to source the refined products from refineries and import terminals so that they can be cost effectively transported to storage facilities. The quantity transported must be according to the capacities of the facilities and should be enough to further satisfy the demand nodes. Therefore, it is vital to efficiently and effectively manage the flows in the entire supply chain.

This objective of this study is to propose a Multi Integer Linear Programming model that will minimize the entire supply chain transport cost based on the relevant logistics aspects in the company's downstream supply chain. The model considers two products i.e., High Speed Diesel and Premium Motor Gasoline, 3 modes of transport (pipeline, truck, train), 5 refineries, 2 import terminals, and 25 depots. The analysis would include the baseline cost and the variation in costs at different stages with change in scenario parameters. The focus is on only PMG and HSD, because they are most widely used and therefore contribute to the majority of the costs. Primary transportation is from the refineries and terminals to depots while secondary transportation is from the depots to the fuel stations.

Additionally, this study introduces new decision metrics to understand and quantify the POSC disruptions using the proposed model. The scope of this research is also to explore the effects on the POSC caused by random and anticipated disruptions which can be used as guidelines of how to tactically mediate the effects from disrupting the entire industry, as to fill the gaps in existing research. The disruptions would be focused on the supply and demand side of the supply chain which will create scenarios such as reduced refinery outputs, increased consumer demand, along with change in the transport cost of fuel from each entity and disruption in the main transport artery causing a shift towards other modes. The tactical decisions would be made as reactive mitigation strategies as they can only be observed once disruptions have occurred and accordingly appropriate strategies can be made to keep the supply chain functional.

1.6 Research Objectives

The main objective of this study is to design an optimization model for the downstream oil supply chain for a multi-echelon, multi-product along with multi-modal transport network design which will lead to an investigation for the significance of using multiple transport networks and wide spread storage facilities. The model would be able to calculate the minimum cost to fulfil the overall requirement of refined petroleum-based products in the country. Thus, later comparing the performance of the model with variations caused by disruptions along different stages of the network.

The secondary objective of this research is to observe the effects on the flows between entities in the POSC. The disruptions in supply and demand sides will result in the change of flows between entities and hence the overall supply network cost. These disruptions can be random or anticipated depending on the scenario situation. At each scenario the minimum cost would be calculated for the overall demand. The goal will be to analyse the effect on cost with the variation in parameters. Different disruptions would have separate impacts on the supply chain resulting in variation of the total network cost. This would also help create mitigation strategies for possible disruption scenarios.

1.7 Significance of the Study

This study contributes to the already established field of supply chain management in the downstream oil sector concerning strategic and operations management, logistics, disruption analyses and network design. The key take aways are:

- The designed model will examine the role of multiple modes of transport in a country wide supply chain that is reliant on import of oil products. Usually, studies consider oil rich countries with abundant reserves across the study area which means that they are less reliant on a robust transport network to fill their needs.
- The highlight of the designed model is to minimize the transportation cost instead of profit maximization which requires more data of operational costs and asset values over time. This study will contain a MILP model that will depict a country wide downstream oil supply chain from refining and importing to fuel stations. This will allow to obtain useful managerial information related to the optimization of logistical activities while understanding the relationship between refining, distribution and logistics.
- This study will also utilize Geographic Information System (GIS) software to track the actual distance between entities so that an accurate understanding of the real supply chain can be achieved. However, it will only be limited to the mode of transport limited by road as digital mapping of rail track and pipelines was not available.
- Usually, studies are more focused on the complete disruption of supply chains with consequences of entire shutdowns and industry standstill. A Monte Carlo simulation allows the use of scenarios to have variations in the parameter of the model supply chain. Thereby using sensitivity analyses to understand the effects disruptions can have, individually and simultaneously, on the overall system.
- Some researchers have included complete installation of new storage locations to cater to the changes in the supply chain. However, because of the absence of asset building data, this study only limits itself to utilizing the current available capacities of storage locations. Also there has been no change in their geographical locations considering that it depicts an actual supply chain, a better understanding can be made.

CHAPTER 2: LITERATURE REVIEW

The following chapter pertains to the literature review on the past work done on the field of downstream oil supply chain, their causes, effects, mitigations and techniques of analysis. The emphasis would be to capture the notable works done in each domain and understand the multi-disciplinary approaches that combine the research areas relevant to this study. The review of literature provides an analysis that describes the ongoing status of research and identify any areas of research which can be better understood by this study.

2.1 Background of Petroleum Supply Chain Issues

Supply chain management in the petroleum industry is filled with various problems and challenges, especially pertaining to logistics and inventory, which are not common in most other process industries. The challenges of logistics are the major source of network costs and have to be delt with in unique ways. Hussain et al. (2006) have shed some light on the challenges and opportunities in the petroleum industry and practices which are used by industry giants around the world.

Modern economy depends on the oil industry, joining global markets in complex supply chains. Because of the complex nature of the modern POSCs, the allied processes of decision making becomes very problematic. To improve the decision-making process, supporting tools are required. Lima et al. (2016) reviewed the utilization of mathematics-based programming techniques in case of distribution-oriented problems, particularly by the multiple entities involved in the downstream oil supply chain.

As the world has become more integrated, the need for effective and robust supply chain management techniques has become paramount. With increase in complexity, the number of variables involved and the difficulty to coordinate between them also increases. From process starting at extraction and going till customer deliver, multiple companies are involved in the complex supply chain. Sinha et al. (2011) implemented multi-agent technology to make the supply chain faster as compared to conventional supply chain practices.

The complexity in a PSC leads to the creation of various forms of risks that need to be understood when planning, designing and operating such an environment. Amor et al. (2018) present a detailed review on the risks associated with the oil and gas industry and provide an understanding to further develop risk management techniques. The study classifies key risks related to every segment of the PSOC. Afterwards, it collects an outline of the risk management modelling techniques. The results expressed that the type of risk is dependent on certain operations of the PSC and whether the country was an exporter or an importer. The methodologies of the risk management are classified in to qualitative, quantitative, and mixed models.

2.2 Case Studies of Petroleum Supply Chain Optimization

Fernandes et al. (2013) takes into account a DOSC network with common resource capacities, installations, demand requirements, and supply sources that includes several entities, echelons, multiple products, and multiple modes of transportation. The downstream PSC network is strategically designed and planned using a deterministic mixed integer linear program, which identifies the best depot sites, capacities, transportation modes, routes, and network effects for long-term planning. For petroleum enterprises at the supply, refining, distribution, and retail phases, the MILP maximizes multi-echelon total profits. A multi-entity PSC network, that was considered, included corporate financial involvement in refineries, shipping, storage depots and inventory. The MILP is evaluated using an actual Portuguese PSC network, which involved local crude oil processing refineries for production and a local hub for supply.

The demand of retail markets can be efficiently satisfied by planning a robust and cost-effective downstream oil supply chain. The distribution cost can be reduced, along with a drastic increase in efficiency by constructing pipelines to link manufacturing and storage facilities. Wang et al. (2019) created a MILP model that optimizes a DOSC by developing new pipeline routes. Focusing on the distribution of refined oil products between storage facilities and using real world data, the model obtained new routes for pipelines. A case of a DOSC in China was conducted with multiple situations analyzed. The method proved to be helpful for decision makers to conduct pipeline route and distribution plan optimization for other DOSCs.

A thorough analysis of the efforts put forth in optimising natural gas transmission lines was given by Mercado et al. (2015). Over the past few years, there has undoubtedly been a significant amount of research on numerous decision-making issues in the natural gas industry, and particularly on pipeline network optimization. A state-of-the-art survey in their research focused on a few key categories, such as short-term basis storage (line-packing challenges), gas quality satisfaction (pooling concerns), and compressor station modelling (fuel cost minimization problems). Addressing both steady-state and transient optimization models, emphasising the modelling features and current best practises for solution methods.

2.3 Uncertainties in the POSC

Uncertainty in the energy supply chains have resulted in huge disruptions in the global oil industry, with many companies facing extreme challenges to supply to their customer while also aiming for decent profit margins. One of strategies to overcome uncertainty is to strategically and tactically plan DOSC with subject to various uncertainty sources. Lima et al. (2021) formulated a mixed-integer linear programming model (MILP) in which uncertainty was accounted for, by using chance constrained programming with fuzzy parameters. It was aimed to determine the design of network and the distribution plan of products in a low-cost manner. The model was validated through a real case study of the Brazilian oil industry. The network was designed by determining the strategic locations to hold warehouses, while their capacities are established by installing specific tanks for each product.

Al-Othman et al. (2008), developed a planning model for a multi-stochastic petroleum organizations' supply chain network and implemented it under uncertain market scenarios for an oil producing country. The model involved activities from crude oil production, refining, as well as distribution. Uncertainties were in the form of demand and price of oil products. It was concluded that, for an oil producing country, the economic uncertainties cannot be able to severely disrupt the supply chain if a tactical balance can be reached between crude exports and processing capacities.

Scheduling refinery maintenance to prevent unexpected shutdowns is one of the issues faced by the petroleum sector. Refineries, hubs, depots, and customers make up the four tiers of the petroleum industry's multi-echelon supply chain network according to Khosrojerdi et al. (2012). The multi-period, linear model takes location/allocation, transportation, and refinery maintenance schedule considerations into account and addresses both strategic and tactical concerns. This model's goals were to simultaneously raise profits and service standards. The trade-off relationship between the two aims is demonstrated by numerical findings. It also demonstrated how the optimum objective value and solution can be significantly impacted by the uncertainty in parameters like the quantity of refineries that are accessible, price, and demand.

2.4 Disruptions Faced by POSCs

Jabbarzadeh et al. (2012) investigated a supply chain design issue with the potential for facility disruptions. The facilities are always susceptible to various forms of disruptions brought on by calamities, intentional defections, and equipment failures. They formulated the issue as a mixed-integer nonlinear program that seeks to maximize the overall system profit. The number and location of facilities, the subset of customers to service, the assignment of customers to facilities, and the cycle-order amounts at facilities are all determined simultaneously by the model. Using numerical experiments, the efficiency of the suggested solution approaches is demonstrated. The computational outcomes also show that there can be substantial advantages to addressing disruptions in the supply chain design model.

Climate change has intensified and increased the frequency of extreme weather events which has resulted in uncertainties in the demand, production, and inventory in supply chains. Ni et al. (2022) proposed a systematic methodology to evaluate the flexibility of supply chains and applied it to demand side management of a DOSC. Several scenarios of disruption in refinery operations, pipeline shutdowns, and increase in demand were generated. A Monte Carlo simulation was utilized to analyze multiple scenarios. The increase in inventory at storage facilities can result in improvement of supply chain resilience by 2.67% to 14.83%.

The fluctuating demand and prices of oil products forced companies to redesign their existing distribution networks and production strategies to improve overall network flexibility and reduce cost. A stochastic mixed integer linear problem is presented for the PSC design. The objective was to design the network under demand uncertainty that maximizes expected net present value (ENPV) of a multi-entity multi-product PSC network. The decisions variables involve depot capacities, transport modes, locations of storage facilities and inventory (Fernandes et al., 2015).

2.5 Strategic and Tactical Planning in POSCs

Zhao et al. (2014) examined China's energy security from a supply chain viewpoint as the nation struggles with issues such a fast-growing economy, an increasing reliance on imported oil, the Malacca conundrum, and unstable global oil prices. To better understand the topic of oil security, they first examine China's oil industry's development stage and earlier studies about its energy security. The current risk is then determined from three perspectives: energy flow, financial, and environmental, using a methodology developed from a supply chain perspective. Finally, strategies for enhancing the nation's energy security are considered, and potential issues are laid out. They concluded that there is an inherent interconnectedness to the danger that could result from China's oil system. There is still great potential for the country to improve oil security by strengthening its strategic oil reserves, improving energy efficiency, and developing its domestic oil tanker fleet.

