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ABSTRACT

RISK BASED MODELS FOR THE OPTIMIZATION OF OIL AND GAS SUPPLY CHAIN CRITICAL INFRASTRUCTURE

**By
Kingsley Oseloka Achebe**

The oil and gas sector faces a broad array of risks and uncertainties, affecting short- and long-term planning, and causing adverse effects in the energy sector. To predict and minimize them, risk based supply chain models were developed for the oil and gas supply chain critical infrastructure.

First, the events and activities were categorized as short term and long term, and their risk ratings derived, by analyzing data from past events and site visits. The result showed that events like the Israel – Arab war, successful hurricane, and production increase or decrease, had a risk rating of approximately 7.

Second, network reliability and connectivity were analyzed using the risk based minimum cut-set model, and its associated algorithms and simulation, for tactical and short term planning. The impact of link failures, due to the risk and risk ratings associated with certain events and activities determined above, which can affect each source-demand pair (i.e., from the crude storage tank to the refinery or from the refinery to the product storage tank) of the network or the whole network, were determined. The result showed that for a real world petroleum supply chain network like the Petrobras (Brazil), this model could identify critical nodes/links in the supply chain network(s) that can be severely affected by failure.

Third, a risk based LP Supply Chain Model (SCM) was developed, and used to analyze the supply chain (SC), for strategic and long term scenarios. The average

expected risk ratings obtained above was used as one of the constraints in simulating different risk scenarios. It was also used to forecast their likely impact on the supply chain, and to come up with alternative ways to manage/minimize risk. The study showed that for a generalized oil and gas supply chain like the Gulf coast area of the US, a very critical (in terms of risk rating), and very severe (in terms of duration) event at the crude source - like crisis in Nigeria or Iraq, occurring during the fall season could likely cause an approximately 35% drop/loss in production of the supply chain. The study also showed that other events like a refinery explosion/fire, tank leak/crack, or pipeline fire/attack that is also very critical and severe, occurring during the fall season, could also lead to an approximately 40% loss/drop in production of the supply chain.

Last, Fault Tree Analysis (FTA) and Model Based Vulnerability Analysis (MBVA) were carried out on the supply chain, to determine whether each source-demand pair analyzed, failed or not, due to the likely impact of any event/threat scenario analyzed above. The analysis were also carried out to show how scarce resources can be allocated for optimum results in protecting these oil and gas supply chain nodes/links from failure. Using the supply chain (SC) of the Gulf coast area as a case study, the result of the simulation showed that investing at least \$200 million to provide Critical Infrastructure Protection (CIP) in the Gulf coast area, can lower vulnerability to as little as 11%, and prevent the potential for huge price increase on the consumers in particular, and the economy in general.

**RISK BASED MODELS FOR THE OPTIMIZATION OF OIL
AND GAS SUPPLY CHAIN CRITICAL INFRASTRUCTURE**

by
Kingsley Oseloka Achebe

**A Dissertation
Submitted to the Faculty of
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in Partial Fulfillment of the Requirements for the Degree of
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Department of Civil and Environmental Engineering

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APPROVAL PAGE

RISK BASED MODELS FOR THE OPTIMIZATION OF OIL AND GAS SUPPLY CHAIN CRITICAL INFRASTRUCTURE

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Dedicated to the memories of my late Parents,
Reuben and Ramotu Achebe. I wish you were both here.

The secret of getting ahead is getting started.
The secret of getting started is breaking your complex overwhelming tasks
into small manageable tasks, and then starting on the first one.
Mark Twain

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CHAPTER 1

INTRODUCTION

1.1 History and Background

The oil and gas industry is principally a Supply Chain Management (SCM) industry, which involves the management of all steps in the delivery of a product or service to consumers. It consists of exploration, drilling, operation of pipelines, and operation of refineries for the production of fuel, plastics, and so on. Trunk line or “transmission pipes” are the arterials that deliver refined products such as gasoline and aviation fuel to terminals at various locations. Distribution refers to the sale and delivery of these products to consumers from storage terminals. In their work, Forrest and Oettli (2003) found out that most of the oil industry still operates its planning, central engineering, upstream operations, and refining, supply, and transportation units as complete separate entities. In view of this, systematic methods for efficiently managing the oil and gas supply chain as one continuous unit must be exploited, viz - a - viz the risks and vulnerabilities that are inherent in each supply chain unit/node.

A wide range of optimization models have been proposed in the oil and gas supply chains, often without taking the inherent risks and vulnerabilities from events, different routes and supply chain units/nodes into consideration. These uncertainties and risks often interrupt the supply chain operations, causing significant adverse effects in the energy sector. It is important to develop risk based optimization models using the oil and gas/ refinery critical infrastructure supply chain operations, to predict, reduce or mitigate the impact of these uncertainties in the oil and gas critical infrastructure supply chain. The need for this important research work is based on the fact that studies (Lewis, 2006)

have shown that oil and gas will remain the most consumed energy for the foreseeable future (Figure 1.1).

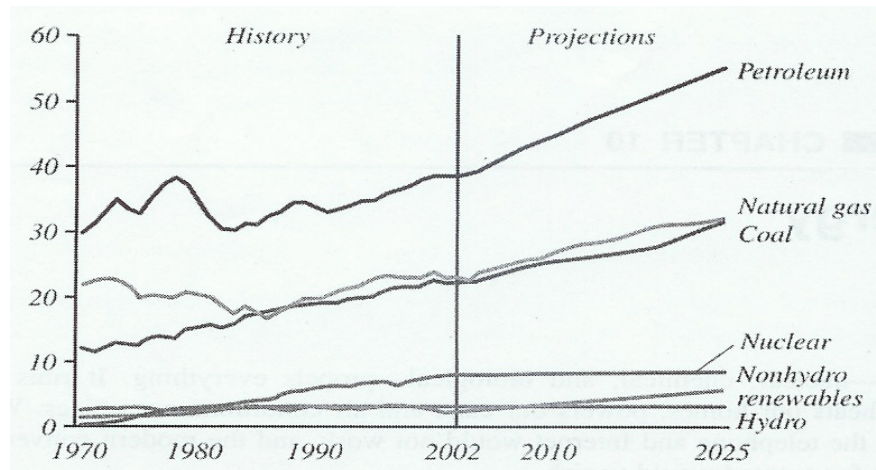


Figure 1.1 Past, present and future energy consumption in the United States: Petroleum and Natural Gas will remain as the most consumed energy for the foreseeable future.

Source: Lewis (2006).

1.2 Objectives

The objectives of this work are:

- To analyze existing supply chain models and :
 - i. develop a risk model that will be used to categorize and derive the various types of risks from analyzing the impacts of prior events on the oil and gas supply chain and subsequently derive their ratings from the weighted risk.
 - ii. develop a risk based SCM that will include:
 - a risk based network reliability analysis model using the modified minimum cut-set method to locate critical links/nodes in the network whose failure from some of events, activities and threats we analyzed their risk ratings in (i) above, will severely affect the supply chain networks

- a risk based Linear Programming (LP) Supply Chain Model (SCM) for strategic and tactical planning in the oil and gas SCM, by using the risk ratings obtained above to simulate different scenarios and alternatives, so as to get and incorporate the likely impact of these events and activities in (i) above on the critical/links/nodes identified in (ii (a)) above on the SC.
- iii. Finally, develop a Fault Tree and Model Based Vulnerability Analysis (FTA and MBVA) models that will be used to show how scarce resources can be allocated for optimum result in hardening/protecting these oil and gas SC nodes/links from failure because of the likely impacts of some of the events and threats analyzed above.
- To manage and minimize /eliminate instability in the oil and gas critical infrastructure.
- To make the industry more resilient.

The models can be applied also to other critical infrastructure supply chains, by varying the variables. These comprehensive yet easy-to-use models can be easily used by executives, risk/supply chain/production managers, transportation and logistics personnel, suppliers and regulators, academicians and students.

CHAPTER 2

LITERATURE REVIEW

2.1 Current Research

Current approaches to managing risks and uncertainties in the oil and gas critical infrastructure supply chains are mostly reactive, employing re-routing of supply and rationing. These lead to increased prices and negative impact on economic activity due to lack of resiliency. The existing models to our knowledge only deal with stream flow rates and not the demand and supply aspects, and do not take into consideration the inherent risks and vulnerabilities from events, different routes, various sources and individual supply chain units.

Abdel-Malek, Kullpattaranirum, and Nanthavanil (2005) modeled the supply chain to assess the growth of the internet as one of today's main business communications tools as a series of tandem queues to estimate the lead time spent at each level of the chain. Micheletto, Carvalho and Pinto (2008) came up with a mathematical programming model that is applied to the operational planning of the utility plant of an oil refinery, where a Mixed Integer Linear Problem (MILP) model is formulated to determine the operational configuration of the plant by minimizing utility costs, and identifying steam losses as well as inefficient units by comparing the optimal solutions with the current operation. Neiro and Pinto (2004) went further to present a general framework for modeling petroleum supply chains, by considering the individual supply chain units as a continuous entity, where the decision variables include stream flow rates, properties, operational variables, and inventory, and facilities assignment.

Thomas and Griffin (1996) work in the area of Supply Chain Management (SCM) can be classified in three categories: buyer – vendor, production–distribution and inventory–distribution coordination. The authors present an extensive literature review for each category. The work by Vidal and Goetschalckx (1997) presented a review of mixed integer problems (MIP) that focuses on the identification of the relevant factors included in formulations of the chain or its subsystems and also highlights solution methodologies.

Bok, Grossmann, and Park (2000) developed an application that will be used in the optimization of continuous flexible process networks. Their modeling considers intermittent deliveries, production shortfalls, delivery delays, inventory profiles and job changeovers. They introduced a bi-level solution methodology that can be used to reduce computational expense. Zhuo, Cheng, and Hua (2000) used a Goal programming method to solve the multi-objective optimization problem, and came up with a supply chain model that involves conflicting decisions in the objective function. Perea, Grossmann, Ydstie, and Tahmassebi (2000) and Perea-López, Grossmann, and Ydstie (2001) present an approach that is capable of capturing the dynamic behavior of the supply chain by modeling flow of materials and information within the supply chain. Information is considered as perturbation of a system control whereas material flows are considered to be control variables. Therefore, this approach is able to react on time and to coordinate the whole supply chain for changing demand and inherent risk conditions. Similarly, Ydstie, Coffey, and Read (2003) apply concepts from dynamics and control in the management of highly distributed supply chains. Important aspects of the supply chain problem are captured in a graph representation, such as topology, transportation,

shipping/receiving and market conditions, assembly/disassembly, storage of assets, forecasting and performance evaluation. Song, Bok, Park, and Park (2002) developed a design problem of multi - product, multi-echelon supply chain. Transportation cost is treated as a continuous piecewise linear function of the distance and a discontinuous piecewise linear function of the transportation volume, whereas installation costs are expressed as a function of the capacity. Feord, Jakeman, and Shah (2002) work proposed a network model whose main objective is to decide which orders should be met, delayed or not to be delivered.

The work by Sear (1993) was probably the first to address the supply chain management in the context of an oil company. The author developed a linear programming network model for planning the logistics of a downstream oil company. The model involves crude oil purchase and transportation, processing of products and transportation, and depot operation. While, Escudero, Quintana, and Salmeron (1999), went further to propose an LP model that handles the supply, transformation and distribution of an oil company that accounts for uncertainties in supply costs, demands and product prices. Dempster, Pedron, Medova, Scott, and Sembos (2000) applied a stochastic programming approach to planning problems for a consortium of oil companies. First, a deterministic multiperiod linear programming model is developed for supply, production and distribution. The deterministic model is then used as a basis for implementing a stochastic programming formulation with uncertainty in product demands and spot supply costs. Lasschuit and Thijssen (2003) pointed out how the petrochemical supply chain is organized and stress important issues that must be taken into account when formulating a model for the oil and chemical industry.

Important developments of subsystems of the petroleum supply chain can be found in the literature. Iyer, Grossmann, Vasantharajan, and Cullick (1998) developed a multiperiod MILP for planning and scheduling of offshore oil field infrastructure investments and operations. The nonlinear reservoir behavior is handled with piecewise linear approximation functions. A sequential decomposition technique is applied. Van den Heever and Grossmann (2000) presented a nonlinear model for oilfield infrastructure that involves design and planning decisions. The authors consider non-linear reservoir behavior. A logic-based model is proposed that is solved with a bi-level decomposition technique. This technique aggregates time periods for the design problem and subsequently disaggregates them for the planning sub-problem. Van den Heever, Grossmann, Vasantharaan, and Edwards (2000) addressed the design and planning of offshore oilfield infrastructure focusing on business rules. A disjunctive model capable to deal with the increased order of magnitude due to the business rules is proposed. Ierapetritou, Floudas, Vasantharaan, and Cullick (1999) studied the optimal location of vertical wells for a given reservoir property map. The problem is formulated as a large scale MILP and solved by a decomposition technique that relies on quality cut constraints. Kosmidis, Perkins, and Pistikopoulos (2002) described an MILP formulation for the well allocation and operation of integrated gas-oil systems whereas Barnes, Linke, and Kokossis (2002) focused on the production design of offshore platforms.

Cheng and Duran (2003) focused on the crude oil worldwide transportation based on the statement that this element of the petroleum supply chain is the central logistics that links the upstream and downstream functions, playing a crucial role in the global supply chain management in the oil industry.

At another level of the supply chain, Lee, Pinto, Grossmann, and Park (1996) concentrated on the short-term scheduling of crude oil supply for a single refinery. Más and Pinto (2003) and Magalhães and Shah (2003) focus on the crude oil supply scheduling. The former developed a detailed MILP formulation comprised of tankers, piers, storage tanks, substations and refineries, whereas the latter addresses a scheduling problem composed of a terminal, a pipeline, a refinery crude storage area and its crude units. Pinto, Joly, and Moro (2000) and Pinto and Moro (2000) focused on the refinery operations. The former work focuses on production scheduling for several specific areas in a refinery such as crude oil, fuel oil, asphalt and LPG whereas the latter addresses a nonlinear production planning. Jia and Ierapetritou (2003) concentrate on the short-term scheduling of refinery operations. Crude oil unloading and blending, production unit operations and product blending and delivery are first solved as independent problems. Each sub-system is modeled based on a continuous time formulation. Integration of the three sub-systems is then accomplished by applying heuristic based Lagrangean decomposition. Wenkai and Hui (2003) studied similar problem to that addressed by Jia and Ierapetritou (2003) and propose a new modeling technique and solution strategy to schedule crude oil unloading and storage. At the refinery level, units such as crude distillation unit and fluidized-bed catalytic cracking were modeled and a new analytical method was proposed to provide additional information for intermediate streams inside the refinery.

Ponnambalam, Vannelli, and Woo (1992) developed an approach that combines the simplex method for linear programming with an interior point method for solving a multiperiod planning model in the oil refinery industry. Still at the production planning

level, Liu and Sahinidis (1997) presented a fuzzy programming approach for solving a petrochemical complex problem involving uncertainty in model parameters. Bok, Lee, and Park (1998) addressed the problem of long-range capacity expansion planning for a petrochemical industry. Deshmukh (2007) designed a model for a decision support system for supply chain risk management.

Ross (2000) formulated a planning supply network model on the petroleum distribution downstream segment. Resource allocation such as distribution centers (new and existing) and vehicles is managed in order to maximize profit. Delivery cost is determined depending on the geographic zone, trip cost, order frequency and travel distance for each customer. Iakovou (2001) proposed a model that focuses on the maritime transportation of petroleum products considering a set of transport modalities. One of the main objectives of this work was to take into account the risks of oil spill incidents. Magatão, Arruda, and Neves (2002) propose an MILP approach to aid the decision-making process to schedule commodities on pipeline systems. On the product storage level, Stebel, Arruda, Fabro, and Rodrigues (2002) present a model involving the decision making process on storage operations of liquefied petroleum gas (LPG).

Lababidi, Ahmed, Alatqi and Al-Enzi (2004), developed an optimization model for the SC of a petrochemical company operating under uncertain operating and economic conditions, by first developing and testing a deterministic model, and, subsequently introducing uncertainties in key parameters like, demands, market prices, raw material costs, and production yield. The authors came to a conclusion that uncertainties have a dramatic effect on the planning decisions of the petrochemical SC. Applequist, Pekny and Reklaitis (2000), presented a new metric for evaluating, design

and planning in chemical manufacturing SC in which there are significant elements of uncertainty and risks. Guillen, Mele, Bagajewcz, Espuna and Puigjaner (2005), considered the design and retrofit problem of a SC consisting of several production plants, warehouses and markets, with their associated distribution systems, under uncertainties, while also noting the profit over the time horizon and resulting demand satisfaction. Santoso, Ahmed, Goetschalckx and Shapiro (2005), in their work proposed a stochastic programming model and solution algorithm for solving SC network design problems of a realistic scale, to quickly compute high quality solutions to large-scale stochastic SC design problems with a huge number of scenarios. Peidro, Mula, Poler and Lario (2009), in their work carried out a review of the literature related to SC under uncertainty, to come up with a starting framework to model uncertainty in SC by applying quantitative approaches. Al-Othman, Lababidi, Alatqi and Al-Shayji (2008), developed a stochastic planning model to study the impact of uncertainty on the supply chain, by performing a sensitivity analysis in market demands and prices of different commodities at $\pm 20\%$ deviation. Stadtler (2005) studied the essence of SCM and advanced planning from two conceptual frameworks; as a SC planning matrix and then, looking at the software that can be used for SC advanced planning, and then outlining the main short comings in SCM. Philpott and Everett (2001) developed a SC optimization model for Fletcher Challenge Paper Australasia (FCPA), known as Paper Industry Value Optimization (PIVOT). This model which is a large MIP model was used to find the optimal allocation of supplier to mill, product to paper machine, and paper machine to customer relations, and subsequently providing significant economic benefits to the company. Jung, Blau, Pekny, Reklaitis and Eversdyk (2004), in their work focused on

determining the safety stock level that can be used to meet a desired level of customer satisfaction by using a simulation based optimization approach. They proposed the use of deterministic planning and scheduling models which incorporate safety stock levels as a means of accommodating demand uncertainties in routine operation. Xu and Zhai (2009), in their paper considered a two- stage supply chain coordination problem that focused on the fuzziness aspect of demand uncertainty, by investigating the optimization of the vertically integrated two-stage SC, that is, under perfect coordination, and non-coordination, and came up with the conclusion that expected SC profit is greater in the coordinated condition than the non-coordinated condition. Petrovic, Roy and Petrovic (1998), in their work described the fuzzy modeling and simulation of a SC in an uncertain environment as the first step in developing a decision support system. Cheng and Lee (2004) developed a MINLP model to deal with the multiple incommensurable goals for a multi-echelon SC network with uncertain market demands and product prices. The authors modeled the uncertain market demands as a number of discrete scenarios with known probabilities.