For optimum long-term scheduling and planning of a refined oil products supply chain, a three successive stage (echelon) model was developed by Alfares (2023). The stages are divided in to refineries and import terminals, distribution centers, and demand markets. Only two types of products: gasoline and diesel are shipped through three different types of transport modes. The strategic element involves the placement and construction of refineries and distribution centers while the tactical element involves the flow of products between entities.

The creation of a strategic planning model for an integrated oil chain is suggested by Ribas et al. (2010), taking into account these sources of uncertainty: refined product demand, crude oil output, and market prices. Three formulations are suggested to deal with these uncertainties: (1) A robust min-max regret model, (2) a bi-stage stochastic model with a limited number of realizations, and (3) a min-max model. These models were applied to the Brazilian oil chain, which consists of 3 major petrochemical facilities, 17 refineries, 16 groups of crude oils, 50 intermediate products, 10 final products, 13 terminals, and a logistic network made up of 278 transportation arcs for pipeline, water, rail, and road modes. The analysis's 10-year time frame. The findings reveal large income disparities between the three formulations, depending on the agent's risk profile.

Pipelines play an important role in the oil supply chains around the world. A deterministic MILP model was proposed by Kazemi et al. (2015), that determined the optimal distribution center locations, capacities, transfer volumes and transportation modes. The model minimized the multi echelon, multi-product cost along the refineries, depots, transport modes and fuel station (demand nodes). Furthermore, the study also proposed another stochastic MILP model with recourse of random disruptions and anticipated disruptions. The model proposed proactive mitigation strategies in the form of varied transfer volumes and for reactive mitigation strategies it employed multimodal transportation strategies. The model was implemented on US downstream oil supply chain and optimized the strategic and tactical costs for stochastic and deterministic contexts. Future work on considering multiple scenarios of disruptions were recommended for PSC.

A highly competitive market forces businesses to structure their operations to maximize their financial results. In a distribution network that includes refineries, ports and few pipeline systems that can transfer oil from the former to the latter, the study by Más et al, (2003) handles short-term crude oil scheduling issues. First, a MILP model is suggested that takes into account a combined depiction of the pipeline and intermediate storage facilities. The assignment of tank lorries to oil piers, as well as vehicle filling and pipeline freight procedures, are decision factors. The answer of this model delivers the preliminary conditions for MILP models that signify the pipeline and intermediate storage infrastructure at a comprehensive level.

Multi-product pipelines often distribute multiple goods to designated delivery points in batches. To improve the detailed scheduling of a multi-product pipeline with many pump stations. Liao et al. (2018) created a continuous-time mixed-integer linear programming (MILP) model based on flowrate database. For the economy and safety of developed scheduling plans, various unit pump cost and flowrate limits that heavily rely on pump operating schemes are provided in the suggested model. Additionally, this research takes into account the actual field processing restrictions, which change with batch interface migration and were hardly ever taken into account in earlier work. And to improve the effectiveness of solving, a brand-new technique for historical flowrate database preparation is described. Finally, through comparing with three real-world cases solved by another two available models, the proposed one performs the best in scheduling optimization as well as substantial reduction of pump cost.

A key component of such models are the transportation operations. Bastidas et al., (2013) produced a thorough analysis of the supply chain models' freight transportation function, and various transportation-related features were noted. Regarding transportation modelling, they discovered one paradigm, two trends, and an outlier. The key anomaly-related finding relates to the lack of correlation between the models' consideration of the transportation cost function and the modelling of transportation operations. Additionally, certain issues about trade-off analysis, private or outsourced fleet considerations, and the significance of time and distance in analysis of transportation costs were also mentioned. For supply chain analysts whose decisions are based on modelling and computer-aided tools, these challenges are anticipated to be important.

Several studies present the operational and tactical planning of downstream PSC. By taking into account demand, supply costs, and selling prices, Escudero et al. (1999) created a two-stage model for supply and distribution scheduling of a multi operator multi product petroleum supply chain. A broad framework for simulating petroleum supply chains is the main goal of Neiro et al. (2004). Then, specific frameworks are suggested for pipelines and storage tanks. The chain's nodes are viewed as a collection of elementary elements connected by intermediary streams. The nodes that represent the pipeline networks, refineries, and terminals are then connected to create the complicated topology. Stream flow rates, attributes, operational factors, inventory, and facility assignment are decision variables. A large-scale MINLP is the multiperiod model that results. Results from the suggested model's application to a real-world firm demonstrate model performance by examining several scenarios.

2.6 Programming Models

The prevalence of using numerical optimization or mathematical programming techniques to build and operate petroleum fields, allocate lift gas and rate, and construct, plan, and manage reservoirs was examined by Khor et al. (2017). Heuristics and linear programming were both used in early applications. It has been possible to create increasingly complicated and insightful models, such as nonlinear programming and mixed-integer linear and nonlinear programs, due to ongoing improvements in computing speed and methods. Numerous formulations and approach to solving problems have been employed, such as continuous and discrete optimization, stochastic programming to deal with uncertainty, and metaheuristics like genetic algorithms to improve solution quality while minimizing computational load.

Sangaiah et al. (2020) discusses a solid mixed-integer linear programming model for planning Liquified Natural Gas sales over a specified time horizon to reduce vendor costs. Since the manufacturer supply parameter is viewed as interval-based uncertain in the real world, it has an uncertain nature. Additionally, a brand-new metaheuristic method called the cuckoo optimization algorithm (COA) is created to effectively handle the issue. To present the research's concluding remarks and management insights, the comparative findings of the deterministic and robust models are examined, and sensitivity analyses are run on the key parameters. To determine the ideal robustness level, a comparison evaluation between the overall vendor profit and the robustness cost is completed.

In distribution systems, networks with centralized hub and far demand nodes are utilized to efficiently replace and move goods between demand nodes. By choosing p hubs from a list of potential hub sites and assigning supply and demand nodes to the hubs, the p-hub center allocation issue seeks to reduce the maximum trip time in networks. The hubs' capabilities are listed. A novel hybrid solution to the p-hub center problem is presented by Bashiri et al. (2013), in which the hub facilities' location is simultaneously dictated by both factors. Fuzzy systems are employed as the foundation of this work since they are used to handle qualitative and ambiguous data. The paper models a hybrid hub solution using fuzzy VIKOR.

Minimizing the expenses of the entire supply chain network is the objective of many supply chain optimization problems. The green supply chain network has, however, been seriously taken into consideration as a solution to this worry to limit its effects on nature, as environmental protection is one of the primary priorities. This article discusses the modelling and development of a green supply chain network for the movement of petroleum products to lower annual costs while taking environmental effects into account. Samadi et al. (2022) takes into account two factors: cost and environmental impact. Oil centers in the facility model have a finite capacity, and there are a variety of transportation alternatives available at various price points for each level of the chain. To solve the problem, they have used two multi-objective particle swarm optimization algorithms and genetic multi-objective optimization algorithm with non-dominant sorting II with a priority-based decoding to encode the chromosome. Finally, they have used TOPSIS method to compare these two algorithms.

Energy security is a crucial challenge for the modern world. The petroleum-based product supply chain is extremely uncertain due to its inherent intricacy coupled with regional and global political dilemmas. The Sri Lankan petroleum supply chain was considered to analyze risk factors and disruptions. An expert opinion survey was conducted coupled with a probability impact analysis to asses risk factors. The findings highlighted that a lack of infrastructure facilities is the main hurdle that stops the country from ensuring energy security. Due to its ever-increasing demand, Gasoline was identified as the most vulnerable refined product. Therefore, a forecasting model was developed utilizing ARIMA to determine future demand of the product. The results illustrate that in the next two years, additional shipments would be required on a monthly basis (Fernando et al., 2021).

2.7 Research gap

The research gap involves finding the effects of multiple disruptions occurring simultaneously and individually on a supply chain. Multiple factors are involved in the mechanisms of an operating supply chain. Therefore, it is necessary to understand the impacts of these factors on both micro and macro levels. Focusing in the reliable design of refined oil product supply chains, that are essential to industry performance, a MILP model coupled with a Monte Carlo sampling of parameters like demand uncertainty, oil products and hub disruptions were generated. A real-world case is used to understand the accuracy, efficiency and applicability of the proposed model. The results would provide an understanding on the effects of uncertainty on the supply chain. The total cost involving the uncertainties is relatively higher than without uncertainties. Uncertainties are also responsible for the change in final construction scheme of the supply chain. However, design changes under uncertainties can improve the reliability of the supply chain without much increase in the overall transport cost.

CHAPTER 3: RESEARCH METHODOLOGY

This chapter of the thesis comprises of the methodology implemented to form the optimization model for the downstream oil supply chain. Section 3.1 focuses on the deterministic model that gives the base line of the operations of the supply chain. Section 3.2 will explain the Monte Carlo simulation to generate scenarios for variations in the parameters. Section **Error! Reference source not found.** explains the parameter setup for the deterministic model which will be validated in Section 3.3. In Section 3.5, supply chain parameter samples are generated. The objective to develop the model is to create a supply chain that resembles a working refined petroleum products supply chain, to understand the operations of a multimodal and multi-product network configuration and performance measure under variable circumstances. The deterministic model would be a particular case of the designed supply chain network, where the parameters used are of the average values of the collected data. This deterministic modal would give us a baseline to understand how the flows between entities and inventories at storage facilities. The MILP is used to find the minimized cost of the network while satisfying the complete demand. Road transportation networks are measured by using the geographical coordinates of the storage facilities and refineries by using GIS to get accurate transport costs via road. The geographical map of all storage facilities is given in **Figure 5**.

Figure 5. Geographical Distribution of Storage Facilities. Locations based on PSO's storage facilities (Pakistan State Oil Company Limited, 2022)

Another model is also created which will consider disruptions in the supply chain based on demand and supply issues. The model would optimize the flows between entities accordingly to the variations in the parameters. The disruptions can be classified in the random and predetermined categories. Based on the results, mitigation strategies can be offered to reduce problems that might hinder the functioning of the entire supply chain.

3.1 Deterministic Supply Chain Model

In the designed MILP model, it is assumed that there is a set *R* of refineries *r* with supply capacities of S_r, a set *D* of distribution centers (depots) *d* with product wise capacities denoted by U_d and a set FS of demand nodes *fs* (fuel stations) with demands of products *p*. The mode of transport is a set T with three modes *t*, namely road, rail and pipe. The complete notation for the deterministic model is provided in **Table 5**.

Table 5. Notations and Parameters used in the Model

Indices	**Description**
R	Index of refineries; r ε R
D	Index of depots; d ε D
I	Index of ports; i ε I
Fs	Index of fuel stations; fs ε FS
T	Index of transport modes; t ε T
P	Index of products; p ε P
Parameters	
$D_{fs,p}$	Daily demand of fuel stations for product p
$C_{r,d,p,t}$	Cost of transport per unit from refinery r to depot d for product p via transport mode t
$C_{i,d,p,t}$	Cost of transport per unit from port i to depot d for product p via transport mode t
$C_{d1,d2,p,t}$	Cost of transshipment per unit from depot d_1 to depot d_2 for product p via

	transport mode t; $d_1 \neq d_2$
$C_{d,fs,p,t}$	Cost of transport per unit from depot d to fuel station fs for product p via transport mode r
$S_{r,p}$	Daily supply capacity of refinery r for product p
$S_{i,p}$	Daily supply capacity of port i for product p
$U_{d,p}$	Storage capacity of depot d for product p
Decision Variables	
$V_{r,d,p,t}$	Volume of product p transported from refinery r to depot d via transport mode t
$V_{i,d,p,t}$	Volume of product p transported from port i to depot d via transport mode t
$V_{d1,d2,p,t}$	Volume of product p transported from depot d_1 to depot d_2 via transport mode t; $d_1 \neq d_2$
$V_{d,fs,p,t}$	Volume of product p transported from depot d to fuel station fs via transport mode t

The supply chain design model includes the location of fuel storage facilities, refineries, and fuel stations along with their capacities. It also includes three modes of transport, flow of products form refineries to depots, transshipment of product between depots and transport of products from depots to fuel stations. The model can choose from multiple modes of transportation to move products provided if a certain mode is available. The following decisions need to be optimized considering the constraints of each entity in the supply chain:

1) Volume of products transported from refinery to depots
2) Volume of products transported from ports to depots
3) Volume of products transshipped between depots
4) Volume of products transported from depots to fuel stations

The mathematical formulation of the deterministic model is presented below.

OBJECTIVE FUNCTION:

Minimize

$$\sum_{r\varepsilon R}\sum_{d\varepsilon D}\sum_{p\varepsilon P}\sum_{t\varepsilon T} V_{r,d,p,t}\,.\,C_{r,d,p,t} + \sum_{i\varepsilon I}\sum_{d\varepsilon D}\sum_{p\varepsilon P}\sum_{t\varepsilon T} V_{i,d,p,t}\,.\,C_{i,d,p,t}$$
$$+\sum_{d1\varepsilon D}\sum_{d2\varepsilon D}\sum_{p\varepsilon P}\sum_{t\varepsilon T} V_{d1,d2,p,t}\,.\,C_{d1,d2,p,t}$$
$$+\sum_{fs\varepsilon FS}\sum_{d\varepsilon D}\sum_{p\varepsilon P}\sum_{t\varepsilon T} V_{r,d,p,t}\,.\,C_{r,d,p,t}$$

Equation 1 Objective function for DOSC Model

CONSTRAINTS:

$$\sum_{d\varepsilon D}\sum_{fs\varepsilon FS}\sum_{p\varepsilon P}\sum_{t\varepsilon T} V_{d,fs,p,t} = D_{fs,p}$$

Equation 2 Demand of fuel at Customer Nodes satisfied by Distribution Centers

$$\sum_{r\varepsilon R}\sum_{d\varepsilon D}\sum_{p\varepsilon P}\sum_{t\varepsilon T} V_{r,d,p,t} \leq S_{r,p}$$

Equation 3 Limits Refineries' supplies to Depots up to production limit

$$\sum_{r\varepsilon R}\sum_{d\varepsilon D}\sum_{p\varepsilon P}\sum_{t\varepsilon T} V_{r,d,p,t} + \sum_{i\varepsilon I}\sum_{d\varepsilon D}\sum_{p\varepsilon P}\sum_{t\varepsilon T} V_{i,d,p,t}$$
$$+\sum_{d1\varepsilon D}\sum_{d2\varepsilon D}\sum_{p\varepsilon P}\sum_{t\varepsilon T} V_{d1,d2,p,t} \leq U_{d,p}$$

Equation 4 Inflow of products, from refineries, ports and other depots, do not exceed the storage capacity of products at each storage facility.

$$\sum_{r\varepsilon R}\sum_{d\varepsilon D}\sum_{p\varepsilon P}\sum_{t\varepsilon T} V_{r,d,p,t} + \sum_{i\varepsilon I}\sum_{d\varepsilon D}\sum_{p\varepsilon P}\sum_{t\varepsilon T} V_{i,d,p,t}$$
$$+\sum_{d1\varepsilon D}\sum_{d2\varepsilon D}\sum_{p\varepsilon P}\sum_{t\varepsilon T} V_{d1,d2,p,t}$$
$$= \sum_{d\varepsilon D}\sum_{fs\varepsilon FS}\sum_{p\varepsilon P}\sum_{t\varepsilon T} V_{d,fs,p,t}$$

Equation 5 Conservation of material at the storage facilities

$$V_{r,d,p,t}, V_{d1,d2,p,t}, V_{d,fs,p,t} \geq 0$$

Equation 6 Non-negativity restriction on the decision variables

The objective function (**Equation 1**) minimizes the overall transport cost of the downstream oil supply chain from the refineries to the depots and from the depots to the fuel stations. The first term represents the combined cost of transport of products from refineries to depots, second term represents the cost of transport of products from ports to depots while the third term is the transshipment cost between depots. Last term accounts for the cost to transport products from depots to fuel stations.

Constraint (**Equation 2**) ensures that the demand of fuel at each fuel station is satisfied by the distribution centers. Constraint (**Equation 3**) limits the supply from the refineries to depot up to the refinery production limit. Constraint (**Equation 4**) ensures that the inflow of products, from refineries, ports and other depots, do not exceed the storage capacity of products at each storage facility. Constraint (**Equation 5**) is the conservation of material at the storage facilities, so that the flow of products to fuel station is not more than the flow of products into the depots. Constraints (**Equation 6**) is the non-negativity restriction on the decision variables.

The deterministic model is the base for the Monte Carlo simulations. In the Monte Carlo simulation, the parameters of transport cost per unit for every mode is changed, along with the supply of products from refineries and the demand of products at fuel stations. The network structure would stay the same in the Monte Carlo simulations as it is in the Deterministic case. The capacities of depots and distance between all entities will remain the same in both cases.

3.2 Monte Carlo Simulation based on the Deterministic Model

Monte Carlo simulation is a method to perform sensitivity analysis, which is to study how a model would respond to inputs generated randomly. The process usually involves random generation of inputs referred to as scenarios. Then a simulation is carried out for each of those scenarios on a computerized model. The outputs of these scenarios are assessed and aggregated. Statistical analysis of these results gives the mean value, distribution of outputs and the maximum and minimum the model can work reliably (Mathworks).

According to the probability distribution of variations in the parameter values which include fuel station demands, refinery supplies and cost of transport between entities, different scenarios have to be generated according to Monte Carlo sampling. All of the uncertain optimization model would become a deterministic optimization problem as a separate scenario.

The designed model in this research is programmed in Python 3.11 and PuLP 2.7 is used as the primary solver. PuLP is an open-source Python library used for Linear Programming written in the Python computer language (Python Foundation). The mathematical model is solved to optimality using algorithms such as the Reversed Simplex Method or Interior Point Methods but some large-scale models take too long to be solved to optimality using these techniques. For the random generation of scenarios, NumPy (Numerical Python) is used. It is a universal standard working with numerical data in Python.

To further understand the effects of uncertainties on the designed model, the general cases for which the scenarios are generated are as followed:

Disruption 1: High demand and low refinery outputs. The demand of refined petroleum products would be higher than the base model, however due to low crude oil availability; the refineries would not be able to provide products at previous levels.

Disruption 2: Low demand and constant refinery output. The demand of refined petroleum products would be lower than the base model, however due to prescheduled crude shipments; the refineries can operate as per their normal routine.

Disruption 3: The cost-of-living crisis has increased the transport cost of fuel per unit. There will be a change in volume of flows between entities across all modes.

Disruption 4: The pipeline network which serves as the backbone for the refined oil movement between the south and the north of the country, is damaged and would need repair. The bulk of the oil transport would shift to the other two modes.

The Monte Carlo simulation would use all of these cases simultaneous, to generate the flows of products from entities. The analysis would include the comparison of simultaneous changes to multiple parameters of a supply chain.

3.3 Data Collection

For assessing the efficiency of the designed model, a realistic case study of the downstream petroleum supply chain of company is chosen. The population divide of the country is such that the majority of the demand for transportation purposes is in the north east of the country in the province of Punjab. The second most fuel is sold in Sindh, with Karachi as the country's largest industrial hub. Khyber Pakhtun Khwa and Baluchistan have relatively low demand of fuel due to less industrialization and scattered population. However, since the majority of the refineries and import terminals are located in the south of the country, the fuel has to be transported northwards to satisfy the demand.

For the initial deterministic model, the parameters are set to the daily refined fuel sales across the country for a company, along with the average refinery outputs per day for the demand and supply. The network of pipelines and train tracks are taken from government studies while the road network is taken by GIS.

For the deterministic model, the number of fuel stations are 3,500 which represents about 36% of the entire fuel stations currently operational in the country. The fuel stations are not divided by province as there are instances of inter provincial transport of refined fuel products. There are 5 refineries spread across the country, with of them providing both products in their capacities. 25 storage facilities are available, with individual capacities for products, divided as per their actual distribution. In this model, there are no disruptions and capacity limits on any of the transport modes as because a working model is to be verified with all constraints.

The MILP model would determine the minimized cost of transporting refined fuel product according to the demand of fuel stations. The key decision variables would be the flow of product between entities via each transport mode. Modeling for random disruptions includes changing the parameters involves the use of scenario generation based on the case vise criteria. The values of supplies from refineries, demand from fuel stations and cost per unit of transport is changed according to a standard deviation.

Disruption 1: There is decrease in the supply of products from refineries thus creating an imbalance in the supply chain. The imports would be expected to rise and flow between the refineries and depots would be reduced.

Disruption 2: There is change in the demand from fuel stations; it has drastically increased from the fuel station demand as per the deterministic model. It would be assumed that overall flow from ports would increase.

Disruption 3: There is change in the per unit cost of transport for the refined fuel products; an increase due to rising cost of fuel. The expectation would be that the flow of products between entities via cheaper bulk transportation modes would increase.

Disruption 4: The main pipeline that was the cheapest form of transport between the refineries in the south and the markets in the north as per the deterministic model. If the pipeline is disrupted, the road and train load would drastically increase. All these scenarios can be divided into either random or predetermined categories as per

Table 6.

Table 6. Categorization of Disruptions in Monte Carlo Simulation

DISRUPTION	TYPE
Disruption 1	Anticipated
Disruption 2	Anticipated
Disruption 3	Anticipated
Disruption 4	Random

A supply chain disruption occurs when the flow of products, information, and capital between stages gets interrupted. The reason behind these interruptions can include natural disasters, political unrest, or even just a problem with one actor in the supply chain. There can be major impacts on businesses and consumers when a disruption occurs in the supply chain. Businesses are forced to find new suppliers or even change their production processes, while consumers have to go without certain products or get charged more to purchase them.

Disruptions in supply chains can have serious impacts on the economy as a whole. Some can cause inflationary pressures and lead to shortages of essential goods. In extreme cases, they can even create economic recessions. In modern economies supply chain disruptions are becoming frequent and more severe. Multiple factors are contributing to the trend; mostly due to increasing globalization, along with modern manufacturing practices, and increasing complexity of supply chains.

According to Lee et al. (2015) most supply chain disruption can be categorized into two segments: random and anticipated. Random disruptions have a high impact but carry a low probability of occurrence. The causes can be natural, political, or related to the system capacity. Scenarios such as natural disasters, war, and capacity costs can be considered as random disruptions. Anticipated disruptions have low impact nut high probability of occurrence. The causes can be due to internal operations or with the flow of information. Forecast inaccuracies, inventory tradeoff, quality as well as system breakdowns or maintenance shut downs can be considered as anticipated disruptions.