Urso, Colpo and Sheble (2006) discussed the need for the integration of process and security systems for oil production platforms, pipelines, and terminals in an oil and gas supply chain. Pitty, Li, Adhitya, Srinivasan and Karimi (2008) demonstrated that a dynamic model of an integrated supply chain can serve as a valuable quantitative tool that aids in decision making in refinery supply chains. Kleindorfer and Saad (2005) in their work provided a conceptual framework that reflects the joint activities of risk assessment and risk mitigation that are fundamental to disruption risk management in supply chains. Yu, Zeng and Zhao (2009) in their work focused on evaluating the impacts of supply

disruption risks by comparing the choice between single and dual sourcing methods in a two-stage supply Chain (SC) with a non-stationary and price sensitive demand. Chopra and Sodhi (2004) analyzed how to manage, analyze and neutralize supply chain risks across the entire supply chain in a rapidly changing environment, and recommended a powerful ‘what if?’ team exercise called stress testing to identify potential weak links in the chain and then select best ways of mitigating them. Adhitya, Srinivasan and Karimi (2007) developed a causal model called the composite-operations graph, to capture the cause-and-effect among all the variables in supply chain operation and then using a rectification graph which captures all possible options to overcome these disruptions. Julka, Karimi and Srinivasan (2002) proposed an agent based framework for refinery supply chain decision support systems (DSSs) that will be used to integrate all the decision making processes of a refinery, by interfacing with other systems in place, and be able to assist different departments concurrently in responding to changes in policies, exogenous events and plant modifications.

In conclusion, to our knowledge, current approaches to managing risks and uncertainties in the oil and gas critical infrastructure supply chains are mostly reactive, employing re-routing of supply and rationing. These lead to increased prices and negative impact on economic activity due to lack of resiliency. The existing models to our knowledge do not take the inherent risks and vulnerabilities from, events, different routes, various sources and individual supply chain units/nodes into consideration. However, logic-based approaches have shown potential to efficiently model and solve large systems without reducing problem complexity (Neiro and Pinto, 2004; Vecchiotti

and Grossman, 2000; Van den Heever and Grossman, 1999; Turkey and Grossman, 1996).

2.2 Risk and Vulnerability

The oil and gas supply chain as illustrated in Figures 2.1, 2.2 and 2.3, shows that crude oil from a well head or international sources is transported to a refinery by a pipeline system or boat. The refinery converts the crude into refined products, which in turn are transmitted over long distance to terminals, where they are stored. Then a distribution network of pipelines, trucks, and so on delivers the product to consumers.

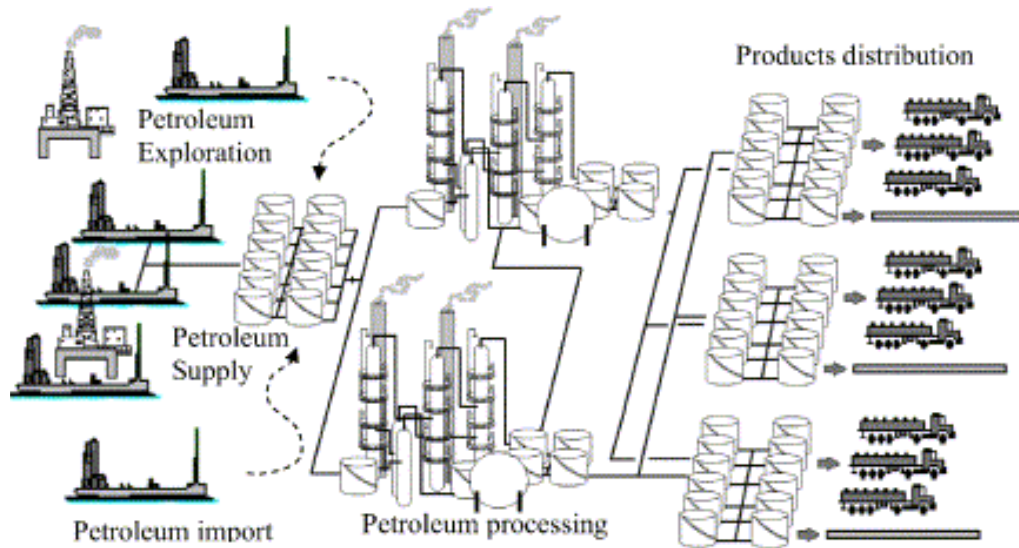


Figure 2.1 General oil and gas supply chain.

Source: Neiro and Pinto (2004).

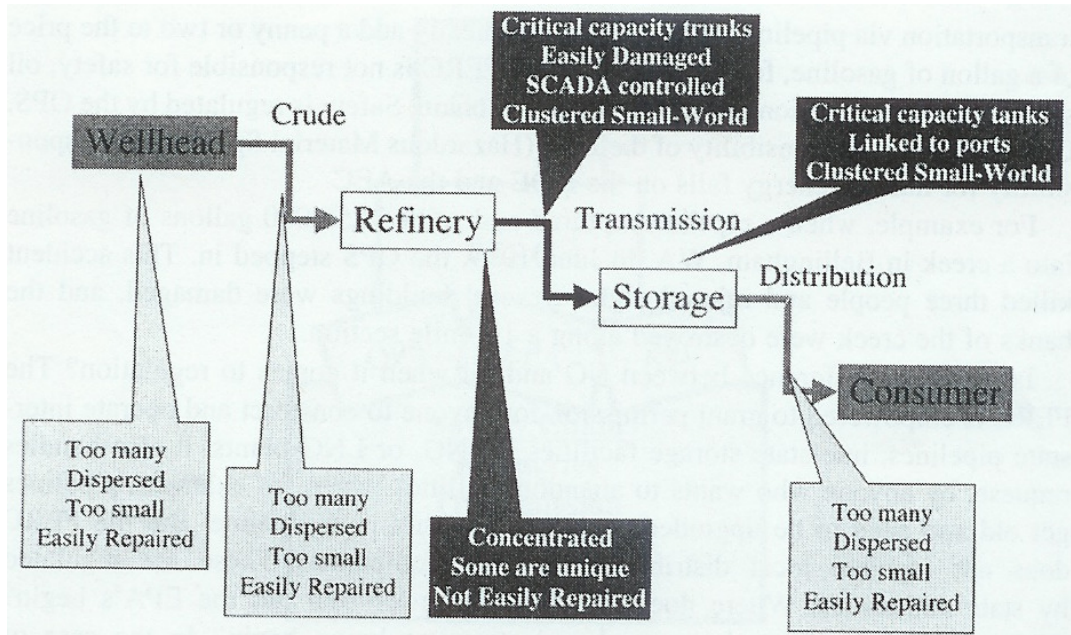


Figure 2.2 Simplified oil and gas supply chain.

Source: Lewis (2006).

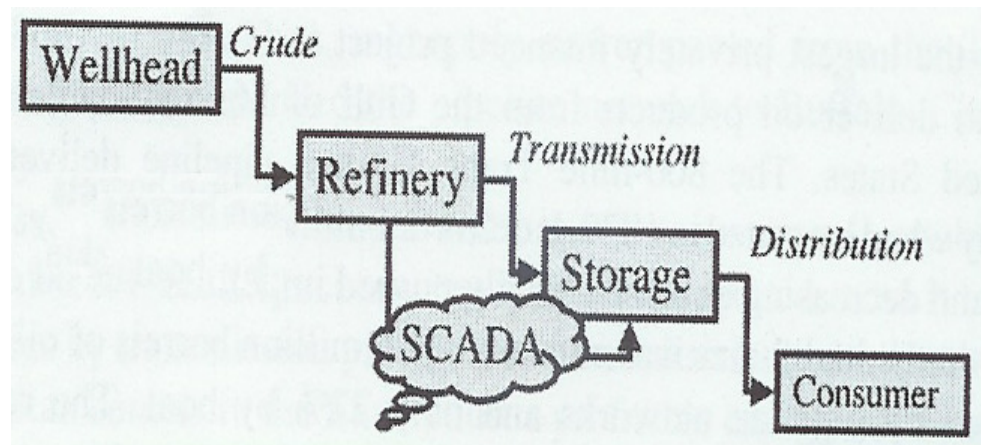


Figure 2.3 Simplified oil and gas supply chain.

Source: Lewis (2006).

The vast miles of US pipelines shown in Figures 2.4 to 2.6 below are monitored by various SCADA systems that report anomalies such as leaks and broken component. Major decisions during production planning include, individual product levels for each

product to meet consumer requirements, as well as operating conditions for each refinery in the network, as well as product and crude transportation scheduling, inventory and management, while making sure that the level of risks/ vulnerabilities is lowered to the level that will ensure acceptable optimum production.

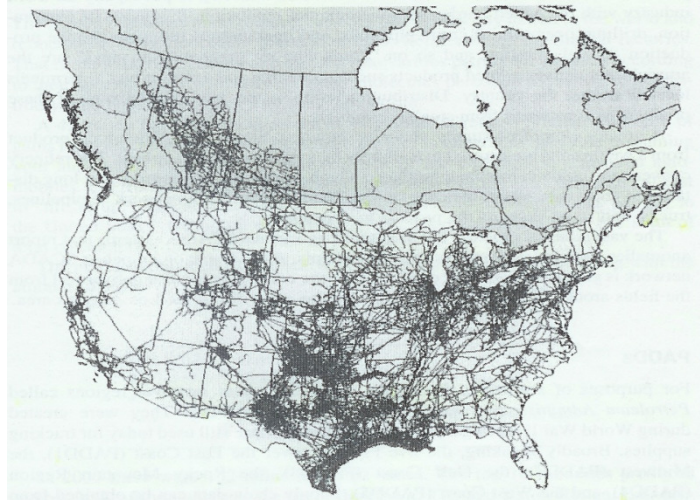


Figure 2.4 Petroleum pipeline network of North America.

Source: Lewis (2006).

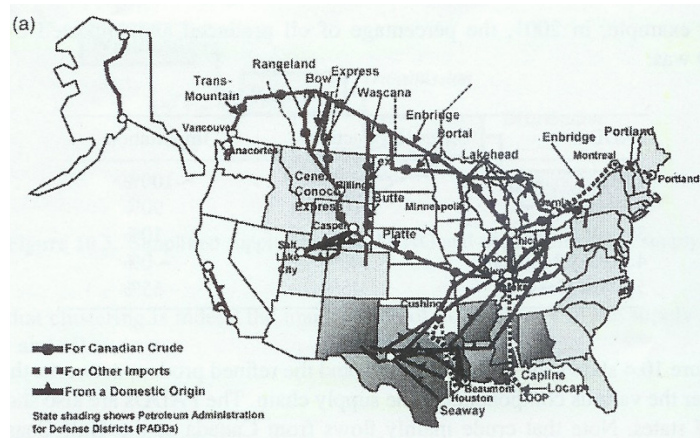


Figure 2.5 Crude oil pipelines.

Source: Lewis (2006).

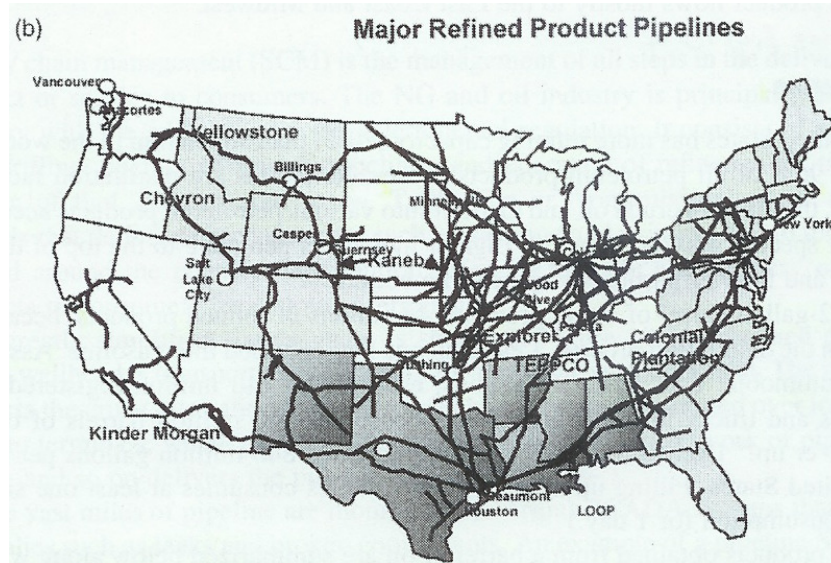


Figure 2.6 Refined oil pipelines.

Source: Lewis (2006).

The vulnerability assessment methods require analysis of a manufacturing process's response to a terrorist attack. However, the methodologies do not include other causes of failure like natural disasters and man - made causes, and also lack of maintenance and perceived neglects of government for basic infrastructural needs like pipe borne water, electricity, healthcare, roads e.t.c., and attacks by local militants where the oil is being explored, example of the latter scenario is Nigeria, the sixth biggest oil producer in the world and Africa's biggest oil producer, where it is reported that the country's production level has dropped below 60% of its expected OPEC quota due to the actions of the local militants, and also Iraq.

2.2.1 Pipeline

Until recently, the pipeline industry has been preoccupied primarily with environmental, safety and maintenance issues. Beyond occasional cases of vandalism, the human factor

was hardly perceived as a threat to the world's vast web of oil and gas pipelines, which, all told, carry roughly half of the world's oil and most of its natural gas.

All this has changed since the 9-11 attack in the US. With the threat of terrorism looming, pipeline operators in the industrialized world have taken action to prevent terrorism from harming energy infrastructure. Although these have made the pipeline system in places like North America and Europe relatively secure, since most U.S. oil and a growing portion of its natural gas come from abroad, *our energy system cannot be protected unless similar security measures are applied at the generating points of oil and gas in the Middle East, the Former USSR, Africa and Latin America.*

Pipelines are very easily sabotaged. A simple explosive device can put a critical section of pipelines out of operation for weeks. This is why pipeline sabotage has become the weapon of choice of the insurgents in Iraq. It is estimated that pipeline sabotage costs the Iraq people more than \$10 billion in oil revenues – and helped to undermine the Iraq re-construction project and subsequently affected the pump price of gasoline to consumers.

In December 2004, Sudanese rebels attacked an oil field, killing 15 people. Chechen guerrillas fighting to sever themselves from Russia are going after the country's gigantic pipeline web of roughly 31,000 miles. Russia is the world's second largest oil exporter and 40% of its revenue is derived from oil. There is no better way for the Chechens to hurt the Russian economy than hindering Russia's capability to export crude. In 2004, pipelines were blown up in Volgograd, Dagestan, Stavropol as well as in and around Moscow.

In India, a separatist rebel group called United Liberation Front of Asom (ULFA), which fights for independence for the oil rich Assam state, has taken responsibility for a number of pipeline attacks. Assam is the source of some 15% of India's onshore crude oil production and, as the country's oil demand grows, the implications of disruption of the flow of oil from there will become increasingly noticeable.

In Southeast Turkey, Kurdish guerrillas belonging to the Kurdistan Workers Party (PKK) have staged a campaign of bomb attacks on an oil pipeline.

In Columbia, terrorist groups, primarily the Revolutionary Armed Forces of Columbia (FARC) and the National Liberation Army (ELN) have attacked the 480-mile Cano Limon Covenas oil pipelines so many times that it became known as "the flute".

Nigeria, who is the 4th largest supplier of crude oil to North America (which includes US), loses between 200,000 – 300,000 barrels per day (bpd) (i.e. 10 – 15% of their total production) to criminal gangs.

Terrorists have also indicated interest in the nearly completed 1,000 mile Baku-Tbilisi-Ceyhan (BTC) pipeline, slated to transport 1 million barrels of oil a day from the Caspian Sea to Western markets through the Turkish port of Ceyhan.

Another problematic area in the pipeline's path is Georgia, where separatists in South Ossetia and Abkhaziz provinces often clash with the Georgian government. In China, the world's fastest growing energy consumer is also vulnerable to terrorist strikes against oil. To satisfy its growing energy needs, China has decided to run pipelines connecting the northwest district of Xinjiang with neighboring Kazakhstan. This means China's oil will be at the mercy of increasingly hostile Muslim Uighur minorities trying to break away from the central regime in Beijing.

But in no oil and gas domain could pipeline sabotage do more damage than in Saudi Arabia, home to one-fourth of the world's oil. Over 10,000 miles of pipeline crisscross Saudi Arabia, mostly above ground. Were concerted pipeline attacks to spread to Saudi Arabia, repeatedly interrupting the Saudi oil supply, the implications for the global economy could be profound.

Whether perpetrated for political or criminal reasons, assaults on oil infrastructure have added a "fear premium" of roughly \$10 per barrel of oil. For the U.S., that imports more than 10 million barrels a day, the spike in oil prices due to oil terror cost close to \$40 billion in 2004.

2.2.2 Supervisory Control and Data Acquisition (SCADA) systems and Distributed Control Systems (DCS)

In order to supply two-thirds of the United States' energy usage, the oil and gas industry depends upon a vast and highly decentralized infrastructure, consisting of roughly 50 refineries, 200,000 miles of oil pipelines, and 2 million miles of gas pipelines. The long production chain begins with exploration and drilling and ends with delivery to consumers.

Supervisory Control and Data Acquisition (SCADA) systems and Distributed Control Systems (DCS) form the backbone of most oil and gas industry operations globally. Controlling this infrastructure is highly complex, requiring many pieces of individual equipment to be monitored. A delicate balance of flows, temperatures, pressures, and other parameters must be maintained to ensure proper refinery plant operations and pipe distribution.