3.4 Validation of the Deterministic Model

This model had 179,600 variables and 7,110 constraints which were solved to an optimal solution in 2.36 seconds which took 7,793 iterations to reach an overall network cost of 1,067,342,436 PKR. As expected, the bulk of refinery flows of High-Speed Diesel (HSD) and Premier Motor Gasoline (PMG) to depots are by pipelines and to make the supply towards the north of the country more cost effective, only those depots are provided with the pipeline fuel supply which already have a further connection to another depot by a pipeline. Since there is an only those depots are provided with the pipeline fuel supply which already have a further connection to another depot by a pipeline. However, to mitigate the low supply of PMG, the depots that are connected with a pipeline with the terminals are provided with a significant volume. The least used mode of transport from refinery to depots is by road. For the mid country refinery, rail transport was used to for both HSD and PMG to transport fuel in the central region as not all depots are connected by pipelines and road transport becomes expensive. For HSD, there is very little transshipment between depots by train and road as the fuel station demand gets fulfilled by road directly from depots. However, some HSD volume does get transported via pipelines. As the demand for PMG is higher, relatively more volumes are transshipped by road and pipelines but no volumes by train.

The overall transportation structure is given in **Table *7***, showing that the majority of movement of fuel was done through road, which is for the final stage of the supply chain i.e., shipments to fuel stations. Pipelines were the second most used transport mode, to allow for efficient and cost-effective movement to up country. Due to the limited railway network in the country, only a fraction of movement is done through rail carriages.

Table 7. Volume (L) of Fuel moved by Transport Mode in Deterministic Model

	ROAD	RAIL	PIPE
HSD	12,278,723	2,539,538	10,717,654
PMG	17,408,147	3,055,137	13,846,280

The volume of refined products flows from refineries are given in **Table 8**. As expected, the refineries are supplying PMG more than HSD due to the fact it is used more in the transport industry, while majority of the HSD is used to generate electricity. The refineries in the north of the country are providing the most supplies as they are the closest to the storage facilities that replenish demand nodes. All three refineries in the south mostly cater to the energy and transport needs in the south of the country while also shipping their products towards the north. Individually, refineries use road the least to transport product in terms of volume. However, where ever there are rail tracks available, the refineries prefer to use the train wagons as well as pipelines. All refineries are preferring to use pipeline mode of transportation as it is the cheapest and the safest mode to transport fuel to storage facilities.

Table 8. Volume (L) of Refined Products from Refineries

REFINERIES	DEPOTS					
	ROAD		RAIL		PIPE	
	HSD	PMG	HSD	PMG	HSD	PMG
1	12,588	184,596	-	-	1,818,167	2,200,041
2	121,439	184,510	1,269,769	1,460,323	1,975,554	1,829,176
3	36,194	176,767	-	-	2,027,968	817,845
4	54,204	185,121	-	888,038	1,004,720	566,933
5	102,427	249,986	-	-	1,760,221	1,303,562
TOTAL	326,852	980,980	1,269,769	2,348,360	8,586,630	6,717,556

The output of ports is given in the **Table 9**. Due to the high use of PMG in the country, both ports import more PMG than HSD, with Port 1 not importing any HSD at all. Due to the white oil pipeline connected with the storage facilities nearest to these ports, it is ideal that these ports also fulfil the upcountry demands as well.

Table 9. Volume (L) of Refined Fuel Imported

PORTS	DEPOTS	
	PIPE	
	HSD	PMG
1	-	1,705,883
2	1,004,719	1,303,561

It can be seen from **Table 10** that the company's supplies of HSD and PMG are around 16% and 31% fulfilled by imported fuel while about 86% and 69% is filled by local refineries respectively.

Table 10. Accumulative Volume (L) of Fuel Supplies.

	HSD	PMG
PORTS	1,567,362	4,565,184
REFINERIES	9,868,986	10,046,896
	11,436,349	14,612,081

In

Table 11, the next stage of the supply chain is considered, transshipment of fuel between depots. Majority of the transshipment is done by pipelines, with PMG being more in demand. Due to lack of a working railway network between storage facilities, no fuel is moved by train wagons. However, some facilities are in the peripheries with no pipeline or train tracks; they are being supplied by roads.

At the final stage of this supply chain, all movement is done through fuel carriages by road. The volume is equivalent to the daily demand of fuel stations across the country. PMG is in higher volume due to it higher use in the transport sector, while HSD is mostly used by the heavy vehicles and constructions equipment. This is illustrated in **Table 12**.

Table 11. Transshipment Volume (L) of Fuels.

TRANSSHIPMENT BETWEEN DEPOTS					
ROAD		RAIL		PIPE	
HSD	PMG	HSD	PMG	HSD	PMG
8,498	75,626	-	-	1,126,305	4,119,280

Table 12. Fuel Station Demand Volume (L).

SHIPMENT TO FUEL STATIONS	
ROAD	
HSD	PMG
11,509,257	16,410,111

3.5 Parameter Generation for Disruption Scenarios

Monte Carlo simulations are applied to create case wise scenarios based on the deterministic model. The simulation uses statistical means with different standard deviations to generate varying parameters for the model to operate on. The parameters are generated separately but the final simulation would include all of the cases so that it can be similar to a real scenario.

DISRUPTION 1: Decrease in the supply of products from refineries thus creating an imbalance in the supply chain.

Table 13 shows the reduced production capacity of refineries on **disruption 1**. There is an overall reduction in production capacity by all refineries for HSD at 42% and for PMG at 40%. The disruption can be due to difficulty in sourcing the crude oil, reduced operations due lack ullage for the less in demand products, or price dispute between the refineries and regulators. Based on these values, multiple cases are generated for reduced refinery production capacity. The average is taken for multiple reduced capacity scenarios. The generated scenarios for Disruption 1 are given in **Figure 6**.

Table 13. Refinery Output Volumes (L) after Disruption 1.

Refineries	Scenarios				Deterministic	
	HSD		PMG		HSD	PMG
	AVG	Std	AVG	Std		
1	955,244	597,118	1,246,122	630,283	1,868,187	2,200,041
2	1,213,197	467,807	566,828	271,532	1,985,095	888,038
3	1,364,766	549,358	764,555	352,437	2,411,213	1,303,562
4	3,744,852	1,522,525	2,457,160	987,646	6,456,869	3,996,275
5	1,419,043	689,117	500,497	216,569	2,358,112	817,845

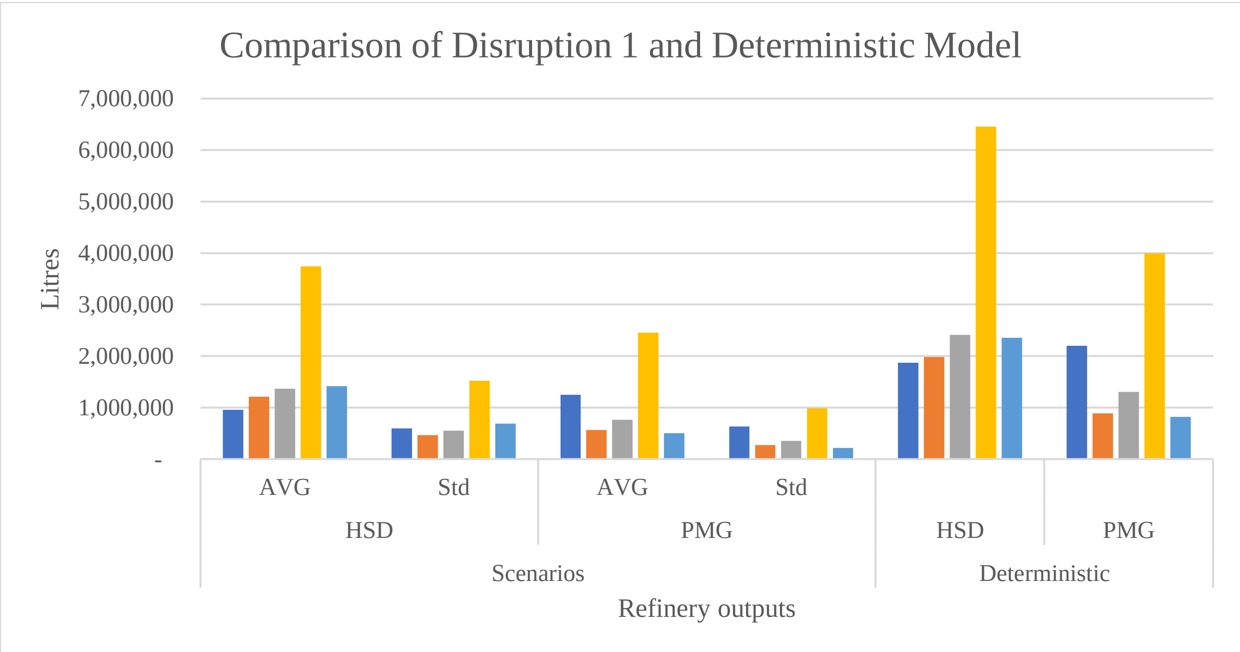

Figure 6. Scenario-wise Refinery Volume (L) Outputs

DISRUPTION 2: Demand from fuel stations; it has drastically increased from the fuel station demand as per the deterministic model.

With the economies slowly recovering from the COVID-19 pandemic, many countries have exponentially increased their need for refined petroleum products. This is due to increase in transport, energy requirements, and industrial complexes ramping up their production of products that require petroleum-based products as their raw material. The increase is given in **Table 14**. The increase in overall demand for HSD is 22% while for PMG is 32%.

Table 14. Product-wise Demand Volume (L) after Disruption 2

Scenario Average		Deterministic	
HSD	**PMG**	**HSD**	**PMG**
14,118,338	21,770,312	11,509,257	16,410,111

DISRUPTION 3: Per unit cost of transport for the refined fuel products; an increase due to rising cost of fuel.

The rise in demand of refined fuel along with the inadequate supplies from refineries has caused a shortage, which in turn has resulted in the rise in per unit cost. Transporting fuel from one point to another also requires a lot of energy. The vehicles that carry fuel between entities, pumps which push fuel inside pipelines, and train engines that pull oil wagons, all require fuel to operate. The high buying cost of fuel leads to rise is transport costs that gets divided per unit of product transported. This is very crucial as all stages require energy for the movement of oil products. The cost comparison between the deterministic model and the Monte Carlo simulation is given in **Table 15**. The highest change to transport per unit of fuel was seen in movement through pipes, followed by movement by road and least in movement through rail. The reason for the lowest change in rail was because the sample in which the scenarios were generated was very small.

Table 15. Per unit Transport Cost (PKR) by modes after Disruption 3.

PKR per Liter					
ROAD		RAIL		PIPE	
Scenario Average	Deterministic Model	Scenario Average	Deterministic Model	Scenario Average	Deterministic Model
0.582	0.500	0.330	0.300	0.301	0.100
0.16		0.10		2.01	

DISRUPTION 4: The main pipeline that was the cheapest form of transport between the refineries in the south and the markets in the north as per the deterministic model. If the pipeline is disrupted, the road and train load would drastically increase.

Pipelines are the backbone of the downstream oil supply chain as the imported refined oil products are directly pumped from the terminals to the storage facilities in the middle of the country. Any disruption in the operations of the WOP would be catastrophic to the entire supply network as the refineries would have to produce as much fuel as possible and the road and railway network would have to take the load over from the pipeline.

The Monte Carlo simulation would be used to analyze the flow of refined product volumes between entities across the supply chain network for all of these scenarios. Since the optimal solution gets varied by changes in the supply parameters, this simulation aims to incorporate multiple scenarios of all those cases and find an optimal solution. The multi-scenario model would incorporate the uncertainty caused by external and internal factors. The comparison with the deterministic model be used to further develop the supply chain parameters like capacity of depots, transport mode constraints and location of depots. The total number of scenarios generated are 50 for each disruption and the same constraints are applied that were in the deterministic model.