As oil and gas companies work to enhance security measures to ensure an uninterrupted supply of these important commodities, they face a number of challenges,

including the need to connect once isolated SCADA and DCSs with business systems and networks; clashing organizational priorities; and no mandate to comply with cyber security – security related standards.

Two factors have moved control system security quickly up the list of priorities for oil and gas companies:

- SCADA systems and DCS used within refineries and to control pipelines are vulnerable to cyber threats, and
- The explosive nature of these commodities makes this industry's infrastructure an attractive target.

Beyond malicious attacks perpetrated by both outsiders and insiders, other sources of vulnerabilities in SCADA and DCS are: vulnerabilities caused by architectural oversights, unaware or untrained employees, partners, and contractors can also be the source of security risks. Common internal causes of security vulnerabilities include poor password protection, failure to update protection software, failure to scan files, inappropriate on - the - job Web surfing and file downloading.

These vulnerabilities leave oil and gas companies susceptible to exploration, attack and loss of proprietary information. To effectively meet NERC CIP compliance and to ensure uninterrupted security stance to prevent:

- Environmental damages
- Regulatory violations
- Interrupted business operations
- Costly equipment damages
- Financial loss

- Potential loss of life

Adding to the pressure is heightened awareness by those outside of the industry about the vulnerabilities of SCADA and DCS systems and the attractiveness of oil and gas pipelines and refineries as an attack target. There is also growing recognition that control systems used in oil and gas plant and pipeline operations are vulnerable to cyber attacks from numerous sources, and companies struggle to address cyber security, on a variety of levels.

Gas and oil companies have also adopted a number of practices to improve efficiency, many of which inadvertently increase the vulnerability of control systems. While the modern SCADA and DCS systems are built-in with much more security, deployments remain insecure, opening these networks to security threats and vulnerabilities.

For instance, SCADA and DCSs within the oil and gas industry are increasingly being integrated with existing business information systems and deployed on common operating systems to supply corporate decision-makers with information needed for real time decision –making, such as setting commodity prices. While this interconnectedness provides corporate decision-makers with access to critical data, it also leads to widespread availability of information about these control systems and their vulnerabilities.

Typically, this connectivity is enabled via the internet, leaving SCADA and DCS systems vulnerable to threats such as automated worms. This interconnectivity also enables hackers to access these systems through which they can deactivate alarms, start or stop equipment, change critical system settings, and more.

Other practices meant to improve business operations, also unintentionally expose these systems to vulnerabilities. One of the key advantages of centralized supervision and remote access is to automate tasks and enable real-time control of the entire system. For instance, gas and oil companies provide remote access for company engineers, contractors via dial-up modems and other means so that off-site personnel can troubleshoot SCADA and DCS problems. Similarly, visiting employees from other locations, hired contractors, and other authorized parties sometimes need to access to the corporate network from their laptop computers.

Maintaining 24/7 operations via remote system access introduces additional vulnerability points. This interconnection with the corporate network introduces new access points to the SCADA and DCS system, through which viruses or malicious code could infiltrate the network and systems. At the same time, the nonstop operational requirements of SCADA and DCS systems, complicates security implementation and testing because systems can never be taken offline.

Additionally, the oil and gas infrastructure is widely dispersed geographically, further complicating efforts to secure it. Even with well-implemented intrusion detection systems, network security staff may only recognize individual attacks, rather than organized patterns of attacks over time.

Competing standards and regulatory guidelines intended for the oil and gas industry only lead to the confusion. In fact, oil and gas companies are not currently required to comply with any cyber security-related standards. Despite national policies, encouraging a resilient infrastructure that can withstand an attack, oil and gas companies may find it cost-prohibitive to meet those expectations.

2.2.3 Refineries

According to Lewis (2006), five of the top ten refineries in the US fall into the geographic clusters called the Gulf coast area, which stretches from south of Houston, TX, to Lake Charles in LA (East), and then to Baton Rouge, LA, and constitutes a critical node in the petroleum supply chain. They produce about 11% of the total refined petroleum products in the US. In fact, the top ten refineries combined, produce 19.4% of all refined products in the US.

Refineries can be shut down because of lack of power, insufficient supply of crude, or fire damage, either by natural causes, attacks, or lack of maintenance. Though power outages may last for only a few hours, destruction of crude oil pipelines can deny service to a refinery for days, while explosion of fire can cause longer term damages, like several months. Thus the cost and probability of each incident will vary without any known certainty.

Refinery replacement can cost more than \$1 billion, and the loss of production (500,000 barrels/day), which can have severe implications on revenues as well as shortages that will lead to price increases at the gasoline station.

According to Lewis et al, Galveston, which is the location of the largest refinery in the US, was the site of the deadliest hurricane in U.S. history in 1900, with over 8,000 people losing their lives. In 1947, also, the largest port disaster in U.S. history wiped out Texas City, when a ship containing fertilizer caught fire and spread throughout the port and much of the town. Records show that over the years, the worst refinery disasters have followed large clusters like Texas City: Whiting, IN; Texas City, Pasadena, and Amarillo, TX; Baton Rouge, LA; Romeoville, IL; and Avon and Torrence, CA. All these show that

refineries are highly vulnerable, and concentrations such as the Galveston Bay cluster are both highly critical to the oil supply chain and vulnerable to damage.

According to Wikipedia, Hurricane Katrina of the 2005 Atlantic hurricane season was regarded as the costliest natural disaster, as well as one of the five deadliest hurricanes, in the history of the United States. It formed over the Bahamas on August 23, 2005 and crossed into southern Florida as a moderate Category 1 hurricane, causing some deaths and flooding there before strengthening rapidly in the Gulf of Mexico. It finally weakened before making its second landfall as a Category 3 storm on the morning of Monday, August 29 in southeast Louisiana. This category 3 hurricane caused severe destruction on the oil and gas supply chain of the Gulf coast area of the US - from central Florida to Texas, due mainly to storm surge.

It was recorded to have damaged or destroyed at least 30 oil platforms and caused the closure of nine refineries, leading to approximately 24% drop in oil production from the Gulf of Mexico in months following the storm. It also caused oil spills/leaks that were estimated at over 200,000 barrels.

A June 2007 report into the possible causes of the high level of damages from Katrina released by the American Society of Civil Engineers showed that the failures of the locally built and federally funded levees in New Orleans, contributed heavily to this disaster. The report also showed that the disaster was found to be primarily the result of system design flaws. In addition, it pointed out that the US Army Corps of Engineers who by federal mandate are responsible for the conception, design and construction of the region's flood-control system failed to pay sufficient attention to public safety.

Efforts are currently being made in order to minimize the future impact of any successful hurricane in the Gulf coast area. The government has been reconstructing many of the levees since the time of Katrina. In reconstructing them, precautions are being taken to bring the levees up to the modern building code standards and to ensure their safety. For example, in every situation possible, the Corps of Engineers are replacing I-walls with T-walls. T-walls have a horizontal concrete base that protects against soil erosion underneath the floodwalls, thereby minimizing the ability of the storm to cause more damages offshore.

2.2.4 Storage

Critical nodes in the storage components of the supply chain are large capacity clusters located in key transportation nodes, such as Perth Amboy, NJ. Most carriers like Colonial, whose 5,500 miles long (from Texas to New York), that delivers an average of 95 million gallons/day of gasoline, kerosene, home heating oil, diesel fuels, and national defense fuels to shipper terminals in 12 states and the District of Columbia, with an estimated 20% market share of the national supply and boasting the largest-capacity petroleum transmission network in the world, have their termination Perth Amboy, NJ, where the products are stored before being distributed by Buckeye Pipeline. These high concentrations of vast supplies in storage tanks in and around Linden Station provides an eye-popping target, thus making Colonial and Linden Station storage facilities a critical link and critical node, respectively in the supply chain.

A fatigue crack on January 2, 1990, in an Exxon pipeline at Linden Station ruptured and spilled an estimated 567, 000 gallons of fuel into the Arthur Kill waterway between New Jersey and Staten Island. The spill caused extensive environmental

damage. In fact, Exxon did not immediately detect the spill because operating staff had disabled the leak detection system, so pumping continued for 9 hours after the pipeline sprung the leak. It was only when Exxon conducted a pressure test, pumping more oil into the water, did a Coast Guard team in small boat noticed oil bubbling to the surface, and determined that the pipeline was the source.

Based, on this fact, it can be said that it is not only feasible for major oil incidents to happen at large storage terminals, but it has already happened.

2.3 Meaning of Vulnerability and Risk in the Context of CIP

Haimes (2004) defined the notion of vulnerability as follows: vulnerability is the manifestation of the inherent states of a system that renders it susceptible to damage or loss. A system is taken in the general sense to be a group of regular interacting and interconnected items that form a unified whole (Ayyub and Klir 2006). In a later publication, Haimes (2006) emphasized that vulnerability is a multidimensional concept best described by a suite of state variables that describe system weaknesses and how they interact to cause loss following a disruptive event. Numerous other researchers have explored the meaning of vulnerability in different contexts (e.g., Villagrán de León 2006; Hellström 2005; McEntire 2005; Agarwal et al. 2003; Paton and Johnson 2001; Weichselgartner 2001; Einarsson and Rausand 1998), and the general consensus is that any aspect of a system that weakens its ability to survive in a disruptive or hostile environment contributes to its overall vulnerability.

It is widely accepted that vulnerability is an important component of risk analysis (see Aven 2007; Haimes 2006; Pinto et al. 2003). As with vulnerability, risk is a multidimensional concept that describes the potential for loss associated with a disruptive

event (Ayyub 2003) where, for a given event or scenario, the risk is the pairing of its probability of occurrence and the consequences given its occurrence (Kaplan and Garrick 1981). It can be inferred from the notions of vulnerability and risk that the weaknesses present in a system contribute to its potential for loss following an adverse event. Thus the quantification of risk necessarily requires meaningful ways to assess and measure vulnerability.

Despite this apparently obvious observation, numerous methods in current use within the critical infrastructure protection community do not assess vulnerability as a primary variable in its broadest sense, but rather capture elements of vulnerability implicitly through the assessment of other parameters. For example, in the Risk Analysis and Management for Critical Asset Protection (RAMCAP) methodology, the parameter “vulnerability” is equated to probability of adversary success, and other non-security related weaknesses are melded together under the heading of consequence assessment (Moore et al. 2007). The marginalization of vulnerability to a security issue is common in many other qualitative and quantitative security risk assessment methods. In contrast, many risk models for natural hazards identify vulnerability as the mapping from a state of damage to degree of loss, though in principle whether a system can be damaged in the first place is a question that should also fall under the heading of vulnerability assessment. Though different methodologies are permitted to slice and dice their expressions for risk in different ways that are all equally valid, they are consistent in their use of inconsistent and usually narrow definitions and measures for vulnerability.

Perhaps one reason for the apparent lack of an explicit definition for vulnerability in its broadest sense is the absence of an accepted understanding of what vulnerability

tries to measure. Recently, Ayyub et al. (2007) developed an extensive expression for asset and portfolio risk in an all-hazards context from which, after careful observation of all risk contributors, emerged a mathematical expression for vulnerability that appears to capture the multidimensional essence of vulnerability. According to the authors, this expression explicitly identifies the major contributors to vulnerability in terms of interventions that limit the scope of outcomes between cause and consequence.

2.4 Impact of Global Warming on future Hurricanes

Observed records of Atlantic hurricane activity (e.g. Emanuel 2007) show a strong correlation, on multi-year time-scales, between local tropical Atlantic sea surface temperatures (SSTs) and the Power Dissipation Index (PDI) (Figure 2.7). PDI is an aggregate measure of Atlantic hurricane activity, combining frequency, intensity, and duration of hurricanes in a single index. Both Atlantic SSTs and PDI have risen sharply since the 1970s, and there is some evidence that PDI levels in recent years are higher than in the previous active Atlantic hurricane era in the 1950s and 60s.

Model-based climate change detection/attribution studies have linked increasing tropical Atlantic SSTs to increasing greenhouse gases, but the link between increasing greenhouse gases and hurricane PDI or frequency has been based on statistical correlations. The statistical linkage of Atlantic hurricane to PDI and Atlantic SST in Figure 2.7 suggests at least the possibility of a large anthropogenic influence on Atlantic hurricanes. When the correlation between tropical Atlantic SSTs and hurricane activity shown in Figure 2.7 is used to infer future changes in Atlantic hurricane activity, it shows a sobering implication. That the large increases in tropical Atlantic SSTs projected for the late 21st century would imply very substantial increases in hurricane destructive

potential--roughly a 300% increase in the PDI by 2100 (Figure 2.8a). Though, the statistical relationship between the PDI and the alternative relative SST measure shown in Figure 2.8b would imply only modest changes of Atlantic hurricane activity (PDI) with greenhouse warming, the general consensus from studies is that if global warming is a reality in the future, it will most likely lead to more severity in the impacts of hurricanes in the Gulf coast region in the future.

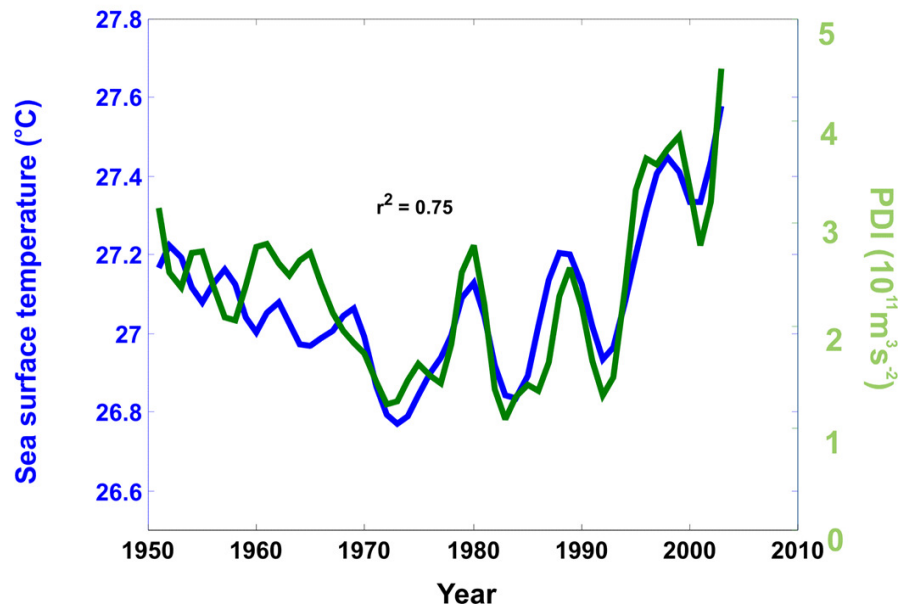


Figure 2.7: Time series of late summer tropical Atlantic Sea Surface Temperature (blue) and the Power Dissipation Index (green) - a measure of Hurricane activity.

Source: Emanuel (2007).

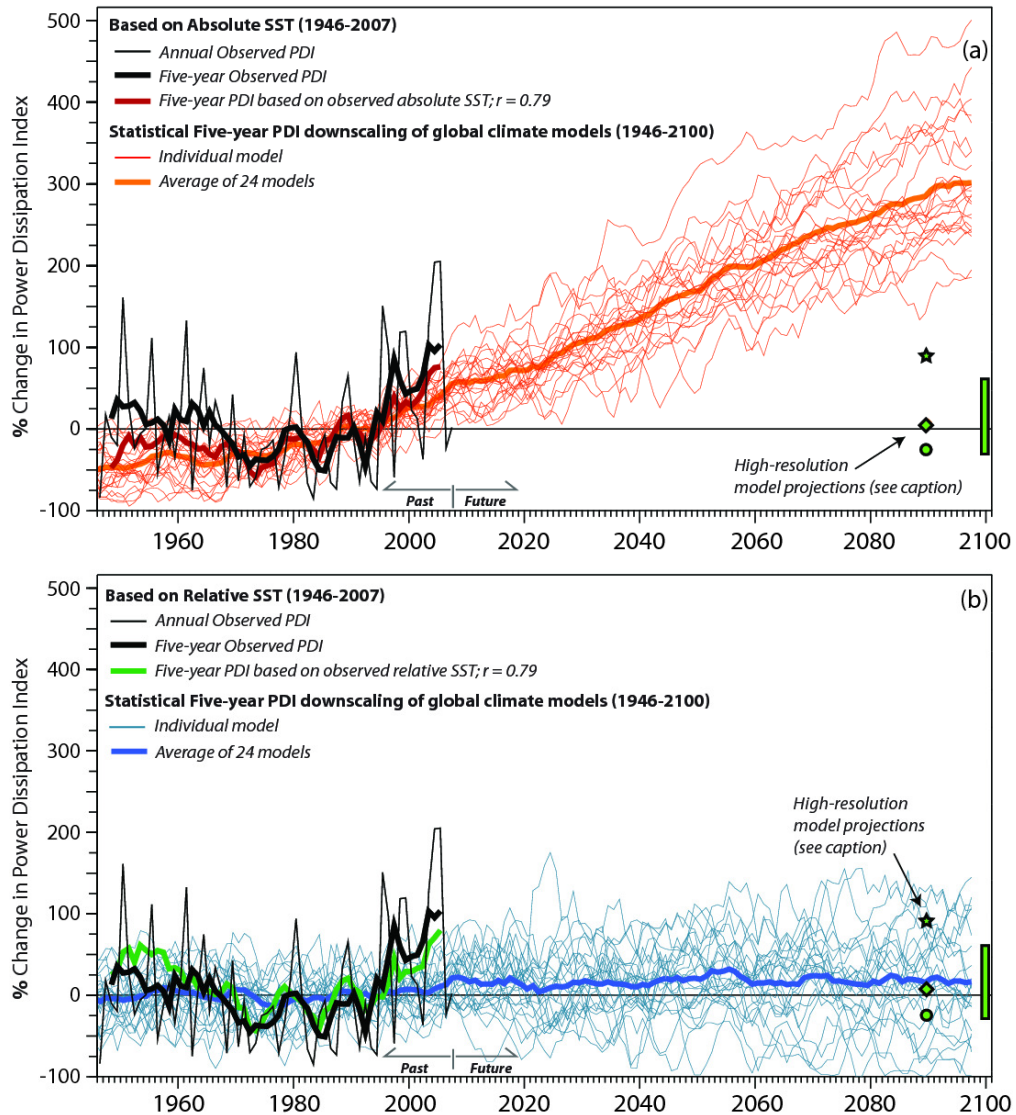


Figure 2.8(a): Statistical model of Hurricane activity based on "local" tropical Atlantic Sea Surface Temperature (SST).

Figure 2.8(b): Statistical model of Hurricane activity based on tropical Atlantic Sea Surface Temperature (SST) relative to SST averaged over the remainder of the tropics.

Source: Vecchi et al. (2008).

CHAPTER 3

EVENTS AND OIL PRICES

3.1 Introduction

Few inputs impact the world economy like the price of oil. Oil powers cars, trucks, boats, airplanes, and even power plants that make up the backbone of the global economy. As oil prices rise, costs go up for transportation companies, squeezing their profit margins and forcing them to raise prices, similarly affecting all the other companies that rely on them to transport products and people. By contrast, most energy companies benefit from higher oil prices, either from higher revenues for oil, or because of increased demand for substitute energy sources such as ethanol and natural gas. 2007 and the first half of 2008 were good times for many energy companies; futures prices rose tremendously, peaking on July 3rd, 2008, at a record high of \$145.85. Since then, however, futures prices have plummeted (dropping below \$50 per barrel by early December), mostly in response to the recession caused by the 2007 Credit Crunch and 2008 Financial Crisis. It has now stabilized between \$70 and \$85 per barrel between 2009 to present (2010). The extreme volatility of this important critical infrastructure led to the study of the history of oil prices fluctuation, and events that caused them, as shown in Figures 3.1 to 3.16, and subsequently analyzing the risk ratings associated with these past events, and using it in the developed model to predict, forecast and prepare for future occurrences and scenarios, so as to minimize or eliminate its adverse impact on the worlds' economy.

Crude Oil prices ranged between \$2.50 and \$3.00 from 1948 through the end of the 1960s. The price oil rose from \$2.50 in 1948 to about \$3.00 in 1957. When viewed in 2006 dollars an entirely different story emerges with crude oil prices fluctuating around

\$17-\$18 during the same period. The apparent 20% price increase just kept up with inflation.

From 1958 to 1970 prices were stable at about \$3.00 per barrel, but in real terms the price of crude oil declined from above \$17 to below \$14 per barrel. The decline in the price of crude when adjusted for inflation was amplified for the international producer in 1971 and 1972 by the weakness of the US dollar.

OPEC was formed in 1960 with five founding members Iran, Iraq, Kuwait, Saudi Arabia and Venezuela. Two of the representatives at the initial meetings had studied the the Texas Railroad Commission's methods of influencing price through limitations on production. By the end of 1971 six other nations had joined the group: Qatar, Indonesia, Libya, United Arab Emirates, Algeria and Nigeria. From the foundation of the Organization of Petroleum Exporting Countries through 1972 member countries experienced steady decline in the purchasing power of a barrel of oil.

Throughout the post war period exporting countries found increasing demand for their crude oil but a 40% decline in the purchasing power of a barrel of oil. In March 1971, the balance of power shifted. That month the Texas Railroad Commission set proration at 100 percent for the first time. This meant that Texas producers were no longer limited in the amount of oil that they could produce. More importantly, it meant that the power to control crude oil prices shifted from the United States (Texas, Oklahoma and Louisiana) to OPEC. Another way to say it is that there was no more spare capacity and therefore no tool to put an upper limit on prices. A little over two years later OPEC would, through the unintended consequence of war, get a glimpse at the

extent of its power to influence prices. The results are dramatically different if only post-1970 data are used.

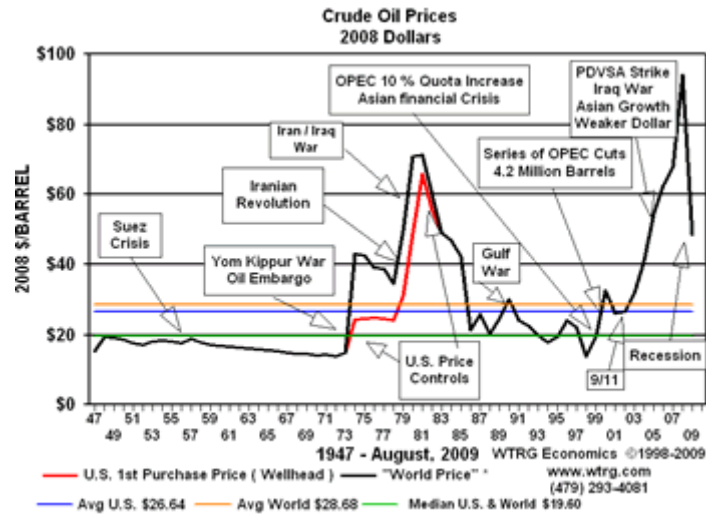


Figure 3.1 Crude oil prices 1947 – August, 2009.

Source: www.wtrg.com (02/26/10)

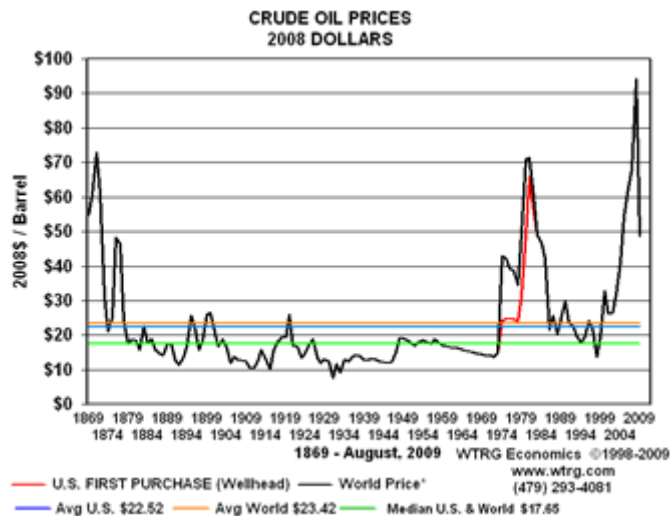


Figure 3.2 Crude Oil Prices 1869-2009.

Source: www.wtrg.com (02/26/10).

In that case U.S. crude oil prices average \$29.06 per barrel and the more relevant world oil price averages \$32.23 per barrel. The median oil price for that time period is \$26.50 per barrel.

If oil prices revert to the mean this period is likely the most appropriate for today's analyst. It follows the peak in U.S. oil production eliminating the effects of the Texas Railroad Commission and is a period when the Seven Sisters were no longer able to dominate oil production and prices. It is an era of far more influence by OPEC oil producers than they had in the past. As we will see in the details below influence over oil prices is not equivalent to control.

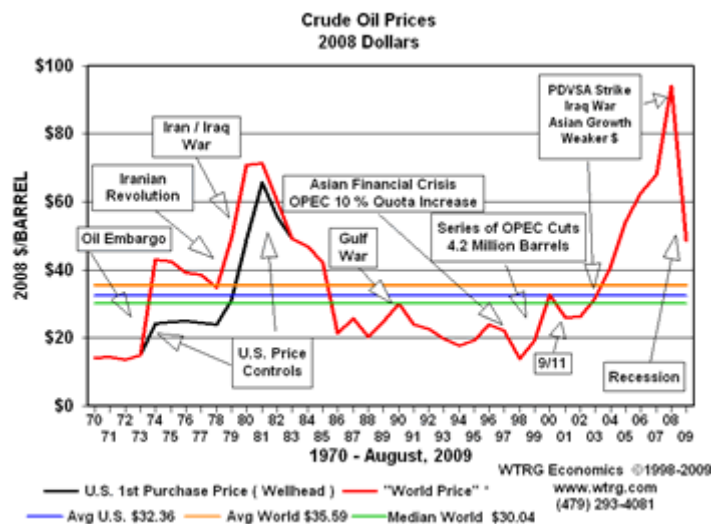


Figure 3.3 Crude oil prices 1970-2009.

Source: www.wtrg.com (02/26/10).

The U.S. petroleum industry's price has been heavily regulated through production or price controls throughout much of the twentieth century. In the post World War II era U.S. oil prices at the wellhead averaged \$24.98 per barrel adjusted for inflation to 2007 dollars. In the absence of price controls the U.S. price would have tracked the

world price averaging \$27.00. Over the same post war period the median for the domestic and the adjusted world price of crude oil was \$19.04 in 2007 prices. That means that only fifty percent of the time from 1947 to 2007 have oil prices exceeded \$19.04 per barrel.

Until the March 28, 2000 adoption of the \$22-\$28 price band for the OPEC basket of crude, oil prices only exceeded \$24.00 per barrel in response to war or conflict in the Middle East. With limited spare production capacity OPEC abandoned its price band in 2005 and was powerless to stem a surge in oil prices which was reminiscent of the late 1970s.

3.1.1 World Price

The only very long term price series that exists is the U.S. average wellhead or first purchase price of crude. When discussing long-term price behavior this presents a problem since the U.S imposed price controls on domestic production from late 1973 to January 1981. In order to present a consistent series and also reflect the difference between international prices and U.S. prices we created a world oil price series that was consistent with the U.S. wellhead price adjusting the wellhead price by adding the difference between the refiner's acquisition price of imported crude and the refiners average acquisition price of domestic crude.

3.1.2 Spot Prices versus Futures Prices

Spot prices are the prices paid for oil here and now - as in, the amount of money you would hand a producer in exchange for their tossing a barrel of oil into the back of your truck. Futures prices, on the other hand, are the prices paid for contracts promising the delivery of oil at a future date. Whether or not the prices of oil futures affect spot prices is one of energy economics' most prevalent modern debates.

Moreover, there really is no "true" spot market for oil, in the sense of that there is a "true" spot market for stock or other financial assets. A "true" spot market requires, as described above, the actual physical transfer of the goods, to the purchaser, directly at the time of purchase, and there simply are no large scale sellers of crude oil, that operate in such a fashion. The "spot" prices that are quoted, involve the transfer of 1000 barrels of crude oil, not one or two. That would require literally 5 of 6 tractor-trailer rigs to carry off back to your house: the transportation costs would approach the value of the oil itself. When one speaks of a "spot" price for crude oil, one is meaning the current trading price, of the next future contract that will come due.

Those that claim that futures prices (and, therefore, speculation) do not affect spot prices argue that people who purchase futures contracts do not actually purchase any real oil. When a fund purchases a futures contract and that contract comes due, it must sell the oil to someone who will actually use it, because that fund has no way of actually keeping the physical product. This means the oil must come to market - no matter what the price. If a firm buys a \$150/barrel futures contract in June for July and the spot price in July is \$140, the firm must buy the oil at \$150, and then it MUST sell the oil at \$140 as well, because it can't actually hold the oil. This means there is no accumulation of oil - firms can't hoard oil, so they can't actually affect the present market. Therefore, it is argued, the prices of futures contracts have no affect on spot prices.

Those that believe futures speculation has an effect on spot prices (at least, those with a sound understanding of economics) argue that when oil futures are traded, oil purchasers, like refiners, try to buy oil at prices that will benefit their margins in both the short and long term. If it is believed that oil prices will rise in the future (indicated by

futures prices being higher than present prices), purchasers will want to stock up on oil at lower prices today and put it in inventory; this drives up demand for crude in the present, forcing oil prices up in the present. Thus, it is argued, high prices for oil futures leads to high prices for oil in the present.

The Very Long Term View. The very long term view is much the same. Since 1869 US crude oil prices adjusted for inflation have averaged \$21.05 per barrel in 2006 dollars compared to \$21.66 for world oil prices.

Fifty percent of the time U.S. and world prices were below the median oil price of \$16.71 per barrel.

If long term history is a guide, those in the upstream segment of the crude oil industry should structure their business to be able to operate with a profit, below \$16.71 per barrel half of the time. The very long term data and the post World War II data suggest a "normal" price far below the current price.

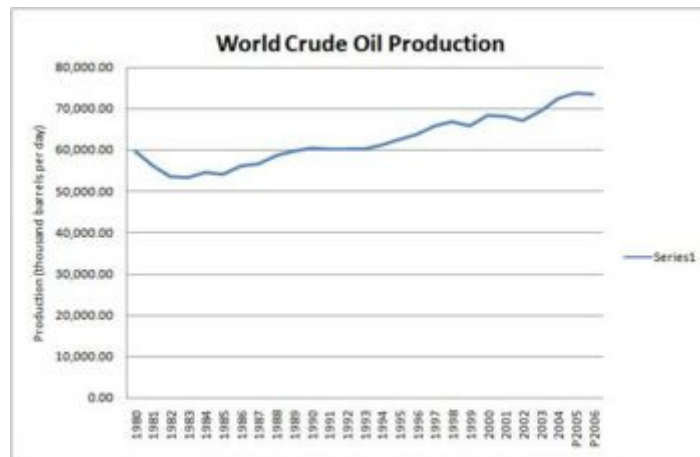


Figure 3.4 World oil production.

Source: www.wikinest.com (02/26/10).

3.2 Causes of Rise or Fall of Oil Prices

Crude oil prices behave much as any other commodity with wide price swings in times of shortage or oversupply. The crude oil price cycle may extend over several years responding to changes in demand as well as OPEC and non-OPEC supply.

3.2.1 Demand Growth Forces Prices Up

Demand for oil, as well as demand for energy in general, is closely tied to the global economic cycle. In periods of economic growth, new factories consume energy, shipping companies transport more goods and consumers take more trips. This demand for energy—or even news suggesting the economy is heating up—pushes up energy prices.

For example, the five major central banks announced in December 2007 that they would pump money into the world economy to help mitigate the possibility of a recession; immediately, the price of oil jumped over \$4 at speculation that energy demand would increase. Conversely, during periods of economic contraction such as recessions, demand for oil and other types of energy tends to fall, leading to reductions in price. In China, for example, manufacturing fell during July and August 2008, and oil prices followed.

The Recent Drop in Oil Prices Due To Demand Destruction. Demand destruction - primarily in the United States - is likely responsible for most of the drop in oil prices that occurred during the third quarter of 2008, and the first quarter of 2010. According to an Energy Information Administration (EIA) report, gasoline consumption in 2008 dropped by 3.4 percent, or 320,000 bpd, from its 2007 levels, it further declined by 0.6 percent throughout 2009, and twelve percent by January, 2010. In the first quarter of 2008,

trucking industry analyst Donald Broughton estimated that 42,000 trucks (over 2% of the United States' fleet), came off the nation's highways. With nearly 1,000 trucking companies filing for bankruptcy, the demand for diesel fuel dropped.

Much of this demand destruction was rooted in the 2007 Credit Crunch, the 2008 Financial Crisis, and the resulting recession in 2008 to 2010 - when unemployment rises, people stop spending and start saving. When people stop spending, companies stop producing. When companies stop producing, demand for energy falls. When demand for energy falls, the price of oil falls. Hence, it is likely that oil prices will remain down until the world economy recovers from its recession.

3.2.2 Production Cuts

The global oil supply is dependent on the ability of oil companies to produce and the willingness of oil-exporting countries to export. Historically, periods of oil price spikes have been caused by oil-exporting countries placing embargoes on certain countries. In 1973, for example, the world's largest oil cartel, OPEC, placed an embargo on oil exports to the Netherlands and the United States, in response to the countries' support of Israel in the Yom Kippur War; the price of oil acquired by refiners increased by approximately 100%, and the U.S. experienced widespread shortages. In 2007, however, despite a 57% increase in prices, the amount of oil exported by the world's top exporters fell by 2.5%. Demand for oil in the world's six largest exporters (Saudi Arabia, United Arab Emirates, Iran, Kuwait, Iraq and Qatar) increased by more than 300,000 barrels, while their exports fell by over half a million barrels. In this case, growing demand in each company acted as a natural embargo, forcing them to meet their own needs before exporting to the rest of the world.

The Financial Crisis of 2008 - 2010 has laid waste to oil prices, by causing a recession so deep even expectations of large supply cuts cannot force prices up. Even with OPEC's cut in production of 2.2 million barrels in 2008, and 4.2 million barrels in 2009 - 2010 - its largest ever - oil futures still fell, as traders ignored decreasing supply and focused on decreasing demand.

3.2.3 Violence against Producers

Since then, oil prices have been volatile because of geopolitical events affecting the ability of upstream oil companies to produce. Terrorist and political attacks can damage drilling rigs or the transportation and refining networks -- including pipelines, shipping facilities, and refineries -- that bring oil from where it is extracted to the consumer. During the spring of 2008, for example, Nigerian rebels initiated attacks on the oil majors' pipelines and deepwater drilling rigs in the country. Despite the fact that OPEC's lead producer, Saudi Arabia, announced it would increase production by 2%, a rebel attack on one of Shell's deepwater rigs sent prices to \$136.

3.2.4 Weather

Strong hurricane seasons can damage offshore oil platforms, reducing the amount of oil produced. Supply can also be artificially reduced or increased by government taxes or subsidies on oil production.

3.2.5 Transportation Bottlenecks

When there are problems with the pipelines that transport oil, it can't get to market; this effectively reduces the supply of crude oil to the world's refiners, causing the supply of refined products to fall. When supplies fall, prices rise. On March 28th, 2008, the day

after the bombing of one of Iraq's primary export charges, Brent crude rose on the London exchange by \$1.01.

3.2.6 Peak Oil and Declining Production

Peak oil refers to the "peak" on the graph of global oil production. Oil must first be discovered, then produced, and will eventually be depleted. Peak Oil is not a theory. It is a fact. Oil has already peaked in the USA and more than 50 other oil producing countries. Oil has a finite supply, so, just the same as the production of any geological commodity, oil production will graphically (mathematically) "peak" and then irreversibly decline.—PGS analyst 00:21, March 2, 2009 (PST)

Once the halfway point "peak" has been passed, production begins to fall and oil prices will rise. Peak Oil is sometimes misunderstood to mean that "we are running out." However, the peak only means we are halfway and there is plenty of oil left, and even conservative estimates are of at least 1.3 Trillion barrels left. The problem is that the oil that is left will not be produced fast enough to meet current or projected needs!—PGS analyst 00:21, March 2, 2009 (PST)

The timing of the peak in global oil production is highly controversial because of the political and economic impacts expected from Peak Oil including the impact on the stocks of all companies in the global marketplace dependent upon oil for its main source of energy. Many analysts believe Peak Oil is imminent, even though estimates of the exact year of the peak vary widely from 2010 to 2050 or beyond. However, some analysts, such as Matthew Simmons, have concluded that global oil production has already peaked and present credible evidence that it has. —PGS analyst 00:21, March 2, 2009 (PST).