CHAPTER 4: RESULTS AND DISCUSSIONS

This chapter describes the acquired numerical results for the deterministic model and the disruption wise scenarios based generated by a Monte Carlo Simulation. Section 4.1 explains the impact of multiple disruptions, while Section 4.2 explains the impact of individual disruptions on the total network cost. Sections 4.3 compares the results of both simulations. In Section 4.4, the discussion is summarized. The comparison would be of the flow of products between entities and the overall cost of the supply chain network in the deterministic model and the case wise scenarios. Furthermore, the results generated would also give insights of the performance of the supply chain when disruptions cause variations in the supply chain parameters. Possible mitigation strategies can be suggested to minimize the effects of disruption on the functions of the supply chain. All of the models are coded in Python and PuLP solver is used to reach model optimality while minimizing the overall transport cost.

4.1 Impact of Simultaneous Disruptions on the Total Network Cost

The purpose of Monte Carlo simulation is to examine the differences resulted in the model solutions due to incorporation of single and multiple scenarios of disruptions. The analysis is done by considering the effects of disruptions individually as well as simultaneously. The Monte Carlo sampling generates 50 variations in the parameters of refinery supplies, customer demands, transportation costs and pipeline disruptions. The results for the multiple simulations are aggregated and the average values of decision variables are calculated. The results of the sensitivity analysis can be useful for future petroleum supply chain designs so that better decisions, in terms of infrastructure expansion and capacity building, can be made. The overall aim is to reduce the cost of logistical operations of the downstream oil of a company. The combined number of variables in the 50 scenarios Monte Carlo simulation are 8,980,000 along with 355,000 constraints. The simulation took 1685 seconds to be solved on an Intel(R) Core (TM) i7-8550U CPU @ 1.80GHz with 16 GB RAM on Visual Studio Code.

Analyzing the results from the simulation provide an insight to the flows between entities and the routes taken to minimize the overall logistics cost. As Pakistan is a net importer of oil-based products, mostly for the transport and energy sectors, the results show a heavy dependence on imports. The difference in volumes taken from refineries and ports can be observed from **Table 16**. An overall increase of 25% for HSD and 53% for PMG can be observed for the model after disruptions have occurred. Imports of HSD increased by 259% and for PMG by 271%. Refineries showed by decrease in product supply of 12% for HSD and 44% for PMG. This was expected as the demand of products increased and the refineries had a short fall in supplies.

Table 16. Volumes (L) taken from Refineries and Ports after disruptions

	After disruptions		Before disruptions	
	HSD	**PMG**	**HSD**	**PMG**
PORTS	5,641,485	16,955,920	1,567,362	4,565,184
REFINERIES	8,662,141	5,541,158	9,868,986	10,046,896
$\sum$	14,303,627	22,497,078	11,436,349	14,612,081

The daily processing capacity of all refineries combined is 8,697,102 L for HSD and 5,535,162 L PMG. **Table 16** also shows that the majority of the refined product available is being supplied and the rest of the demand is being fulfilled by imports. Comparing with the proposed model, previous to incorporating disruptions, for PMG about 31% was imported while 69% was procured from local refineries; for HSD only 13% was imported while about 87% was from local refineries. After the disruptions the percentages for imports increased considerably, for PMG about 75% was imported while 25% was procured from local refineries; for HSD only 39% was imported while 60% was from local refineries. All of this points to the vulnerable downstream oil supply chain that can become entirely dependent on imported fuel for majority of the transports sector’s needs. However, HSD is still being supplied far more than PMG, highlighting that the industries relying on this fuel can still function in case of large disruptions.

As expected, the overall network cost has drastically increased due to the four disruptions being considered in to the same model. The average minimum cost for the Monte Carlo simulation is 1,553,475,313 PKR as compared to the Deterministic Model’s 1,067,342,436 PKR which is an increase of 45%. From **Figure 7** the trend for the minimum cost at optimum flows between entities can be observed. Initially the value is at the highest possible at scenario 1, but with progression of the model the overall trend starts to decrease. Most of the total costs stay within an interval of $1*10^9$ PKR of each other. During the last few scenarios, it can be observed that the variation has started to decrease and the values are beginning to converge, confirming that the model would eventually reach to point with very little change.

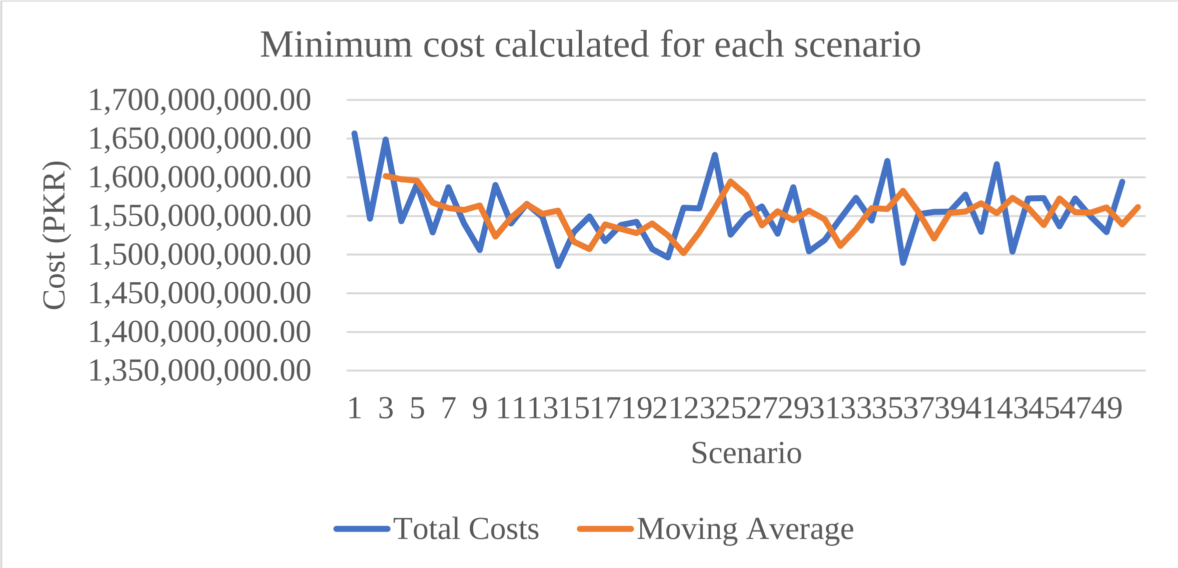

Figure 7. Scenario-wise Minimized Network Transport Cost (PKR).

The reason for the drastic increase in overall network cost is due to the increase in fuel demand which increased in volume to be transported. Coupled with the increase in cost, all of the scenarios provide a higher optimal solution which was calculated previously in the proposed model.

The output from refineries can be observed from **Table 17** as expected the overall refined products sourced from refineries is less than the deterministic model. The volume flow by road and rail has increased because of the disruption caused by the non-functional white oil pipeline.

Comparing it the deterministic model, the shares of refineries has changed considerably. Refinery 1 contributions are decreased by half for both products. Refinery 2 contributions are decreased the most, as after disruptions only one-third of the its previous supplies are available. Refinery 3 contributions are decreased the least as after disruption it is still providing almost 70% of its previous supplies. Refinery 4 has varying contributions by product; for HSD it is contributing more than its previous quantity while for PMG it shows a decrease of 40 percent. Refinery 5 also shows varying product contributions as 70% of previous HSD supplies were still provided while only 30% of PMG supplies made it to the market.

Table 17. Refinery Output Volumes (L) after considering all disruptions

REFINERIES	DEPOTS					
	ROAD		RAIL		PIPE	
	HSD	PMG	HSD	PMG	HSD	PMG
1	300,644	-	-	-	645,374	1,246,122
2	-	-	732,627	566,876	468,127	-
3	-	50,000	-	-	1,369,851	716,812
4	2,175,123	1,543,641	337,999	913,326	1,227,575	-
5	498,762	173,547	-	-	906,060	330,833
TOTAL	2,974,529	1,767,188	1,070,626	1,480,202	4,616,986	2,293,767

Transshipment between storage facilities has also increased especially by road. This transshipment is essential as there are no pipelines and railway tracks directly connecting the ports with the storage facilities in the north. However, due to lack of railway network between storage facilities, it could not be implemented. For both HSD and PMG, pipeline volumes increased more than two-fold, this is because of the higher demand of fuel and increased cost of transportation by other modes. The results are depicted in **Table 18**. Even though there were pipeline disruptions, the volume of fuel transported, by bypassing the non-operational part of the supply chain, increased the overall transshipment by pipelines.

Table 18. Transshipment Flow Volumes (L) after considering all disruptions

TRANSSHIPMENT BETWEEN DEPOTS					
ROAD		RAIL		PIPE	
HSD	PMG	HSD	PMG	HSD	PMG
1,204,898	3,497,183	-	-	2,740,518	10,329,836

In terms of import, both products showed an increase of more than five times their Deterministic values. Lack of refined products from the local refineries along with surge in use of petroleum products makes sense to increase imports to fulfil the demand. As shown in **Table 19**, both import terminals are being used, with the majorly PMG being imported to fulfil transport industry requirements. Comparing the post disruption supply chain with the pre disruption supply chain, Port 1 now imports more refined products as compared to Port 2. Previously, Port 1 did not have HSD imported through it; however now more than 18% of its imported fuel is HSD. Since both depots are connected by pipeline, the increase in volume imported also increases the pipeline use between ports and depots.

Table 19. Import Volumes (L) after considering all disruptions

PORTS	DEPOTS	
	PIPE	
	HSD	PMG
1	2,747,850	12,190,087
2	2,893,636	4,765,833

Finally, the fuel stations are being provided with more fuel to satisfy their demands. **Table 20** shows the increase in shipments to fuel stations from depots by road. Majorly PMG bearing more used by vehicles and other transport machinery, as per original deterministic model. The increase in shipment corresponds to the increase in demand at fuel stations as per disruption 2. For HSD the shipment increase was around 22% and for PMG 32%, which is in line with the increase in overall demand defined in the disruption 2.

Table 20. Fuel Station Shipment Volumes (L) after considering all disruptions

SHIPMENT TO FUEL STATIONS	
ROAD	
HSD	PMG
14,112,008	21,773,347

4.2 Impact of Individual Disruptions on the Total Network Cost

The entire downstream petroleum supply chain is comprised of multiple entities.

Refined oil is procured from refineries or gets imported through ports. The products get transported by pipelines, train wagons and road carriages to storages facilities. During, the final stage, they get transhipped to other storage facilities or customer nodes, depending on the requirement. Different kinds of disruptions effect separate segments of the supply chain. The impacts may be observed on the entire operations but they originate at certain levels and entities. It is therefore important to understand the specific impact of each kind of disruption on the specific entities as well as on the whole supply chain mechanism.

4.2.1 Impact of Disruption 1

Issues with the upstream segment, maintenance shut downs or dispute over pricing can lead to reduce supplies from crude oil refineries. This can lead to a reduction in the overall availability of the products in the market. Downstream sector companies would have to find other sources for procuring oil products. The most suitable way is to import HSD and PMG by via ports and tranship them to high demand regions through pipelines. This is also suitable as the ports are directly connected with the cross-country pipelines and mid-country storage facilities. The second impact of low supplies would be reduced inventory of high demand fuel. The reduced inflow of products would only be able to cater the demand of customer and not allow companies to retain safety stock. **Table 21**, shows the reduced supplies from refineries after Disruption 1. Compared to the deterministic model, the accumulative reduction is HSD supplies is 32% while for PMG supplies is 31%.

Table 21. Refinery Output Volume (L) after Disruption 1

REFINERIES	DEPOTS					
	ROAD		RAIL		PIPE	
	HSD	PMG	HSD	PMG	HSD	PMG
1	8,182	83,068			1,181,809	1,430,027
2	66,791	83,030	698,373	511,113	1,086,555	1,006,047
3	18,459	79,545			973,425	392,566
4	35,883	83,304		310,813	665,125	375,310
5	48,141	112,494			827,304	612,674
TOTAL	177,456	441,441	698,373	821,926	4,734,216	3,816,623

In **Table 22**, the supply from refineries has considerably decreased while imports have increased. The increase in imports for HSD is less than for PMG, mostly due to the dramatic decrease in refinery output for PMG as compared to HSD. This signifies that the local production capacity for PMG was more affected as compared to HSD.

Table 22. Change in Supply Volumes (L) from Ports and Refineries after Disruption 1

	After Disruption 1		Before Disruption 1	
	HSD	PMG	**HSD**	**PMG**
PORTS	17,363,817	12,416,603	1,567,362	4,565,184
REFINERIES	8,206,817	5,389,024	9,868,986	10,046,896

4.2.2 Impact of Disruption 2

The difference between the supply and demand side of the supply chain would create an imbalance in the supply chain. This would require tactical decisions to be made to maximize the supply to high demand regions at the cost of reduced supplies to low demand regions. The supply would have to be fulfilled by importing more refined oil products and transhipping it upcountry. The supplies from refineries and ports are represented by **Table 23**. The imports of both, PMG and HSD, have grown four times while refinery outputs have marginally increased.

Table 23. Change in Supply Volumes (L) from Ports and Refineries after Disruption 2

	After Disruptions		Before Disruptions	
	HSD	PMG	**HSD**	**PMG**
PORTS	5,641,485	16,955,920	1,567,362	4,565,184
REFINERIES	15,561,392	12,624,535	9,868,986	10,046,896

Tactically, it would be better to increase sale cycles and move product from storage to customer sites as quickly as possible. The increased demand would be able to cope with the increased flow. Comparing it to the flow of products to the consumer sites in the deterministic model, there is a significant increase after disruption 2. Primarily due to the increase in PMG, by almost 50%. The increase is HSD sales were almost 30%. This volume flow to fuel stations is given in **Table 24**.

Table 24. Volume (L) of Fuel sent to Fuel Stations after Disruption 2

SHIPMENT TO FUEL STATIONS	
ROAD	
HSD	PMG
16,944,575	30,469,236

4.2.3 Impact of Disruption 3

Cost of transporting fuel from refineries, ports and depots has increased significantly. This has resulted in the higher operating charges which lead to lower profits for the entities involved in the supply chain. In term of material flows, bulk transportation through pipelines increased mostly along with significant growth in movement by fright and trucks. Comparing it with the flows provided in the deterministic model, the increase for HSD and PMG, through pipelines, are 18% and 35% respectively, shown in **Table 25**. This is because pipelines offer the least cost to transport fuel over long distances. With the added advantage of being connected to multiple storage facilities, transshipment becomes more efficient.

Table 25. Volume (L) of Fuel Transshipped between Storage Facilities by all modes after Disruption 3

TRANSSHIPMENT BETWEEN DEPOTS					
ROAD		RAIL		PIPE	
HSD	PMG	HSD	PMG	HSD	PMG
135,918	1,672,828	-	-	3,228,566	14,045,018

Conversely, use of road transport has also decreased due to the higher cost associated. However, due to the limited pipeline infrastructure, road use has not been eliminated as far off storage facilities are not connected by pipelines and are therefore only serviced by road carriages. HSD experienced a larger decrease in volume flows as compared to PMG, primarily because it is less used by transport vehicles.

Volume flow by railway did not change as there are no railway linkages between storage facilities. Similar to the deterministic model, only refineries were able to move refined fuel products on railway wagons. Although being cheaper than road carriage, the railway network remains under-utilized. Areas with moderate volume and low road infrastructure can be effectively catered by railway networks.

4.2.4 Impact of Disruption 4

Interruptions in operations of the POSC can be expected in terms of facility breakdowns and operational shutdowns. The pipeline network is at the core of the downstream oil supply chain as the fuel that is imported by ports gets transhipped to the north, cost-effectively, through it. This means that any issues that hinder the flow of products through the pipeline can end up disrupting the entire supply chain.

The disruption would result in shift of flows from pipeline to other transport modes, especially road carriages. The reason is that the demand has to be fulfilled and the railway network is neither developed nor widespread enough to accommodate the volume otherwise handled by the pipeline. The volume provided in **Table 26**, show a decrease of 20% for HSD and 16% for PMG, for movement through pipelines. However, the remaining volume gets shifted upon road carriages with HSD and PMG showing a 25% and 35% increase.

Table 26. Volume (L) of Fuel Transshipped between Storage Facilities by all modes after Disruption 4

TRANSSHIPMENT BETWEEN DEPOTS					
ROAD		RAIL		PIPE	
HSD	PMG	HSD	PMG	HSD	PMG
1,506,123	4,721,197	-	-	2,192,414	8,883,659

Another important impact of this disruption would be increase in the transhipment between storage facilities. As road carriages are mostly limited to transporting fuel at lower distances, it would be economical to limit their routes to close markets. This would create more transshipment stages, each having its own loading and offloading operations that can lead to more vapour evaporation.

The refineries in the north of the country would also be heavily burdened as the supply coming from the import terminals would be reduced and hence forth create a regional shortage.

This would mean that there would be an imbalance of refinery capacity utilization. The refineries in the south of the country would be able to produce refined oil products but would not be able to transport them to the desired markets. The time to bring petroleum products to markets would increase, in effect increasing operational costs and delays to market.

4.3 Comparison of the Impacts of Individual Disruptions on the Supply Chain Cost

The overall network cost varies with the nature of disruption that is introduced into the supply chain model. This is because the effect is only limited to a certain segment of the supply chain. However, the common results of any disruption in a supply chain are increase in total network costs, more delays, and increase in product cost. Entities involved at all stages of the supply chain are adversely affected as operational mechanisms have to be adjusted with market circumstances while customers have to deal with increase buying costs and product shortages. The total network cost comparison between disruptions is given in **Figure 8**, The costs associated with all disruption scenarios are higher than the cost calculated of the deterministic model.

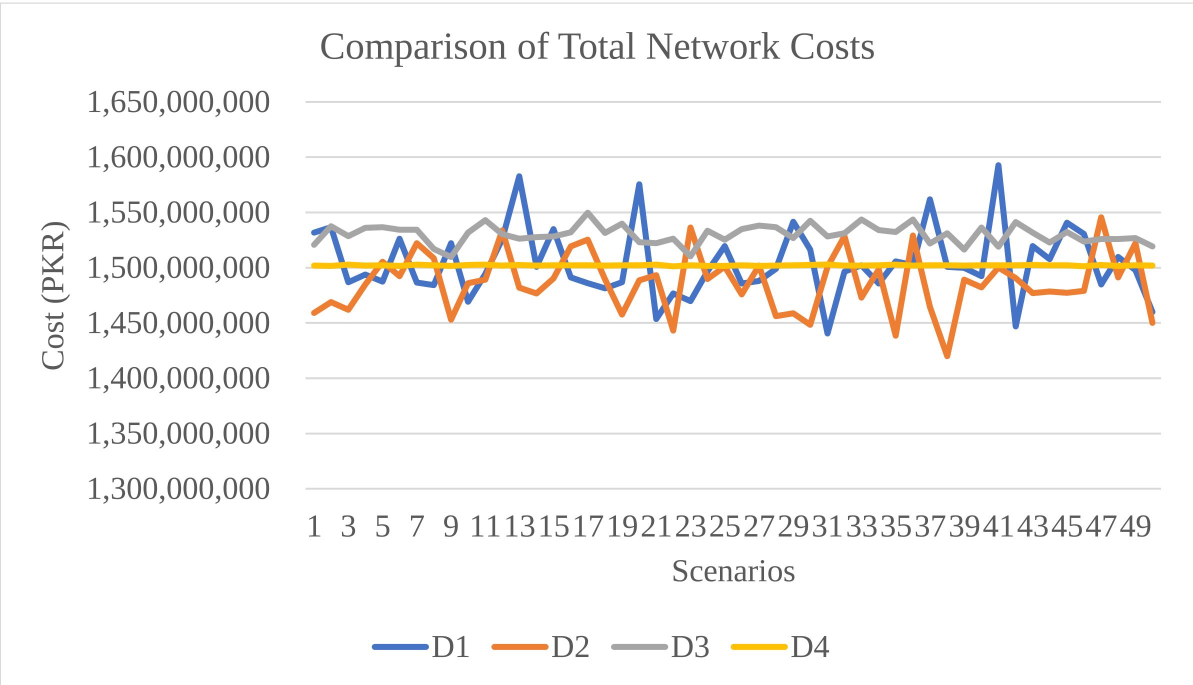

Figure 8. Total Network Costs (PKR) After Each Disruption

Disruptions caused by increase in demand of fuel caused the most increase in the overall supply chain cost. Demand for both fuels increased due to the economic recovery efforts after the COVID-19 pandemic. The rise in demand led to more volume being procured, stored and transported which increased the operational cost of the entire supply chain. Transport cost is the highest contributor as all of the movement in the second echelon of the supply chain is done by road. Both, pipeline and rail, transport modes also show an increase in volume flows as well. Volume flows from refineries and import terminals are also increased to fulfil the demand requirements.

Disruptions on the supply side caused the second most increase in overall network cost. The reason for this is because the local refineries were not able to provide enough products to the high demand regions which ultimately led to procurement of imported fuel. The distance between the high demand regions and import terminals added to the increase in total network costs as the fuel had to be transhipped cross country to areas which could have been easily supplied by refineries, which in this this case were facing production issues.

Increase in transport cost impacted the supply chain network to a lesser extent compared to supply and demand side disruptions. All transport modes showed an increase in the cost to move refined fuel products. The highest increase in cost per unit volume was of road carriages, followed by pipeline, and then railway carriage. The impact of this disruption shifted to the flow of products towards the pipeline mode. The route which connected multiple storage facilities was more prominent as it allowed for cross country movement at the least operational cost. In the first stage of the supply chain, refineries also increased rail carriage flows whenever the infrastructure was available. Due to lack of any other transport mode available, the last stage of the supply chain is solely serviced by road carriages. The cost associated with supplies to customer nodes is the largest contributor to the increase in total network cost due to multiple customer nodes being supplied by a single storage facility and the distance between the two entities.

Bulk oil pipeline disruptions caused the least impact on the total supply chain network costs. The white oil pipeline connecting storage facilities, near import terminals, with the storage facilities in the north of the country was not operating. This created an unanticipated supply chain disruption by reducing the flow of products towards the high demand regions. The supply chain was least affected by this disruption due to availability of other transport modes which were able to absorb the volume otherwise moved through the pipeline. The cost increase was due to the movement of fuel by road carriages. Transshipment also increased as road movement is limited to only between storage facilities that are near to each other. Railway movement was not used due to lack of proper infrastructure.

The overall analysis of the multiple disruption scenarios shows that the increase in demand effects the total supply chain cost the most, followed by reduction in supplies by the local refineries. Increase in transport costs along with any operational disruptions affect the total network costs to a lesser degree. This is because of presence of substitute services that can be utilized to mitigate the effects of these disruptions. Transport modes compete with each other based on price, availability and reliability. Any issue with one mode creates an opportunity for the reaming modes to cover up for the volume lost. This is not possible for supply and demand side disruptions as there are no substitutes for the refined fuel products and therefore are most sensitive to market forces. Mitigation strategies are only limited to alternate sourcing and increase in inventory capabilities, which also increase operational costs.