Currently being analyzed and discussed is the issue of whether Peak Oil is being "masked" by the drop in demand due to the global economic crisis and that maybe the Peak is being shaped into more of a plateau. This would be similar to the Peak in US oil production that was predicted as early as 1956 and subsequently actually occurred in 1971, but was not confirmed until about 1974. The fact that the actual Peak cannot be accurately predicted, but will only be confirmed years later suggests that aggressive action should be taken to alleviate the economic and political impacts of Peak Oil well before the Peak. Unfortunately, it may already be too late to plan intelligently for Peak Oil impacts and the world now faces extreme distress, in securities markets and otherwise.—PGS analyst 00:21, March 2, 2009 (PST)

Theories that opening the Arctic National Wildlife Refuge and offshore drilling sites in the U.S. to development would alleviate gasoline prices are likely misguided; Jim Sweeney, director of the Precourt Institute for Energy Efficiency at Stanford University, says that offshore U.S. reserves would account for just 1% of worldwide consumption, but wouldn't be productive for 10-15 years.

3.2.7 U.S. Dollar Value Fluctuations Cause Positive Feedback on the Price of Oil

The United States imports much of its oil, and that oil is purchased abroad in U.S. dollars. The price of oil, in fact, is pegged to the dollar. The changing value of the dollar in comparison to other currencies impacts the price paid by end users. A strong dollar means a lower price, in dollars, for oil, and a weak dollar means more dollars must be spent to purchase the same amount of oil. Currency fluctuations are complex (for a more complete discussion see currency fluctuations) but the value of a currency is impacted by

the relative value of goods imported and exported by an economy (known as the trade balance), its interest rates, the size of its national debt, and its economic growth.

3.2.8 Speculation

Some analysts believe that oil prices are at record highs because of speculation about the 'future' value of oil. Specifically, these analysts claim that the belief that oil supply is lower than it is and the belief that future oil supply will be just as low has led traders to inflate the prices of oil futures. When oil futures are traded, oil purchasers, like refiners, try to buy oil at prices that will benefit their margins in both the short and long term. If it is believed that oil prices will rise in the future (indicated by futures prices being higher than present prices), purchasers will want to stock up on oil at lower prices today and put it in inventory; this drives up demand for crude in the present, forcing oil prices up in the present. Thus, high prices for futures oil leads to high prices for oil in the present.

OPEC, believes that record fuel prices are not a function of supply and demand, but a function of Western government policy and rampant speculation, and has used this belief as an excuse not to raise production by the amounts demanded by the West. While much of the data shows that production has been slowing, it's likely that speculation could account for some of the present price spikes.

When oil prices closed at record highs for five days in a row during the week of May 5th, 2008, a House of Representatives committee announced an investigation regarding the role of hedge funds and investment banks in pushing up prices. In June 2008, the U.S. commodities futures regulator announced new rules requiring daily large trader reports, and position and accountability limits for foreign crude contracts traded in the U.S.

3.2.9 Contango Causes Some Oil Price Volatility

In early March, 2009, an April 2009 oil delivery contract traded for \$38.10, while an April 2010 contract traded for \$50.26, making it \$12.16 more profitable for oil companies to hold onto their oil until April 2010. When the future price of a commodity (e.g. oil) is higher than its present price, a situation known as "contango", it is more profitable for a commodities producer (e.g. XOM) to store the commodity and sell it at a later date. This causes oil price volatility through various channels: for example, storage of a commodity causes supply to be reduced in the present, raising spot prices, while expectations regarding future supply increase - thereby reversing the cycle, which then causes contango all over again. The wider the spread between the present price and a future price, the heavier the contango and the heavier the volatility.

3.2.10 Wars

There have been so many wars in history, which have had a direct cause in the availability and prices of crude and petroleum products. Two of these wars are discussed below.

3.2.10.1 Yom Kippur War - Arab Oil Embargo. In 1972 the price of crude oil was about \$3.00 per barrel and by the end of 1974 the price of oil had quadrupled to over \$12.00. The Yom Kippur War started with an attack on Israel by Syria and Egypt on October 5, 1973. The United States and many countries in the western world showed support for Israel. As a result of this support several Arab exporting nations imposed an embargo on the countries supporting Israel. While Arab nations curtailed production by 5 million barrels per day (MMBPD) about 1 MMBPD was made up by increased

production in other countries. The net loss of 4 MMBPD extended through March of 1974 and represented 7 percent of the free world production.

If there was any doubt that the ability to control crude oil prices had passed from the United States to OPEC it was removed during the Arab Oil Embargo. The extreme sensitivity of prices to supply shortages became all too apparent when prices increased 400 percent in six short months.

From 1974 to 1978 world crude oil prices was relatively flat ranging from \$12.21 per barrel to \$13.55 per barrel. When adjusted for inflation the price over that period of time world oil prices were in a period of moderate decline.

3.2.10.2 Crises in Iran and Iraq. Events in Iran and Iraq led to another round of crude oil price increases in 1979 and 1980. The Iranian revolution resulted in the loss of 2 to 2.5 million barrels per day of oil production between November, 1978 and June, 1979. At one point production almost halted.

While the Iranian revolution was the proximate cause of what would be the highest prices in post-WWII history, its impact on prices would have been limited and of relatively short duration had it not been for subsequent events. Shortly after the revolution production was up to 4 million barrels per day.

Iran weakened by the revolution was invaded by Iraq in September, 1980. By November the combined production of both countries was only a million barrels per day and 6.5 million barrels per day less than a year before. As a consequence worldwide crude oil production was 10 percent lower than in 1979.

The combination of the Iranian revolution and the Iraq-Iran War cause crude oil prices to more than double increasing from \$14 in 1978 to \$35 per barrel in 1981.

Twenty-six years later Iran's production is only two-thirds of the level reached under the government of Reza Pahlavi, the former Shah of Iran. Iraq's production remains about 1.5 million barrels below its peak before the Iraq-Iran War.

3.2.11 Negative Feedback on Rising Prices Offsets Some of the Increases

Rising oil prices can force major purchasers of oil to turn to other fuel types. The U.S. Military, for example, in May of 2008 tested a jet that broke the sound barrier using synthetic fuel. The military is the largest single consumer of oil in the U.S., at 1.5% the country's total, and rising oil prices drove the Defense Department's energy bill up 25% in 2007. Since estimates stated that commercial-scale synthetic-fuel refineries could sell the fuel at just \$55 a barrel, the military has started pushing away from oil - which could actually drive oil prices down.

The Chinese government was also forced to act on rising global oil prices. On June 20th, China announced that it had raised diesel prices by 18% and gasoline prices by 16%; oil prices on world futures markets immediately fell by \$4, as higher prices in China were expected to lead to decreased demand in China, thereby leading to decreased world demand.

Even regular consumers were forced by soaring fuel prices to change their habits, turning to gas-efficient cars or simply driving less; gasoline demand in the U.S. fell at the beginning of June 2008 by 3.8% from the year before, while consumption fell 1.9%.

3.2.12 US Oil Price Controls - Bad Policy?

The rapid increase in crude prices from 1973 to 1981 would have been much less were it not for United States energy policy during the post Embargo period. The US imposed price controls on domestically produced oil in an attempt to lessen the impact of the

1973-74 price increase. The obvious result of the price controls was that U.S. consumers of crude oil paid about 50 percent more for imports than domestic production and U.S. producers received less than world market price. In effect, the domestic petroleum industry was subsidizing the U.S. consumer.

Did the policy achieve its goal? In the short term, the recession induced by the 1973-1974 crude oil price rise was less because U.S. consumers faced lower prices than the rest of the world. However, it had other effects as well.

In the absence of price controls U.S. exploration and production would certainly have been significantly greater. Higher petroleum prices faced by consumers would have resulted in lower rates of consumption: automobiles would have had higher miles per gallon sooner, homes and commercial buildings would have been better insulated and improvements in industrial energy efficiency would have been greater than they were during this period. As a consequence, the United States would have been less dependent on imports in 1979-1980 and the price increase in response to Iranian and Iraqi supply interruptions would have been significantly less.

3.2.13 OPEC's Failure to Control Crude Oil Prices

OPEC has seldom been effective at controlling prices. While often referred to as a cartel, OPEC does not satisfy the definition. One of the primary requirements is a mechanism to enforce member quotas. The old joke went something like this. What is the difference between OPEC and the Texas Railroad Commission? OPEC doesn't have any Texas Rangers! The only enforcement mechanism that has ever existed in OPEC was Saudi spare capacity

With enough spare capacity at times to be able to increase production sufficiently to offset the impact of lower prices on its own revenue, Saudi Arabia could enforce discipline by threatening to increase production enough to crash prices. In reality even this was not an OPEC enforcement mechanism unless OPEC's goals coincided with those of Saudi Arabia.

During the 1979-1980 periods of rapidly increasing prices, Saudi Arabia's oil minister Ahmed Yamani repeatedly warned other members of OPEC that high prices would lead to a reduction in demand. His warnings fell on deaf ears.

Surging prices caused several reactions among consumers: better insulation in new homes, increased insulation in many older homes, and more energy efficiency in industrial processes, and automobiles with higher efficiency. These factors along with a global recession caused a reduction in demand which led to falling crude prices. Unfortunately for OPEC only the global recession was temporary. Nobody rushed to remove insulation from their homes or to replace energy efficient plants and equipment -- much of the reaction to the oil price increase of the end of the decade was permanent and would never respond to lower prices with increased consumption of oil.

Higher prices also resulted in increased exploration and production outside of OPEC. From 1980 to 1986 non-OPEC production increased 10 million barrels per day. OPEC was faced with lower demand and higher supply from outside the organization.

From 1982 to 1985, OPEC attempted to set production quotas low enough to stabilize prices. These attempts met with repeated failure as various members of OPEC produced beyond their quotas. During most of this period Saudi Arabia acted as the swing producer cutting its production in an attempt to stem the free fall in prices. In

August of 1985, the Saudis tired of this role. They linked their oil price to the spot market for crude and by early 1986 increased production from 2 MMBPD to 5 MMBPD. Crude oil prices plummeted below \$10 per barrel by mid-1986. Despite the fall in prices Saudi revenue remained about the same with higher volumes compensating for lower prices.

A December 1986 OPEC price accord set to target \$18 per barrel but it was already breaking down by January of 1987 and prices remained weak.

The price of crude oil spiked in 1990 with the lower production and uncertainty associated with the Iraqi invasion of Kuwait and the ensuing Gulf War. The world and particularly the Middle East had a much harsher view of Saddam Hussein invading Arab Kuwait than they did Persian Iran. The proximity to the world's largest oil producer helped to shape the reaction.

Following what became known as the Gulf War to liberate Kuwait crude oil prices entered a period of steady decline until in 1994 inflation adjusted prices attained their lowest level since 1973.

The price cycle then turned up. The United States economy was strong and the Asian Pacific region was booming. From 1990 to 1997 world oil consumption increased 6.2 million barrels per day. Asian consumption accounted for all but 300,000 barrels per day of that gain and contributed to a price recovery that extended into 1997. Declining Russian production contributed to the price recovery. Between 1990 and 1996 Russian production declined over 5 million barrels per day.

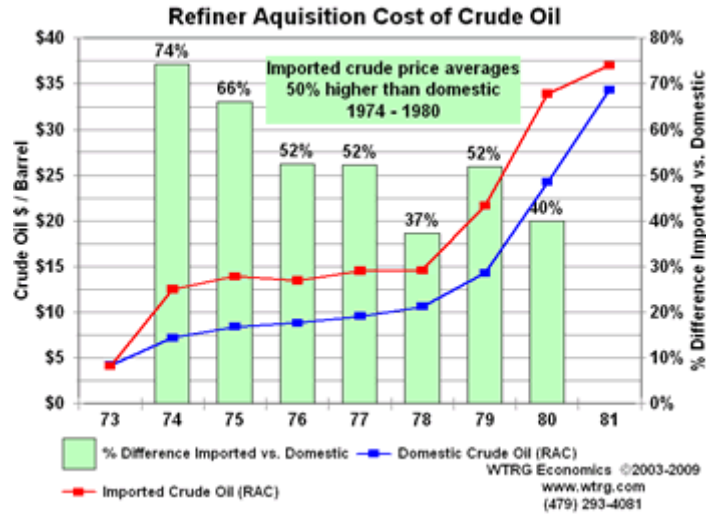


Figure 3.5 US oil price controls, 1973 – 1981.

Source: www.wtrg.com (02/26/10).

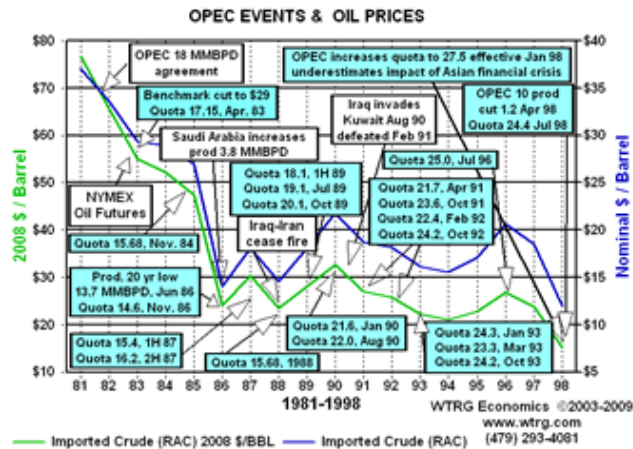


Figure 3.6 World events and crude oil prices, 1981-1998.

Source: www.wtrg.com (02/26/10).

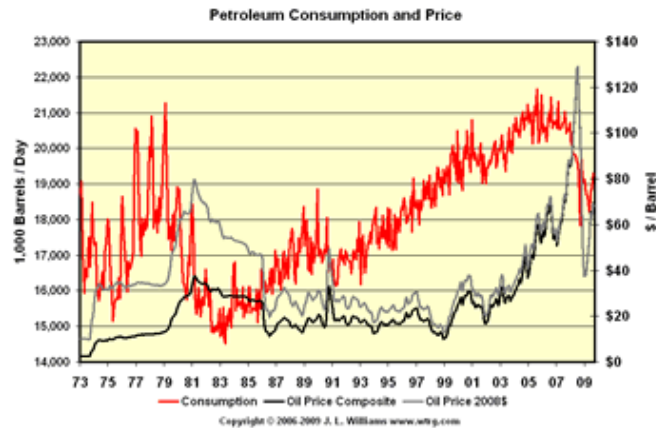


Figure 3.7 US petroleum consumption.

Source: www.wtrg.com (02/26/10).

Russian production increases dominated non-OPEC production growth from 2000 forward and was responsible for most of the non-OPEC increase since the turn of the century.

Once again it appeared that OPEC overshot the mark. In 2001, a weakened US economy and increases in non-OPEC production put downward pressure on prices. In response OPEC once again entered into a series of reductions in member quotas cutting 3.5 million barrels by September 1, 2001. In the absence of the September 11, 2001 terrorist attack this would have been sufficient to moderate or even reverse the trend.

In the wake of the attack crude oil prices plummeted. Spot prices for the U.S. benchmark West Texas Intermediate were down 35 percent by the middle of November. Under normal circumstances a drop in price of this magnitude would have resulted in another round of quota reductions but given the political climate OPEC delayed additional cuts until January 2002. It then reduced its quota by 1.5 million barrels per day and was joined by several non-OPEC producers including Russia who promised

combined production cuts of an additional 462,500 barrels. This had the desired effect with oil prices moving into the \$25 range by March, 2002. By mid-year the non-OPEC members were restoring their production cuts but prices continued to rise and U.S. inventories reached a 20-year low later in the year.

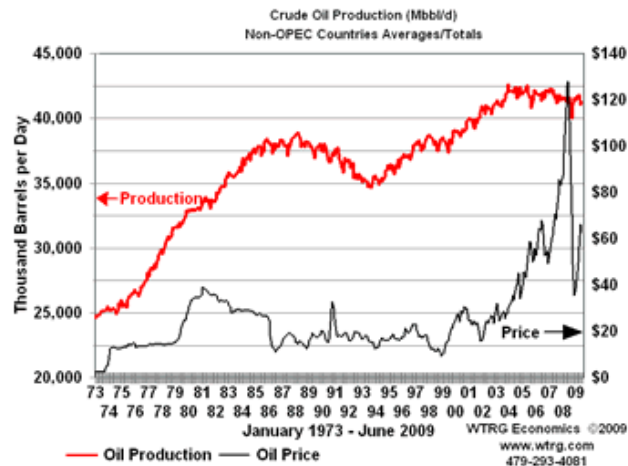


Figure 3.8 Crude oil production (Non-OPEC) 1973-2009.

Source: www.wtrg.com (02/26/10).

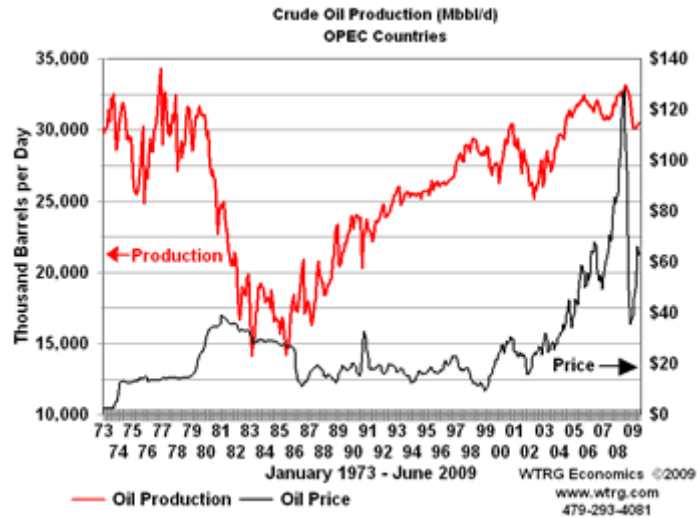


Figure 3.9 Crude oil production (OPEC) 1973-2009.