4.4 Discussion

The results generated from the simulation give an idea regarding the flow of volumes between entities and the pattern of routes taken to minimize the network transport cost. The solutions obtained by the model can be considered in line with the results of previous studies done on the topic of disruptions on POSCs. Zhang et al. (2019) mentioned that the unavoidable disruptions increased the overall network cost. Additionally, the overall cost with uncertainties is higher than it would be without them. The supply chain system's structure and operational mode are both impacted by the uncertain system conditions, in addition to the layout of the network plan.

There is a significant increase in the dependency on imported petroleum products, especially in the case of PMG. This finding is crucial for understanding Pakistan's energy security and highlights the need for strategies to diversify fuel sources and reduce import reliance. The disruptions have led to a decrease in the supply of refined products from local refineries, with some substantial reductions. Similarly, the Sri Lankan petroleum supply chain was considered to analyze risk factors and disruptions. Their findings highlighted lack of infrastructure facilities which is the main hurdle that stops the country from ensuring energy security (Fernando et al., 2021).

This decrease in domestic production emphasizes the need for contingency plans and strategies to enhance the resilience of local refineries. The analysis shows a shift in transportation modes, particularly an increase in road and rail transportation due to disruptions in the white oil pipeline. This highlights the importance of maintaining and upgrading transportation infrastructure to ensure the smooth flow of petroleum products. Kazemi et al.

(2015), proposed proactive mitigation strategies in the form of varied transfer volumes and for reactive mitigation strategies to be employed in multimodal transportation strategies.

Transshipment between storage facilities has increased significantly, particularly by road. This is an essential component of the supply chain, bridging the gap between ports and storage facilities. The results underscore the importance of efficient transshipment mechanisms in response to supply disruptions. The increase in imports of both HSD and PMG, along with changes in the preferred import terminals, suggests the need for strategic decisions regarding import infrastructure and distribution channels to ensure the uninterrupted supply of petroleum products. Fuel stations are receiving more products to meet the increased demand, especially for PMG. This aligns with the growth in the transport sector and underlines the importance of ensuring a stable and reliable fuel supply to support economic activities.

The insights gained from the sensitivity analysis can guide policymakers, industry stakeholders, and supply chain managers in making informed decisions to enhance the resilience of the petroleum supply chain, reduce import dependency, and minimize the economic impact of disruptions.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

The objective of this research is to design an optimized downstream oil supply chain by understanding the effects of multiple types of disruptions. The methodology involved comparing the effects of multiple disruption scenarios. on a downstream supply chain, individually as well as simultaneously. Disruption of any kind would ultimately would lead to increase in network costs, as well as reduced service quality for the customers.

The petroleum industry involves the global processes of exploration, refining and marketing of oil and its derived products. Much of the worlds' energy needs are met by burning fossil fuels which converts chemical energy into mechanical and electrical energy. Due to the heavy reliance on petroleum-based products, the petroleum supply chain must operate efficiently and robustly. However, as the supply chain becomes complex so do the myriad of challenges and hurdles that can potentially break the entire supply network. Therefore, it is of the utmost importance to form strategies that optimize the usefulness of a PSC network under all kinds of disruptions caused by uncertainties in the numerous parameters that form it. This research aims to create a MILP model that optimizes a multi-stage, multi-product, multi-modal downstream petroleum supply chain network of company in an oil importing country. Only two products are considered i.e., PMG and HSD. The study is divided into two stages; a deterministic model that provides that baseline operating conditions of the supply chain working under no disruptions, and a Monte Carlo simulation of the same model under different disruption scenarios, considered individually and simultaneously. The aim is to understand the volume flow of products between entities and the overall impact of these disruption on the entire supply chain network cost.

The disruption scenarios have variations in terms of the parameters they impact. The scenarios are considered simultaneously to resemble a situation in which all kinds on disruptions can happen at once. While individual comparison allows for the understanding the targeted impact on the supply chain functions. The comparison is done between the deterministic model and the average volume flows between entities across all scenarios. The results highlight the need to plan and construct supply chain strategically and operate tactically to reduce the overall transport cost. The simulations are done for "1 day" period where the parameters are set to a daily average of the oil industry.

The results illustrate that simultaneous disruptions can increase the overall network transport cost by as much as 50%. Issues in the production of refined oil by refineries results in a decrease in volume movement from refineries to storage facilities. The increase in demand from the customers can lead to rise in the flow of volume form storage facilities. Both of these disruptions compound the need for more imported fuels in the supply chain to counter the effect of shortage in supply and fulfil the overall demand. The third disruption simulates the effect of rising cost of doing business for the company as the transport cost per unit increases across all modes. More volume has to be transported through pipelines to make the supply chain cost effective and tactical decisions have to be made to fulfil high demand regions. Finally, a structural disruption in terms of pipeline shut down is examined that forces that company to shift its transporting operation by road and an overall increase in transshipment between storage facilities so that oil tankers have to move less distances in one journey.

Comparing the disruptions separately, it was concluded that demand side issues have the greatest effect on the total network cost, due to the increase in volume flows as well as increased procurement operations. Followed by supply side disruptions, which force increase in imports that have to be transhipped cross country. Thereby incurring long distance transport costs. Increase in transport costs had low impact on the overall network cost due to increase in flows of bulk movement modes such as pipelines. Operational disruptions had the least impact as there were substitute transport available which were able to fill in for the lost volume.

This research improves on the understanding of downstream oil supply chains for import reliant countries that do not have widespread developed infrastructure. The impact of disruptions on certain supply chain segments can be observed as well their effects on the entire supply chain cost can be quantified. Statistical approaches such as Monte Carlo simulation are effectively used to simplify complex systems.

The scope of this research is limited to observing only very few disruption scenarios, which is not ideal for real world supply chain systems, and hence the results can only be related under certain conditions. For future studies it is recommended to simulate the effects of these disruptions on inventory volumes of depots. Along with how these effects can be minimized by implementing structural and strategical improvements that can be replicated in other similar markets. Also, a different method of quantifying the effects of random disruptions can be utilized to compare results, considering that Monte Carlo sampling is a rather simple technique.

REFERENCES

Alfares, H. K. (2023). Optimum Planning of a Distribution Supply Chain for Refined Oil Products. In H. K. Alfares (Ed.), Applied Optimization in the Petroleum Industry (pp. 209–235). Springer International Publishing. https://doi.org/10.1007/978-3-031-24166-6_9

Al-Othman, W. B. E., Lababidi, H. M. S., Alatiqi, I. M., & Al-Shayji, K. (2008). Supply chain optimization of petroleum organization under uncertainty in market demands and prices. European Journal of Operational Research, 189(3), 822–840. https://doi.org/https://doi.org/10.1016/j.ejor.2006.06.081

Amor, R. Ben, & Ghorbel, A. (2018a). The risk in Petroleum Supply Chain: A review and typology. International Journal of Scientific and Engineering Research, 9(2), 141–163.

Amor, R. Ben, & Ghorbel, A. (2018b). The risk in Petroleum Supply Chain: A review and typology. International Journal of Scientific and Engineering Research, 9(2), 141–163.

Anthony Sampson. (1975). The Seven Sisters: The Great Oil Companies and the World They Shaped. The Viking Press, Inc.

Azad, N., Saharidis, G., Davoudpour, H., Malekly, H., & Yektamaram, S. (2013). Strategies for protecting supply chain networks against facility and transportation disruptions: An improved Benders decomposition approach. Annals of Operations Research, 210. https://doi.org/10.1007/s10479-012-1146-x

Bashiri, M., Mirzaei, M., & Randall, M. (2013). Modeling fuzzy capacitated p-hub center problem and a genetic algorithm solution. Applied Mathematical Modelling, 37, 3513–3525. https://doi.org/10.1016/j.apm.2012.07.018

Bravo Bastidas, J., & Vidal, C. (2013). Review: Freight transportation function in supply chain optimization models: A critical review of recent trends. Expert Systems with Applications: An International Journal, 40, 6742–6757. https://doi.org/10.1016/j.eswa.2013.06.015

Energy Institute. (2022). Statistical Review of World Energy Data.

Escudero, L. F., Quintana, F. J., & Salmeron, J. (1999). CORO, a modelling and an algorithmic framework for oil supply, transformation and distribution optimization under uncertainty. European Journal of Operational Research, 114(3), 638–656. https://EconPapers.repec.org/RePEc:eee:ejores:v:114:y:1999:i:3:p:638-656

Etemad, B., & Luciani, J. (n.d.). World Energy Production 1900 – 1985.

Fernandes, L. J., Relvas, S., & Barbosa-Póvoa, A. P. (2013). Strategic network design of downstream petroleum supply chains: single versus multi-entity participation. Chemical Engineering Research and Design, 91(8), 1557–1587.

Fernandes, L. J., Relvas, S., & Barbosa-Póvoa, A. P. (2015). Petroleum Supply Chain Network Design and Tactical Planning with Demand Uncertainty. In A. P. F. D. B. Póvoa & J. L. de Miranda (Eds.), Operations Research and Big Data: IO2015-XVII Congress of Portuguese Association of Operational Research (APDIO) (pp. 59–66). Springer International Publishing. https://doi.org/10.1007/978-3-319-24154-8_8

Fernando, M., & Sigera, I. (2021). Assessing the Oil Supply Chain Risk in Sri Lankan Petroleum Industry. 2021 Moratuwa Engineering Research Conference (MERCon), 374–379. https://doi.org/10.1109/MERCon52712.2021.9525691

Hussain, R., Assavapokee, T., & Khumawala, B. (2006). Supply chain management in the petroleum industry: challenges and opportunities. International Journal of Global Logistics & Supply Chain Management, 1(2), 90–97.

International Trade Centre. ITC Trade Map. Retrieved from International Trade Center: https://intracen.org/

Jabbarzadeh, A., Naini, S., Davoudpour, H., & Azad, N. (2012). Designing a Supply Chain Network under the Risk of Disruptions. Mathematical Problems in Engineering, 2012. https://doi.org/10.1155/2012/234324

Kazemi, Y., & Szmerekovsky, J. (2015). Modelling downstream petroleum supply chain: The importance of multi-mode transportation to strategic planning. Transportation Research Part E: Logistics and Transportation Review, 83, 111–125. https://doi.org/10.1016/j.tre.2015.09.004

Khor, C. S., Elkamel, A., & Shah, N. (2017). Optimization methods for petroleum fields development and production systems: a review. Optimization and Engineering, 18(4), 907–941. https://doi.org/10.1007/s11081-017-9365-2

Khosrojerdi, A., Hadizadeh, A., & Allen, J. (2012). Designing a Dynamic Bi-Objective Network Model for a Petroleum Supply Chain. In 62nd IIE Annual Conference and Expo 2012.

Liao, Q., Zhang, H., Xu, N., Liang, Y., & Wang, J. (2018). A MILP model based on flowrate database for detailed scheduling of a multi-product pipeline with multiple pump stations. Computers & Chemical Engineering, 117, 63–81. https://doi.org/https://doi.org/10.1016/j.compchemeng.2018.05.002

Lima, C., Relvas, S., & Barbosa-Póvoa, A. (2021). Designing and planning the downstream oil supply chain under uncertainty using a fuzzy programming approach. Computers & Chemical Engineering, 151, 107373. https://doi.org/https://doi.org/10.1016/j.compchemeng.2021.107373

Lima, C., Relvas, S., & Barbosa-Póvoa, A. P. F. D. (2016). Downstream oil supply chain management: A critical review and future directions. Computers & Chemical Engineering, 92, 78–92. https://doi.org/https://doi.org/10.1016/j.compchemeng.2016.05.002

Maersk. (2023). 5 reasons for supply chain disruption.