Source: www.wtrg.com (02/26/10).

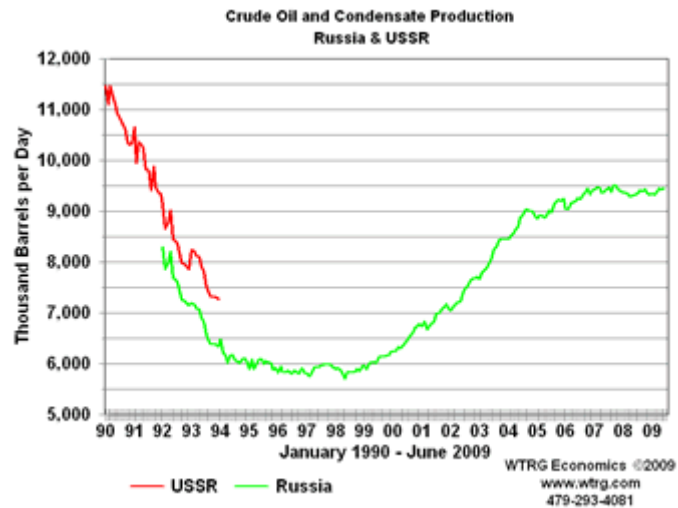


Figure 3.10 Russian crude oil production.

Source: www.wtrg.com (02/26/10).

OPEC continued to have mixed success in controlling prices. There were mistakes in timing of quota changes as well as the usual problems in maintaining production discipline among its member countries.

The price increases came to a rapid end in 1997 and 1998 when the impact of the economic crisis in Asia was either ignored or severely underestimated by OPEC. In December, 1997 OPEC increased its quota by 2.5 million barrels per day (10 percent) to 27.5 MMBPD effective January 1, 1998. The rapid growth in Asian economies had come to a halt. In 1998 Asian Pacific oil consumption declined for the first time since 1982. The combination of lower consumption and higher OPEC production sent prices into a downward spiral. In response, OPEC cut quotas by 1.25 million b/d in April and another 1.335 million in July. Price continued down through December 1998.

Prices began to recover in early 1999 and OPEC reduced production another 1.719 million barrels in April. As usual not all of the quotas were observed but between early 1998 and the middle of 1999 OPEC production dropped by about 3 million barrels per day and was sufficient to move prices above \$25 per barrel.

With minimal Y2K problems and growing US and world economies the price continued to rise throughout 2000 to a post 1981 high. Between April and October, 2000 three successive OPEC quota increases totaling 3.2 million barrels per day were not able to stem the price increases. Prices finally started down following another quota increase of 500,000 effective November 1, 2000.

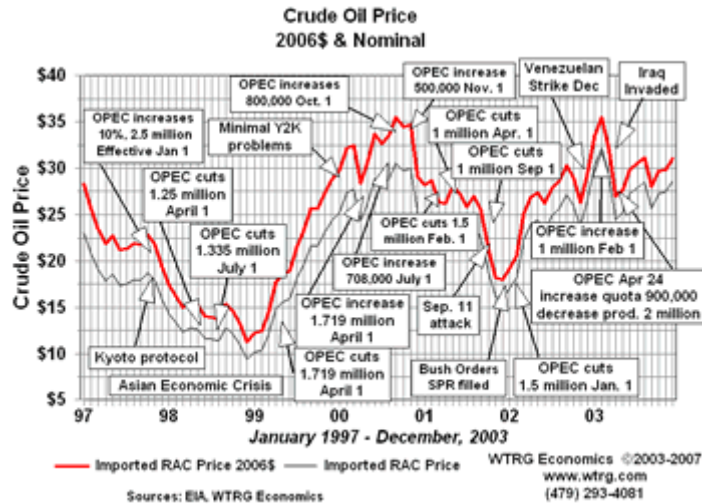


Figure 3.11 World events and crude oil prices 1997-2003.

Source: www.wtrg.com (02/26/10).

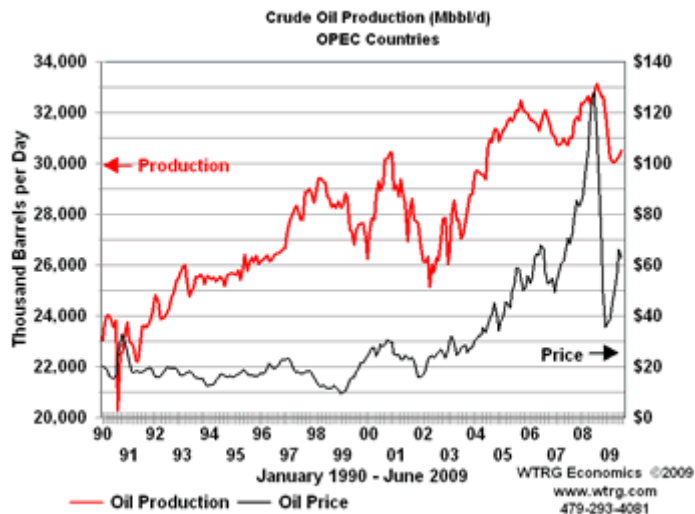


Figure 3.12 OPEC production 1990-2007.

Source: www.wtrg.com (02/26/10).

By year end oversupply was not a problem. Problems in Venezuela led to a strike at PDVSA causing Venezuelan production to plummet. In the wake of the strike Venezuela was never able to restore capacity to its previous level and is still about

900,000 barrels per day below its peak capacity of 3.5 million barrels per day. OPEC increased quotas by 2.8 million barrels per day in January and February, 2003.

On March 19, 2003, just as some Venezuelan production was beginning to return, military action commenced in Iraq. Meanwhile, inventories remained low in the U.S. and other OECD countries. With an improving economy U.S. demand was increasing and Asian demand for crude oil was growing at a rapid pace.

The loss of production capacity in Iraq and Venezuela combined with increased OPEC production to meet growing international demand led to the erosion of excess oil production capacity. In mid 2002, there was over 6 million barrels per day of excess production capacity and by mid-2003 the excess was below 2 million. During much of 2004 and 2005 the spare capacity to produce oil was under a million barrels per day. A million barrels per day is not enough spare capacity to cover an interruption of supply from most OPEC producers.

In a world that consumes over 80 million barrels per day of petroleum products that added a significant risk premium to crude oil price and is largely responsible for prices in excess of \$40-\$50 per barrel.

Other major factors contributing to the current level of prices include a weak dollar and the continued rapid growth in Asian economies and their petroleum consumption. The 2005 hurricanes and U.S. refinery problems associated with the conversion from MTBE as an additive to ethanol have contributed to higher prices.

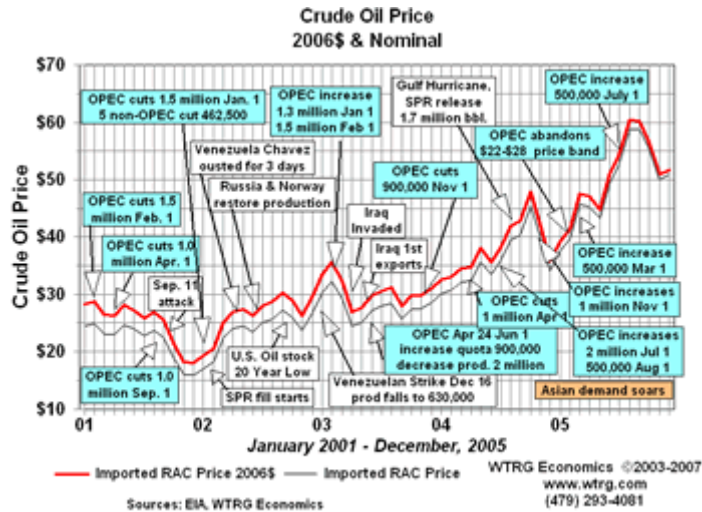


Figure 3.13 World events and crude oil prices 2001-2007.

Source: www.wtrg.com (02/26/10).

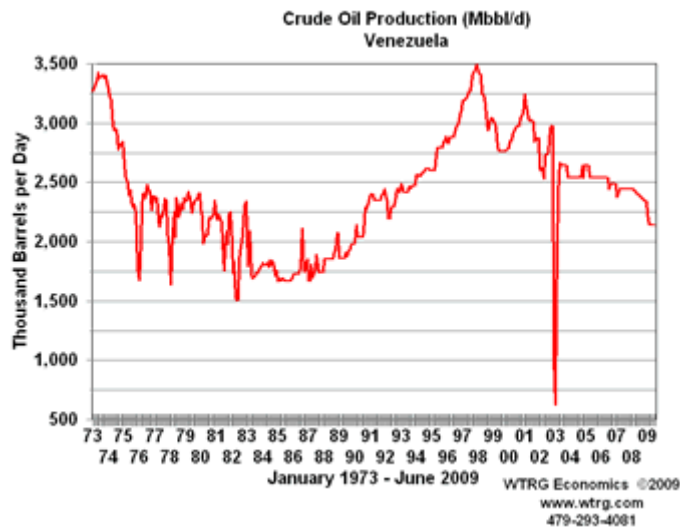


Figure 3.14 Venezuelan oil production.

Source: www.wtrg.com (02/26/10).

One of the most important factors supporting a high price is the level of petroleum inventories in the U.S. and other consuming countries. Until spare capacity became an issue inventory levels provided an excellent tool for short-term price forecasts. Although not well publicized OPEC has for several years depended on a policy that amounts to world inventory management. Its primary reason for cutting back on production in

November, 2006 and again in February, 2007 was concern about growing OECD inventories. Their focus is on total petroleum inventories including crude oil and petroleum products, which are a better indicator of prices than oil inventories alone.

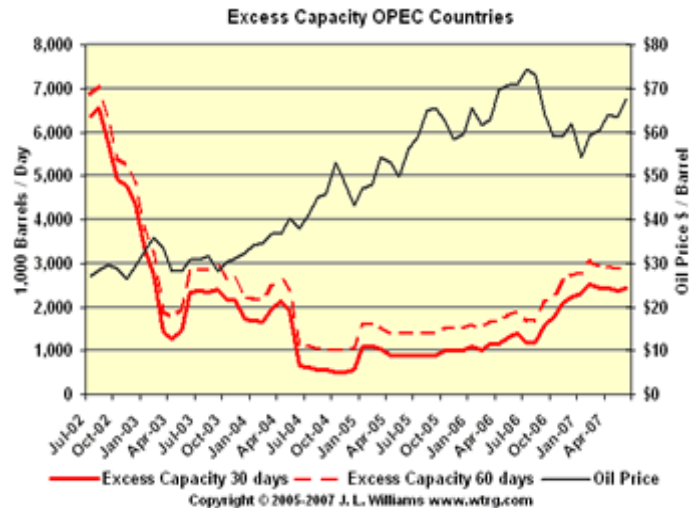


Figure 3.15 Excess crude oil production capacity.

Source: www.wtrg.com (02/26/10).

3.3 Analysis of Events Affecting Oil Prices between July 2008 and May, 2010

- July 14th, 2008:** After oil prices reached new highs of \$147 the week before, U.S. President George W. Bush lifted the Executive Ban on Offshore Drilling in an effort to expand domestic oil supplies; because offshore reserves will take years to start producing, however, oil futures fell marginally, settling over \$145 per barrel.
- July 15th, 2008:** After Ben Bernanke told Congress that high energy prices were creating an inflationary environment, worries about how high energy prices were affecting the economy caused a run on August futures, plummeting the price of oil by 4%, to \$138.74 - the greatest single-day drop in 20 years.
- July 30th, 2008:** Reports of low consumer demand for gasoline causing suppliers to cut stocks by 3.5 million barrels drive oil prices up by \$4.39, to \$127.10.
- August 13th, 2008:** Crude futures settle at \$113.77 on worries about a strengthening dollar and declining demand in industrial nations.

- **September 2nd, 2008:** Oil prices drop to just over \$105 per barrel after Hurricane Gustav doesn't do nearly as much damage to oil production as expected.
- **September 9th, 2008:** Oil prices fell to \$103.26, as forecasts of impending Hurricane Ike project it to hit land south of major Texas refineries.
- **September 15th, 2008:** Oil prices fell below \$97 during early trading. Causes speculated on range from lower-than-expected damage from Hurricane Ike to the deepening economic crisis in the U.S., fueled by the collapses of Freddie Mac, Fannie Mae, and Lehman Brothers, the crumbling of other major banks like Wachovia and Washington Mutual, and the growing consolidation of the industry as seen in the acquisition of Merrill Lynch by Bank of America.
- **October 10th, 2008:** Oil prices slide all week, closing at \$77.70 on the NYMEX, as fears over global recession lead to panic in the market.
- **October 13th, 2008:** Oil prices rebound on fickle investor sentiment, rising back above \$80 to \$81.19. Goldman, however, revises its projections for year-end oil prices down to \$70 from \$115.
- **November 18th, 2008:** NYMEX WTI December contracts fell below \$55/barrel, to \$54.50, on continued investor worries that the global economy is entering a prolonged recession.
- **December 2nd, 2008:** Prices drop to \$47.36 after the National Bureau of Economic Research announced that the U.S. is officially in a recession.
- **December 10th, 2008:** Crude Oil is at \$43.25.
- **January 6th, 2009:** As Israel's invasion of Gaza and it's fighting with Hamas escalates, crude prices shoot up, with February Brent crude futures rising \$2.71 to \$49.62 per barrel.
- **January 8th, 2009:** U.S. government reports of increased crude and gas inventories forces NYMEX WTI February contracts down by \$3.24, to \$45.34.
- **March 18th, 2009:** Oil falls to \$48.14, as government data shows inventories of gasoline have risen by 3.2 million barrels, contradicting analyst expectations of a decline of 2.1 million barrels.
- **May 8th, 2009:** WTI rises to \$58.57, its highest point in 2009, thanks to investor expectations that the worst of the recession had passed. Other commodities surged as well.

- **May 12th, 2009:** Oil hits \$60.08 before settling back down to \$58.85, rising above \$60 for the first time since November 2008. Many have explained the surge as the result of a drop in the relative value of the dollar.
- **May 29th, 2009:** Contracts for July deliveries of WTI rise to \$64.65, after OPEC announces it will maintain production, rather than cut it, because of strengthening in global demand.
- **June 9th, 2009:** July contracts for light, sweet crude settled at \$70.01, breaking \$70 for the first time in 7 months; speculation about rampant speculation is rampant.
- **June 15th, 2009:** On statements by the Russian Finance Minister regarding the stability of the dollar as the global reserve currency, the dollar appreciated, pushing oil prices briefly below \$70.
- **July 7th, 2009:** Oil prices fall to \$64.05 a barrel, despite attacks on oil infrastructure by Nigerian rebels, as new unemployment numbers in the developed world cause investor optimism to take a hit.
- **December 7th, 2009:** Oil prices closed at a seven-week low at \$75.47. Even with this drop oil prices continue to stay relatively high even with increases in production and dropping demand in the U.S. Rising inventories and production are serving increased demand from China and India.
- **January 28th, 2010:** As U.S. demand for oil products continues to slip, prices closed at the lowest level in a month at \$73.67. The EIA reported a drop in U.S. crude inventories of 3.9 million barrels while gasoline stockpiles rose by 2 million barrels. Refining hit a 13 year low of 13.6 million b/d for the time of year. Oil prices dropped 12 percent since January 11th on concerns about the growth of economies for the U.S. and China.
- **February 18th, 2010:** Oil prices were volatile during the week closing at \$77.33 on the 17th. Prices were affected by movement of the euro and news toward a U.S. economic recovery. The API reported that U.S. crude inventories fell by 63,000 barrels and as a potential indicator of weak demand, inventories for gasoline and distillates increased by nearly 3 million barrels. It was reported that U.S. gasoline demand fell to the lowest levels since the 2008 gulf hurricanes, which could partially be attributed to record snowstorms across much of the U.S.
- **April 20, 2010:** Deepwater Horizon in the Gulf of Mexico. 11 workers died in the worst oil drilling disaster in the waters off the coast of the United States.

3.4 Who Benefits from Rising Oil Prices and Loses from Falling Oil Prices

- Alternative energies like wind, solar, and geothermal, as well as alternative fuels like biofuels, ethanol, cellulosic ethanol, and fuel cells all see increases in demand when the price of oil, their main competitor, increases.
- Coal companies like Peabody Energy, Arch Coal, CONSOL Energy, and Massey Energy Company see sales growth, as rising oil prices cause consumers to demand more local sources of energy; the U.S. is the world's second largest coal producer, after China, and there are estimates stating that U.S. coal deposits have more energy than the world's remaining oil reserves.
- Hybrid car manufacturers like Toyota, Honda, GM, Ford, and Nissan benefit from higher oil prices because high oil prices lead to higher gas prices, causing consumers to seek out ways to reduce the amount of gasoline they use. Auto makers that have announced plans to produce electric cars also can benefit, and will if oil prices start to rise again over the next few years; these companies include Daimler, Renault, Toyota, General Motors, and Mitsubishi.
- Independent Oil and Gas companies benefit the most from high oil prices, as they can extract crude at a relatively constant cost from a reserve, but sell it at higher and higher prices. The higher the price of oil, the larger an EandP company's margins.
- Oilfield services see day rates (and, thus, margins) skyrocket, as upstream oil companies scramble to increase production, causing demand for drilling rigs and other oilfield services go through the roof. Machine tools and accessories companies also benefit, as they sell individual parts to oilfield services companies that build, retrofit, and repair rigs.
- Deepwater drilling contractors like Transocean and Diamond Offshore Drilling are even better off than their peers in the oilfield services industry; there are far fewer deepwater rigs in the world than normal rigs, and with conventional wells drying up, oil companies have been willing to pay more to get at the difficult-to-reach reserves. Before the oil price collapse in the middle of 2008, floating offshore rigs could go as high as \$292,000, while deepwater oil exploration rigs were contracting at above \$800,000 per day.
- The oil majors are the very largest of the non-national oil companies, and are vertically integrated. These companies explore for and produce crude oil and natural gas; they transport it by pipeline and tanker; they refine crude oil into finished petroleum products; and they also market crude oil, natural gas, and refined petroleum products to industrial users and retail consumers. The majors get most of their money from selling refined petroleum goods; vertical integration allows them to sell high-priced crude to themselves at production costs, causing the margins on these goods to go through the roof. Often,

however, they must buy crude to supplement their own production, as their refining capacities are greater than their upstream production capacities. This offsets some of their profitability.