Más, R., & Pinto, J. (2003). A Mixed-Integer Optimization Strategy for Oil Supply in Distribution Complexes. Optimization and Engineering, 4, 23–64. https://doi.org/10.1023/A:1021808313306

MathWorks. Monte Carlo Simulation. Retrieved from https://www.mathworks.com/discovery/monte-carlo-simulation.html

Neiro, S., & Pinto, J. (2004). A general modelling framework for the operational planning of petroleum supply chain. Computers & Chemical Engineering, 28, 871–896. https://doi.org/10.1016/j.compchemeng.2003.09.018

Ni, W., Liang, Y., Li, Z., Liao, Q., Cai, S., Wang, B., Zhang, H., & Wang, Y. (2022). Resilience assessment of the downstream oil supply chain considering the inventory strategy in extreme weather events. Computers & Chemical Engineering, 163, 107831. https://doi.org/https://doi.org/10.1016/j.compchemeng.2022.107831

OCAC. (2021). Pakistan Oil Report 2020-2021. Karachi: Oil Companies Advisory Council.

OPEC. (n.d.). About Us: A brief History. Retrieved from Organization of the Petroleum Exporting Countries: https://www.opec.org/opec_web/en/about_us/24.htm

PACRA. (2022). Pipeline Network Sector Study. The Pakistan Credit Rating Agency Limited.

PAPCO. Papco Company Profile. Retrieved from PAPCO: https://papco.com.pk/about-papco/company-profile/

Python Foundation. Optimization with PuLP. Retrieved from PuLP Website: https://coin-or.github.io/pulp/#

R. J. Forbes. (1955). Bitumen and Petroleum in Antiquity. Studies in Ancient Technology, Vol. 1:1–123(2nd ed).

Ribas, G., Hamacher, S., & Street, A. (2010). Optimization under uncertainty of the integrated oil supply chain using stochastic and robust programming. International Transactions in Operational Research, 17, 777–796. https://doi.org/10.1111/j.1475-3995.2009.00756.x

Ríos-Mercado, R. Z., & Borraz-Sánchez, C. (2015). Optimization problems in natural gas transportation systems: A state-of-the-art review. Applied Energy, 147, 536–555. https://doi.org/https://doi.org/10.1016/j.apenergy.2015.03.017

Samadi-Parviznejad, P., & Amini, M. (2022). Optimizing The Transportation of Petroleum Products in A Possible Multi-Level Supply Chain. International Journal of Innovation in Engineering, 2(3), 67–83. https://doi.org/10.59615/ijie.2.3.67

Sangaiah, A. K., Tirkolaee, E. B., Goli, A., & Dehnavi-Arani, S. (2020). Robust optimization and mixed-integer linear programming model for LNG supply chain planning problem. Soft Computing, 24(11), 7885–7905. https://doi.org/10.1007/s00500-019-04010-6

Sinha, A. K., Aditya, H. K., Tiwari, M. K., & Chan, F. T. S. (2011). Agent oriented petroleum supply chain coordination: Co-evolutionary Particle Swarm Optimization based approach. Expert Systems with Applications, 38(5), 6132–6145. https://doi.org/https://doi.org/10.1016/j.eswa.2010.11.004

Trade Development Authority of Pakistan. (2021). Petroleum Sector of Pakistan and its Trade Dynamics. Islamabad.

Wang, B., Liang, Y., Zheng, T., Yuan, M., & Zhang, H. (2019). Optimisation of a downstream oil supply chain with new pipeline route planning. Chemical Engineering Research and Design, 145, 300–313. https://doi.org/https://doi.org/10.1016/j.cherd.2019.03.009

Zhang, W., Li, Z., Liao, Q., Zhang, H., Wang, B., Huang, S., Xu, N., & Liang, Y. (2019). A Stochastic Linear Programming Method for the Reliable Oil Products Supply Chain System With Hub Disruption. IEEE Access, 7, 124329–124340. https://doi.org/10.1109/ACCESS.2019.2938326

Zhao, C., & Chen, B. (2014). China’s oil security from the supply chain perspective: A review. Applied Energy, 136, 269–279. https://doi.org/10.1016/j.apenergy.2014.09.016

APPENDIX

List of Equations

Python code
Import the optimization library or algorithm (e.g., SciPy, PuLP, Pyomo)
Import Libraries
import pandas as pd
import pulp
import numpy as np

Read data files from Excel and turn them into data frames
Transport cost df = pd.read_excel("file path", sheet_name="Sheet 1")
Generate data frames for all transport costs for between entities and involving all routes

# Read the depot storage capacities from Excel
depot_storage_df = pd.read_excel("file path", sheet_name="Sheet1")
Generate data frames for all storage capacities of all refined products for all depots involved in the supply chain.

# Read the Refinery production from Excel
refinery_production_df = pd.read_excel("file path", sheet_name="Sheet1")
Generate data frames of supplies capacities of all products for all refineries

# Read the Port Capacity from Excel
Port_capacities_df = pd.read_excel("file path", sheet_name="Sheet")
Generate data frames for import capacities of all refined products for all ports

# Read the Customers list from Excel
sold_by_fuelstations_df = pd.read_excel("file path", sheet_name="Sheet1")
Generate data frames that show the quality sold by fuel stations

The data frames are not converted to dictionaries, with the entities as keys
# Create a dictionary to hold the cost per liter between refineries and depots
mode_entity_costs = {(row["R1"], row["D1"]): row["Cost (PKR)/litre"] for _, row in previously_created_df.iterrows()}
The same can be created for transport costs between all supply chain entities.

# Create a dictionary to hold the depot capacities
depot_capacities = {row["LOCATION"]: row["Capacity(Litres)"] for _, row in depot_storage_df.iterrows()}
Generate similar dictionaries representing storage of all depots

# Create a dictionary to hold the refinery production by products
refinery_production_capacity = {row["Refinery"]: row["Capacity(Litres)/day"] for _, row in refinery_production_df.iterrows()}
Generate dictionary that represents the has refinery as keys

# Create a dictionary to hold the import capacity by products
import_capacity = {row["Port"]: row["product"] for _, row in Port_capacities_df.iterrows()}
Generate dictionary which represents the import capacities and has ports as keys
Create a dictionary to hold the fuel stations product wise sales

FS_sales = {row["FUEL STATIONS"]: row["Sales(Litres)"] for _, row in sold_by_fuelstations_df.iterrows()}
Create a dictionary for the daily sales of fuel stations by product

# Create the problem
problem = pulp.LpProblem("FuelTransportProblem", pulp.LpMinimize)
Define the Linear programming problem and set the operation to Minimize the function

Create a list of refineries and depots
Generate the list of entities across the echelons
Create the decision variables
Generate dictionaries of linear programming variable type by using PuLP. The variable should represent the volume transported between entities. Variables should be representing the different products and modes of transport. And should have non negative value.
product_source_volume_mode = pulp.LpVariable.dicts("label", (refineries, depots), lowBound=0)

Create the optimization function

problem += (pulp.lpSum(mode_source_costs[(r, d)] * product_volume[r][d] for r in source for d in destinations) +…..)
The objective function is the sum of the product of the costs to transport refined fuel between all entities using all modes of transport.
The stages span across three echelons comprising of refinery to depots, ports to depots, depot to depots, and depot to fuel stations. The three modes are pipe, road, and train. Only two products are considered i.e., PMG and HSD.

Constraints
# Sales constraint
for fs in fuel_stations:
    problem +=(pulp.lpSum(shipment_to_fuelstations [d][fs] for d in depots)) == FS_sales [fs]
The supplies to fuel stations should be equal to the demand of reined fuel

# Add refinery preferrence constraints
for d in depots:
    problem +=(pulp.lpSum(product_refinery_volume_mode[r][d] for r in refineries) +
 >= pulp.lpSum(product_port_volume_pipe[p][d] for p in ports))
The supplies from refineries should be more than the supplies from imports.

# Add the depot balance constraints
for d in depots:
    problem +=(pulp.lpSum(product_refinery_volume_road[r][d] for r in refineries) + …) <= pulp.lpSum(product_shipment_to_fuelstations [d][fs] for fs in fuel_stations)

The volume of products entering the depots should be more than the volume of products leaving the depots

```
# Add the storage HSD capacity constraints
for d in depots:
    problem +=HSD_depot_inventory[d]<= HSD_capacities[d]
```

The volume entering depots should not be more than the capacity of the depot to store the refined products

```
#SUPPLY CONSTRAINT

for r in refineries:
    problem +=( pulp.lpSum(HSD_refinery_volume_road[r][d] for d in depots) + \
              pulp.lpSum(HSD_refinery_volume_rail[r][d] for d in depots) +\
              pulp.lpSum(HSD_refinery_volume_pipe[r][d] for d in depots)) <=
HSD_refinery_production_capacity [r]
```

The volume of product being supplied to the depots should not be more than the volume available to refineries.

```
#SUPPLY CONSTRAINT

for p in ports:
    problem +=( pulp.lpSum(product_port_volume_pipe[p][d] for p in ports)) <=
product_import_capacity [p]
```

The volume transhipped to depots by ports should not be more than the volume being imported at ports

```
# Solve the problem
status = problem.solve()
```

The solve statement output the solution of the LP problem.

```
# Create a Data Frames to store the refinery volumes
```

Generate data frames that align the decision variables into index and columns based on the product, source and destination of the supply chain

```
product_source_volumes_mode_df = pd.DataFrame ( index = refineries, columns =
destination)
…
```

```
# Assign optimal values to the refinery volumes by modes Data Frame
```

Assign the data frame values previously generated by the decision variable dictionaries

```
for r in refineries:
      for d in depots:
         product_source_volumes_mode_df.loc[r, d] =
product_source_volume_mode[r][d].varValue
```

```
print(Optimal_volumes)
print(decision_variables_df)
```
This is to be repeated for all decision variables to get the corresponding variables

```
# Get the count of variables and constraints
num_variables = len(problem.variables())
num_constraints = len(problem.constraints)


# Create a Pandas Excel writer using XlsxWriter as the engine
excel_writer = pd.ExcelWriter("file path.xlsx")
product_shipment_to_destination_df.to_excel(excel_writer, sheet_name='label', index=False)
# Add more data frames as needed

# Close the Pandas Excel writer and output the Excel file
excel_writer.save()
```

Monte Carlo sample generation code

Function to Generate Random Samples for Transport Costs

```
# Define functions for generating random samples for transport costs
# Function to generate random samples for refinery transport costs
def generate_ samples (num _ samples,df):
    samples = {}
    for i in range (num _ samples):
        sample _ values = {
            (row["Source"], row["Destination"]): max(0, np.random.normal(row["Mean"],
row["Std"]))
            for _, row in df.iterrows()
        }
        samples[i] = sample_values
    return samples
```

This function is used to generate random samples of supply chain parameters. The number of samples generated would depend of the user input taken form “num_samples”. Variations of this function would be created for refinery supply variation, demand variations, cost variations and pipeline disruptions.

The Monte Carlo simulation would be written in the following manner. The for loop would run for the number of samples specified.

```
for i in range(num_samples):

  # Create the Optimization Problem
  problem = pulp.LpProblem(f"label {i}", pulp.LpMinimize)

  #  Optimization Code
  # Define decision variables, objective function, and constraints
  # Create the decision variables
```

product_source_volume_mode = pulp.LpVariable.dicts("label", (refineries, depots), lowBound=0)

Each time the decision variables have to be redefined.

```
# Define the objective function
problem += (pulp.lpSum(mode_source_cost_samples[i][(r, d)] * product_source_volume_mode[r][d] for r in refineries for d in depots) +
        ..)
```

The decision variables are dictionaries with the samples number as their keys, and each time the specific sample would be used only.