- Industrial gases vendors such as Praxair (PX) benefit from high prices because they sell hydrogen, which is necessary for the extraction of heavy and non-conventional oil (i.e. tar sands, shale oil), and production of these types of oil increases as prices rise.
- With the price of oil having been above \$100 per barrel, the world's waste management companies (like Waste Management (WMI)) are considering "landfill mining", as high-quality polyethylene prices have doubled since the summer of 2007, making the world's trash landfill operators' treasure.

3.5 Who Loses from Rising Oil Prices and Wins from Falling Oil Prices

Rising oil prices pose challenges for many companies as well as consumers, which is why rising oil prices are often seen as damaging to the economy.

- Rising oil prices increase costs for many companies. These costs may be difficult to pass on to customers, who are loathed to pay more for the same goods, thereby eroding profit margins.
- Rising oil prices reduce consumer demand for products that consume oil.
- Rising oil prices make travel and shipping more expensive.

Oil and Gas Refining and Marketing companies buy crude oil, process it, and sell the processed product to the end market. Companies like Sunoco, Valero, and Western Refining are all prolific U.S. refiners. When these companies must purchase crude oil at a higher price, they then have to sell the refined product (gasoline, jet fuel, diesel, etc.) at a higher price, which then causes demand to drop as people travel less. Furthermore, refined goods prices rise by a smaller amount than crude price. At the end of the 1990s, oil traded below \$20/barrel, while gasoline cost under \$1.50. In June 2008, crude traded at around \$121 (after rising to over \$135), while gasoline averaged \$4.10. Oil prices rose

by a factor of six, while gasoline prices rose by less than a factor of three. The clear losers, in this case, are the companies that make and sell gasoline, though when oil prices fall, they fall further than gasoline prices, making refiners the winners.

- Shipping companies are harmed by higher oil prices because oil is necessary to operate the planes, trucks, and ships that transport goods around the globe. These companies include brand-name shipping companies like FedEx and UPS, industrial shipping companies like TNT and Con-Way Trucking, and international shipping companies like Teekay Shipping and Frontline. LTL trucking companies, however, are relatively shielded from fluctuations in diesel fuel prices, as the industry generally passes on fuel price surcharges to its customers like Wal-Mart Stores (WMT). Also, aircraft leasing companies such as Aircastle (AYR) are hurt by rising oil prices.
- Airlines like Delta, Northwest, United, and American Airlines are harmed by rising oil prices; in the past, jet fuel has accounted for 10-15% of an airline's cost, but by mid-2008 they made up 30-50% of costs, albeit before the price collapsed below \$50/barrel.
- The lodging industry sees declines in occupancy rates and revenues when oil prices rise, as higher travel prices cause fewer consumers to take vacations.
- Other vacation and travel alternatives (e.g. cruise lines like Royal Caribbean Cruises and Carnival) see higher fuel costs, forcing them to raise prices and drive potential customers away.
- The Chemical industry is harmed by higher oil prices because petroleum is a key ingredient in plastics. As the price of oil rises, plastics become more expensive to produce, causing margins to shrink.
- The retail industry is harmed by rising oil prices because shipping companies charge higher prices, making it more difficult for retailers to get their products to market and forcing them to raise prices. Discount retailers, including Family Dollar Stores, Dollar Tree Stores, Big Lots, Wal-Mart, Target and Dollar General are especially exposed as their consumers generally have lower incomes, making them more sensitive to rising energy prices.
- Online retailers that subsidize the cost of shipping, like Amazon.com and Overstock.com, are forced to pay part of the shipping price increases, causing margins to shrink.
- Car companies that are heavily dependent on sales of SUVs for profits, such as General Motors and Ford, see fewer sales as consumers tend to reduce their purchases "gas-guzzlers" when oil prices are high.

- Automotive parts retailers like AutoZone, Advance Auto Parts, and O'Reilly Automotive, who depend on heavy driving and automotive wear-and-tear, struggle when drivers conserve due to high oil prices and demand fewer repairs.
- Automotive retailers like AutoNation and CARMAX depend on replacement demand for new cars due to wear-and-tear, which decreases as fewer people drive.
- Chinese manufacturers lose their low-cost production advantage, as rising oil prices cause the prices of whatever is being shipped from China to be artificially inflated. Lower oil prices, at around \$20/barrel, were equivalent to low tariff rates (about 3%). With the oil that was being used in shipping during the 2nd quarter of 2008, the equivalent tariff rate was around 9% and rising (until the bubble burst).

3.6 Chapter Conclusion

From the above narratives it is clear that a lot of instability has occurred and is still occurring in the oil and gas sector supply chain. In this study models which will enable the risk ratings of the impacts of these events and activities on the supply chain to be derived will be developed, and also try to determine its economic impact on both a generalized and site specific supply chains.

The figures in this chapter will be analyzed, to derive the probability and consequences of some of the events and activities on the supply chain, which will enhance the chances of successful modeling in the succeeding chapters.

The events will be categorized as either short term or long term events. Some long term events and activities to be analyzed are;

- political instability (terrorism, wars)
- demand growth
- production cuts

- violence against producers
- weather
- transportation bottlenecks
- peak-oil and declining production
- dollar fluctuations
- speculation

While the some short term events to be analyzed are:

- Pipe leaks/breaks
- Redundancy failures
- Refinery fire/explosion
- Power outage
- Tank farm crack/leaks

CHAPTER 4

METHODOLOGY AND APPROACH

4.1 Research Overview

The energy sector faces a broad array of uncertainties and risks, in supply, demand, transportation and market conditions. These uncertainties and risks that can interrupt the supply chain operations, causing significant adverse effects in the energy sector can be caused by natural disasters, equipment failures or terrorist attacks, political, economical or environmental concerns, speculation or sky-rocketing demands from emerging economies.

It is important to develop a risk based optimization model using the oil and gas/refinery critical infrastructure supply chain operations, to predict and manage these uncertainties in the oil and gas critical infrastructure chain.

This research will endeavor to address these uncertainties and risks in the oil and gas critical infrastructure supply chains by developing and analyzing different models that can be used in achieving that.

These easy-to-use models which can be easily used by executives, risk/supply chain/production managers, transportation and logistics personnel, suppliers and regulators, academicians and students, and can also be applied also to other critical infrastructure supply chains, by varying the variables are highlighted below in Sections 4.2 to 4.5.

4.2 Events and Activities Risk Rating Model Analysis

The prototypical expression for risk in the homeland security context is traditionally written as:

$$\text{Risk} = \text{Threat} \times \text{Vulnerability} \times \text{Consequence} \quad (4.1)$$

Where the total risk is the combination or Cartesian product of all relevant threat types, system weaknesses, and consequences resulting from when the damage-inducing mechanisms associated with the threats interact with the vulnerabilities. Risk, as equation 4.1 would suggest, tells a series of stories of all that could go wrong from initiating threat event to final outcome, where the heart of these stories, that is, the vulnerabilities, describe those weaknesses that must interact to make this scenario true. As a first step toward a quantitative expression for vulnerability, it would seem that vulnerability provides a mapping between the set of initiating threat events and the set of outcomes, such as is shown in Figure 4.1. In this view, any statement of vulnerability to a given initiating threat event must always be in reference to some degree of loss or adverse outcome, whether descriptive, qualitative, or quantitative in nature. Generic statements, such as “my vulnerability is high,” are inherently ambiguous unless they are associated with some particular consequence, if even expressed on an arbitrarily constructed or vaguely defined scale (e.g., “my vulnerability to significant consequences is high”).

In their seminal paper, Kaplan and Garrick (1981) put forth a quantitative definition of risk that is derived from the answers to three fundamental risk questions:

- What can go wrong? - Risk
- How likely is it to go wrong? - Vulnerability
- What are the ensuing consequences? - Risk

The first question establishes a complete set of risk scenarios in narrative form and provides the basis for evaluation and quantification. As later elaborated by Kaplan et al. (2004), the level of specificity and detail chosen to articulate each scenario greatly affects how likelihood and consequence are assessed. Given a set of all possible scenarios of a specified type, highly detailed scenarios are larger in number and require more analytical effort to ascertain and assess, but provide a high resolution account and understanding of total risk. In contrast, less specific scenarios are fewer in number, but coincide with a greater uncertainty in the loss dimension to account for inexplicit variations in the nature and sequence of events between cause and consequence. For example, consider the very specific scenario “a medium-sized car bomb attack occurring at the federal building in downtown at 9:00am next Thursday.” The details of this scenario permit a very good assessment of vulnerability to different degrees of loss given its occurrence, but completing the risk picture requires the decision maker to consider all variations that account for different times, days, locations, delivery systems, and threat types. A less specific version of this scenario is “an explosive attack occurring in the region sometime in the next year” is inclusive of all specific scenarios of the previous example, but as such it is difficult to make an all-encompassing assessment of overall vulnerability due to the wide variations in circumstances. Since vulnerability was defined to be a mapping from cause to consequence, it is thus important to construct scenarios that permit meaningful statements of vulnerability.

Given a scenario, the risk, R_{ij} , can be expressed mathematically as the triplet of a scenario, e_i ($i = 1, 2, \dots, m$), the probability/vulnerability of this scenario (that is the overall vulnerability), $p_{ij}/V_T(c_j, e_i)$, and consequence, c_j ($j = 1, 2, \dots, n$), as follows:

$$R_{ij} = (e_i, v_T, c_j) \quad (4.2)$$

The equation above defines the risk triplet (Kaplan and Garrick 1981), where the scenario provides a narrative of a situation, the consequence is a valuation on the final outcome resulting from this situation, and the probability measures the likelihood that scenario e_i will lead to the consequence c_j or the vulnerability of node/route v_T . The total risk, R , is the set of all ordered triples, i.e., $R = \{R_{ij}\}$. The vulnerability v_T of the node can be derived from equation 4.3 below:

$$V_T(c_j, e_i) = \Sigma \Sigma (1 - I_s(e_i))(1 - I_k(e_i))(1 - I_H(e_i, d_k))(1 - I_R(c_j, c_{p,m}))(1 - I_I(c_{p,m}, d_k)) \quad (4.3)$$

In order to derive the node/route vulnerability to an event or a threat scenario in equation 4.3 above, we will try to explain how they will be derived based on both the protection and response mechanisms that are in place to minimize or eliminate the successful occurrence of any such event.

McGill and Ayyub (2007) explores the concept of vulnerability in the context of critical infrastructure protection with the intent to establish an operational definition that provides a basis for meaningful measurement, by following a systematic consideration of the general elements of risk by observing that vulnerability as a notion provides a

mapping between an initiating threat event and a resulting degree of loss. They proposed a mathematical expression for overall vulnerability that divides the notion into two categories - protection vulnerability that focuses on those aspects of a system that influence the probability of damage or compromise given the occurrence of an initiating threat event (e.g., security system weaknesses, target accessibility, and fragility of targets), and response vulnerability that focuses on those aspects of a system that influence the probability of a specified degree of loss given damage or compromise (e.g., intrinsic resistance to loss and effectiveness of response and recovery capabilities

4.2.1 Protection Vulnerability

The category protection vulnerabilities consider all contributors to overall vulnerability between the initiating threat event and damage of targets. That is, given the occurrence of an initiating threat event, protection vulnerability measures the probability of suffering a specified level of damage, whether in terms of damage or compromise of affected elements or size of an exposed human population. If damage cannot be reliably prevented following an initiating threat event, a target is vulnerable unless the system compensates with suitable strategies to control the ensuing losses. According to the event tree in Figure 4.2, a simple mathematical expression for protection vulnerability, $V_p(e_i, d_k)$ to a specified level of damage, $d_k \in D$, where D is a set of damage states, can be obtained as

follows:

$$V_p(e_i, d_k) = \Pr(S|e_i)\Pr(K|S, e_i)\Pr(d_k|K, S, e_i) \quad (4.4)$$

Where $\Pr(S | e_i)$ is the probability of adversary success given the occurrence of the initiating threat event, $\Pr(K | S, e_i)$ is the probability that the target will be exposed to the damage-inducing mechanisms of the threat given adversary success, and $\Pr(d_k | K, S, e_i)$ is the probability of damage given exposure of the target. According to this equation, an adversary must defeat a defender's protective measures, successfully execute the damage-inducing mechanisms of the attack, and then damage or compromise the target at a specified level, d_k , to achieve success. Equation 4.4 assumes that failure of the attacker to overcome the security system OR failure of the attacker to successfully execute his attack given the opportunity OR failure of the attack to cause damage d_k will result in no loss. Expressed in terms of favorable defender characteristics, Equation 4.4 can be rewritten as:

$$V_p(e_i, d_k) = (1 - I_s(e_i))(1 - I_k(e_i))(1 - I_H(e_i, d_k)) \quad (4.5)$$

Where:

$I_s(e_i) = 1 - \Pr(S|e_i)$ is the effectiveness of security system interventions with respect to initiating threat event e_i ,

$I_k(e_i) = 1 - \Pr(K | S, e_i)$ is the effectiveness of interventions (intrinsic and extrinsic) that seek to deny execution of the attack against the specified target according to e_i given defeat of the defender force, and

$I_H(e_i, d_k) = 1 - \Pr(d_k | K, S, e_i)$ measures the effectiveness of hardness interventions (intrinsic and extrinsic) of the target that minimize the ability to achieve damage state d_k given exposure to the damage-inducing mechanisms associated with e_i .

Based on Equations 4.4 and 4.5, the three primary dimensions of protection vulnerability are security system weaknesses, target accessibility, and fragility of target elements.

In the event of no security, complete target accessibility, and fragile targets, $I_S = I_K = I_H = 0$ and $V_P = 1$.

Note that for natural hazards, $I_S = 0$ and $I_K = 0$ since at the present time few feasible interventions are available to stop natural events once they are initiated. According to these simplifications, Equation 4.5 can be rewritten for natural hazards as:

$$V_P(e_i, d_k) = (1 - I_H(e_i, d_k)) \quad (4.6)$$

4.2.2 Response Vulnerability

The category response vulnerabilities consists of all contributors to vulnerability that influence the degree of loss that would be realized given that specified initiating threat event e_i resulted in damage state d_k . That is, response vulnerability measures the probability of a specified consequence or outcome associated with a given damage state. If loss cannot be effectively controlled, then the asset is vulnerable unless this deficiency is compensated for by effective protective measures that minimize probability of adversary success. A simple mathematical expression for response vulnerability, $V_R(c_j, d_k)$, for a given degree of loss, c_j , resulting from damage state d_k can be expressed as:

$$V_R(c, d_k) = \sum \Pr(c | c_{p,m}) \Pr(c_{p,m} | d_k) \quad (4.7)$$

Where:

$\Pr(c_{p,m} | d_k)$ is the probability that a loss, $c_{p,m}$, could result from damage state d_k (which is a measure of the intrinsic resistance of the target systems to loss).

$\Pr(c_j | c_{p,m})$ is the probability that the actual loss is c_j in light of the effectiveness of response and recovery capabilities given that the unmitigated loss was $c_{p,m}$, and the summation is taken over all m states of unmitigated loss.

Equation 4.7 assumes that the response vulnerabilities are assessed independently of the scenario that initiated damage state d_k , which may be true for the “crisp” consequence dimensions such as direct economic damage and number of fatalities, but less true for the “softer,” less ascertainable dimensions such as psychological impact. Expressed in terms of favorable defender characteristics, Equation 4.7 can be rewritten as:

$$V_R(c_j, d_k) = \sum (1 - I_R(c_j, c_{p,m})) (1 - I_i(c_{p,m}, d_k)) \quad (4.8)$$

Based on Equation 4.8, the two dimensions of response vulnerability are intrinsic susceptibility of a system to loss following damage and the effectiveness of response and recovery capabilities.

4.2.3 Overall Vulnerability

Given the expressions for protection vulnerability, V_P , and response vulnerability, V_R , the overall vulnerability, V_T , of a target to a given degree of loss, L , resulting from initiating threat event e_i can be expressed as:

$$V_T(c_j, e_i) = \sum V_P(e_i, d_k) V_R(c_j, d_k) \quad (4.9)$$

Using the expressions for V_P in Equation 4.5 and V_R in Equation 4.8, overall vulnerability can be expressed in expanded form as:

$$V_T(c_j, e_i) = \sum \sum (1 - I_s(e_i))(1 - I_k(e_i))(1 - I_H(e_i, d_k))(1 - I_R(c_j, c_{p,m}))(1 - I_I(c_{p,m}, d_k)) \quad (4.10)$$

Where the summation is taken over all possible damage states k .

Equation 4.10 permits statements about the vulnerability of a system to a specified degree of loss resulting from a specified initiating threat event. For example, a team of analysts and engineers can employ Equation 4.10 to assess the overall vulnerability of a company to 100 or more fatalities following a truck bomb attack in an underground parking structure. To make statements about overall vulnerability of the company to 100 or more fatalities resulting from an explosive or malicious attack in general (considering all delivery modes, targets, and intrusion paths) requires an aggregation of the overall vulnerability for each individual attack profile and initiating threat event considered.

For classes of natural hazard events, one could partition the set of initiating threat events according to established intensity scales, such as the Saffir-Simpson scale for tropical cyclones, Richter scale for earthquakes, or Fujita scale for tornadoes.

Given a complete set of initiating threat events, the overall vulnerability to loss resulting from each initiating threat event is assessed by considering the effectiveness of existing interventions for reducing protection vulnerability and response vulnerability in light of the intensity of the damage-inducing mechanisms associated with the threat. More specifically, the effectiveness of interventions (both extrinsic and intrinsic) to improve security (I_S), decrease target accessibility (I_K), and enhance target hardness (I_H) are assessed with respect to each initiating threat event to determine the corresponding probability of damage. Independent of an initiating threat event, the effectiveness of interventions to improve intrinsic resistance to loss (I_I) and enhance response and recovery capabilities (I_R) is considered to determine the probability of realizing a specified degree of loss given damage. That is, the assessment of protection vulnerability considering I_S , I_K , and I_H requires the analyst to specify a set of damage states, and the assessment of response vulnerability considering I_I and I_R requires the analyst to specify a set of loss levels or ranges of interest. If it can be assumed that loss is tied strictly to damage, then response vulnerability can be assessed independently of protection vulnerability.

These risk ratings can either increase or decrease, based on the level of vulnerability, critical nodes hardening, availability of redundancy, response package in place and risk reducing mechanism inherent in each route.

The events will be categorized as either short term or long term events. Some long term events and activities to be analyzed are;

- political instability (terrorism, wars)
- demand growth
- production cuts
- violence against producers
- weather
- transportation bottlenecks
- peak-oil and declining production
- dollar fluctuations
- speculation

While some short term events to be analyzed are:

- Pipe leaks/breaks
- Redundancy failures
- Refinery fire/explosion
- Power outage
- Tank farm crack/leaks

4.3 Risk Based Network Reliability Analysis Model

A network reliability model using the risk based minimum cut-set method will be developed to determine the impact of link failures from some of the events and threats we analyzed their risk rating in Section 4.2 above, on the source-demand connectivity of the oil and gas supply chain.

The proposed model will be a modification of the work by Yang et al. (1996). In their work they focused on the impact of link failures on source-demand connectivity, which was used as a measure of the mechanical reliability of the network. The mechanical reliability index was computed using the minimum cut-set method, with the identification of these minimum cut-sets consisting of four stages:

- i. For source – demand pairs.
- ii. For individual demand nodes.
- iii. For a group of demand nodes, and
- iv. For all demand nodes in the system.

By using these multiple – stage approach, the total number of simulations required in the analysis is greatly reduced. The minimum cut-set of all the links/chain in the network will be determined by using the generalized network algorithm below to solve the optimization model that will be used in the simulations.

In this work, the minimum cut-set model was modified by introducing risks into the existing model.

The results obtained from this reliability analysis will then be used to locate crucial links/chain in the network, whose failure will severely impair the source-demand connectivity and proffer CIP that can be used to minimize/eliminate these vulnerabilities.

4.3.1 Network Representation

In their work, Yang et al. (1996) analyzed the interrelationship among various system components of a water distribution system by transforming it into a network representation of nodes and links. Water supply sources, demand points, junctions, surface water reservoirs, and ground-water recharge basins are represented by nodes,

while pipes, water treatment plants, pumping stations, and power plants are represented as links.

In this study the modified model in the oil and gas sc will be applied, by first transforming it into a network representation of nodes and links. Where the crude sources, demand points, storage tanks, and refineries are considered as nodes, while, the pipes, boat, ship and tankers, that is the transportation system, will be taken as links.

Then, the risk ratings of various nodes and links, based on some of the likely events, activities, and threats from Section 4.2, that can impact the SC will be included in trying to determine the critical nodes/links in the network which failure will affect the overall network reliability.

The optimum resource allocation to mitigate and manage the impact of failure on the SC network, by hardening these critical source-demand pairs will be shown using the fault tree analysis in Section 4.5.

For this study, the focus is on whether a demand node can get petroleum products from the available sources through the available refineries; therefore source-demand connectivity is used as the criterion for defining system success. The results of this research will be used to locate critical links in the network and also allocate resources to harden and mitigate against failure, using the calculated risks of likely events or activities that can impact the network causing failure of the supply chain network(s) (*Note: failure will be said to have occurred when the likely threat scenarios will lead to a calculated risk that is greater than or equal to a threshold allowable risk for each source-demand pair*).

If all intermediate nodes were assumed to be reliable, source-demand connectivity can only be affected by the network configuration and the reliability of the links. Connectivity between any two nodes in the oil and gas sc network will be based on two factors, as put forward by Yang et al. (1996). That is

1. Existence, and
2. Availability of a connecting route.

It means that by design one specified node may not be reachable by another specified node in the network. Even when there exist a connecting route between the two nodes, their connectivity would be severed should one or more components on this route fail.

4.3.2 Reliability of Oil and Gas Supply Chain Network

The source-demand connectivity will be evaluated at the four levels of progressive aggregation and four respective reliability measures as defined by Yang et al. (1996).

These are

1. Source-demand pair reliability – the probability that a specified demand node is connected to a specified source node.
2. Individual demand reliability – the probability that a specified demand node is connected to at least one source node.
3. Group-demand reliability – the probability that each of the demand nodes in the group is connected to at least one source node; and
4. System-demand reliability – the probability that each of the demand nodes in the network is connected to at least one source node.

4.3.3 Minimum Cut-Set Method

The risk based minimum cut-set method will be used, to compute the network reliability of the oil and gas sc. This involves the generation of a number of component failure

events whose effects on the system will be determined one at a time, with its advantage being that it can be easily programmed and implemented on a computer, in addition, that they are directly related to the modes of system failure and, so, can be used to identify situations in which a system might fail.

The model proposed that the network reliability of the supply chain be evaluated at four different levels, and then went on to give the definitions of the minimum cut-set corresponding to the different levels as follows.

1. A minimum cut-set for a source-demand pair was defined as a set of links, which, when all links of the set fail simultaneously, will disrupt the connectivity of the specified source node to the specified demand node, but when any one link in the set does not fail, does not cause the disruption.
2. A minimum cut-set for an individual demand node was defined in the same manner as above, except that the context of connectivity is between all sources to the individual demand node.
3. While for group demand, the author stated that a failure is considered to have occurred when one or more demand nodes of the group are disconnected from all the sources.
4. Finally, for system demand, failure was said to have occurred if at least one demand node in the system is disconnected from all the sources.

In general, as noted above, the set of links responsible for the failure in the manners described above is a minimum cut-set.

It can be inferred that once the minimum cut-sets for source-demand pairs are identified, the minimum cut-sets for individual demand, group demand, and system demand can be obtained simply by combining the results obtained from source-demand pairs.

These procedures are highlighted in the sub-sections below.

4.3.3.1 Minimum Cut-Set for Source-Demand Pair.

That only links in the associated sub-network are considered in the identification of the minimum cut-sets for a

specified source-demand pair. The associated sub-network to be examined for a source-demand pair is all the links connecting these two nodes and all the intermediate nodes connected by the links.

4.3.3.2 Minimum Cut-Set for Individual Demand Pair.

That since an individual-demand node fails only when it cannot be reached by any of its sources, only simultaneous failures of all the connections to its sources can cause an individual demand to fail. So, the minimum cut-sets for a demand node can be derived directly by combining the minimum cut-sets of its source-demand pairs.

4.3.3.3 Minimum Cut-Set for Group Demand Pair.

That failure of group demand occurs when any one of the demand nodes in the group loses connectivity to any source. Since the failure of any demand node in the group is also a failure of group demand, the minimum cut-sets of group demand can be derived directly from the minimum cut-sets of the selected demand nodes.

4.3.3.4 Minimum Cut-Set for System Demand Pair.

If system demand is of concern, all the demand nodes in the network will be selected. Therefore, the procedure for identifying the minimum cut-sets of system demand is similar to that for group demand except for the demand nodes considered.

4.3.4 Optimization Model for Identification of Risk Based Minimum Cut-Set for Source Demand Pair

The optimization model that will be used in this study will be a modification of the one proposed by Yang, et al. (1996) for the operation of water distribution network, where the objective was to minimize the water shortage at demand nodes.

This model that will be used for simulating the effect of the removal of a link set on connectivity of source-demand pair, for example, (s,d), in the oil and gas supply chain network, is described as follows:

$$\text{Min } z = \sum_{k \in N^1} [q_k - \sum_{[i:(i,k) \in A]} x_{(i,k)}] \quad (4.11)$$

Subject to:

$$\sum_{[i:(i,k) \in A]} x_{(i,k)} - \sum_{[i:(i,k) \in A]} x_{(k,i)} = 0, \quad \forall k \in N^2 \quad (4.12)$$

$$\sum_{[i:(i,k) \in A]} x_{(k,i)} \leq r_k \quad \forall k \in N^3 \quad (4.13)$$

$$\sum_{[i:(i,k) \in A]} x_{(i,k)} \leq q_k \quad \forall k \in N^1 \quad (4.14)$$

$$\sum_{[i:(i,k) \in A]} x_{(i,k)} \leq q_k \quad \forall k \in N^1 \quad (4.14)$$

$$\sum_{[i:(i,k) \in A]} r_{(i,k)} \leq R_k \quad \forall k \in A \quad (4.15)$$

In which, $x_{(i,k)}$ = flow volume in the link from node i to node k.

r_k = quantity supply at source node i , ($r_k = \infty$, if $i = d$ and 0 , if $i \neq d$)

q_k = quantity of demand at demand node k , ($q_k = 1/\infty$, if $k = d$ and 0 , if $k \neq d$)

$r_{(i,k)}$ = risk rating of events that affect each set of links

R_k = maximum allowable risk for the entire network

N^1 = index set of demand nodes in the network

N^2 = index set of refinery nodes in the network

N^3 = index set of crude demand nodes in the network

A = set of links in the network

In identifying the minimum cut-sets of a source-demand pair, a simulation is made for each candidate set. For each candidate set, the capacities of the links in the set are changed from their original values to zeros to simulate the removal of this link set.

Given an assumption of infinitesimally small demand, connectivity of a given source-demand pair is preserved if the resultant value of the arc flow to the demand node is greater than zero, i.e., it is a critical node if quantity demanded (q_k) at the node is greater than the supply from the link to the nodes ($x_{(i,k)}$), all subject to the allowable constraints.

4.3.5 Computation of Risk Based Network Reliability

Yang, et al. (1996), in their work stated that the associated minimum cut-sets of individual demand, group demand, and system demand are different, and that their reliability values are determined separately. Though, the computational procedure is the same, except for the minimum cut-sets considered.

The authors' definition of minimum cut-set infers that all components of a minimum cut-set must have failed simultaneously to cause a system failure. Based on their assumption that link failures are independent of each other, the failure probability

and most importantly, the overall network reliability of a minimum cut-set S_i , which can be a minimum cut-set for individual demand, group demand, or system demand, that will be used in this study, will be the modified model, which includes some of the risk ratings from events, activities and threats that can impact the links/nodes of the network, that is:

$$P(Z_i) = \sum_{j=1}^{n_i} P_j = P_1 \cdot P_2 \dots \dots \dots P_{n_i} \quad (4.16)$$

In which,

P_j = failure probability of the j th link in S_i

Z_i = failure event of S_i , and

n_i = total number of links contained in S_i

Also,

$$R(S_i) = \sum_{i=1}^{n_i} \sum_{k=1}^{n_i} r_{(i,k)} \quad (4.17)$$

Where:

$R(S_i)$ = risk ratings of a minimum cut-set S_i , and

$r_{(i,k)}$ = risk rating of events that affect each set of links

The author stated that, if failure of the examined network or sub-network (individual demand, group demand, or system demand) occurs, it implies that at least one of its minimum cut-sets has failed.

Based on the above, the failure probability of the network will then be computed as follows:

$$P_f = P(Z_1 \cup Z_2 \dots \cup Z_M) = \sum_{i=1}^M P(Z_i) - \sum_{i=2}^M \sum_{j=1}^{i-1} P(Z_i \cap Z_j) + \dots + (-1)^{M-1} P(Z_1 \cap Z_2 \cap \dots \cap Z_M) \quad (4.18)$$

Likewise, the risk rating of the network will be computed as follows;

$$R_f = (R_{S1} \cup R_{S2} \dots \cup R_{SM}) = \sum_{i=1}^M R_{Si} - \sum_{i=2}^M \sum_{k=1}^{i-1} (R_{Si} \cap R_{Sk}) + \dots + (-1)^{M-1} (R_{S1} \cap R_{S2} \cap \dots \cap R_{SM}) \quad (4.19)$$

Based on the above, the upper and lower bounds of the failure probability of the network can be obtained by truncating the higher-order terms. Where computation of the first term in equation 4.19 will yield the upper bound (P_f^U), from which subtraction of the second-order term will yield the lower bound (P_f^L). That is:

$$P_f^L = \sum_{i=1}^M P(Z_i) - \sum_{i=2}^M \sum_{j=1}^{i-1} P(Z_i \cap Z_j) \leq P_f \leq \sum_{i=1}^M P(Z_i) = P_f^U \quad (4.20)$$

The authors stated that if the difference between the upper and lower bounds is insignificant, equation 4.19 can be approximated by,

$$P_f \approx P^U_f = \sum_{i=1}^M P(Z_i) \quad (4.21)$$

The above greatly reduces the computational work.

The network reliability of the oil and gas supply chain network, its composite probability of failure probability, as derived based by Yang, et al. (1996), is,

$$R_n = 1 - P_f \quad (4.22)$$

While, the modified risk based network reliability model, is,

$$R_{nr} = R_n - R_f \quad (4.23)$$

4.4 LP Supply Chain Models

The oil and gas supply chain can be broadly described through three classes of units that are classified according to their function in the chain. These are processing, storage tanks and pipelines units.

The developed model follows that earlier developed by Neiro et al. (2004), where the authors modeled the oil and gas supply chain as a continuous entity for planning and scheduling using stream flow rate. They modeled the three critical nodes units (i.e., refinery/processing, storage and pipelines units) separately as three independent nodes,

while they finally connected them together to come up with one continuous supply chain model, whose overall objective function is;

$$\begin{aligned} \text{Max } Z = & \sum_{u \in \cup_{dem}} \sum_{t \in T} C_{p_{u,t}} \cdot Dem_{u,t} - \sum_{u \in \cup_{port}} \sum_{t \in T} C_{pet_{u,t}} \cdot QF_{u,t} - \sum_{u \in \cup_{pu}} \sum_{t \in T} \\ & [Cr_u + \sum_{u \in VOu} (C_{V_{u,v}} \cdot V_{u,v,t})] \cdot QF_{u,t} - \sum_{u \in \cup_f} \sum_{t \in T} C_{inv_u} \cdot Vol_{u,t} - \sum_{u \in \cup_p} \\ & \sum_{t \in T} C_{inv_u} \cdot Vol_{u,t} - \sum_{u \in \cup_{pipe}} \sum_{t \in T} Ct_u \cdot QF_{u,t} \end{aligned} \quad (4.24)$$

Subject to:

- Processing units at refineries constraints,
- Petroleum and product tanks constraints, and
- Pipeline of crude oil and products constraints.

The modifications that was carried out in developing the model for this study are

- To model with demand and supply and not stream flow rates
- To include risk ratings of threats, events and activities we calculated in Section 4.2, in the model.

The models for the three chain units i.e. processing, storage tanks and pipelines units, were developed separately as three independent nodes, while the overall network supply chain model was then developed by connecting these independent nodes representing refineries, storage and pipeline networks into one continuous supply chain model. Risk ratings calculated as explained in Section 4.2 above, will be used as one of the constraints in running these models.

Decision variables are the quantity of raw materials (crude) from each source and quantity of product (petroleum products) from processing units, all subject to risk, processing capacity, crude, storage, demand, quality and non - negativity constraints, towards an optimum solution.

The proposed model, which is based on realistic assumptions and easy to understand mathematical terminologies, is applied to a real world operation by analyzing different scenarios. The next three sub - sections will present the mathematical model of each element highlighting their particularities, while sub - Section 4.4.4 presents the overall oil and gas supply chain model based on these three classes of elements.

4.4.1 Refinery/Processing Unit Model

Processing unit is defined as a piece of equipment that is able to physically or chemically modify the material fed into it. According to this definition, processing units are all those that compose the refinery topology and are modeled based on that.

- **Objective Function:** maximize revenue. That is, to maximize the net revenue (dollars) at the j th refinery's gate on one barrel of the k th product from the i th crude.

This net unit value is determined by crediting the yield of each product with its refinery gate realization, debiting each product for the manufacturing expenses associated with it, and also debiting the costs of producing, transporting, distilling and storing one barrel of the crude.

$$\text{Max Revenue: } ((\sum (\text{Sales of Products}) - (\sum (\text{Cost of Crude} + \text{Cost of} \quad (4.25)$$

$$\text{Production}))$$

$$\text{Max } Z = \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} (((0.4 x_{ij,t} + 0.15 x_{ij,t} + 0.2 x_{ij,t} + 0.24 x_{ij,t}) (r_{ijk})) - (c_i x_{ij,t} + t_{ij} x_{ij,t} + m_{ij} x_{ij,t} + e_{ijk} x_{ij,t} + s_{ij} x_{ij,t} + s_{ijk} x_{ij,t})) \quad (4.26)$$

Where:

$$p_{ij} = \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} (c_i + t_{ij} + m_{ij} + e_{ijk} + s_{ij} + s_{ijk}) \quad (4.27)$$

In order to make clear what is involved in equations 4.26 and 4.27 above, a hypothetical calculation is carried through for an individual crude-oil-refinery assignment. The problem is to consider the assignment of the *i*th crude oil to the *j*th refinery, and to trace through the various cost elements involved in taking this crude from the producing field, transporting and storing it at the refinery, processing and storing the products there, and then disposing of the finished products at the refinery gate.

Where, volumetric yield (y_k) in percent in 1 barrel of crude is;

Gasoline –	40%
Kerosene –	15%
Heating oil –	20%
Residual fuel oil –	24%
Volume loss in refining –	1%

That is:

$$y_k x_{ij} = (0.4 x_{ij} + 0.15 x_{ij} + 0.2 x_{ij} + 0.24 x_{ij}) \quad (4.28)$$

- Constraints: If there are m refineries and n crude oil source, the problem reduces to the following constrained-maximum form:

1) Plant constraints at each refinery.

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} x_{ij,t} \leq Q_{j,t} \quad (4.29)$$

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} y_k x_{ij,t} \leq D_{j,t} \quad (4.30)$$

2) Crude constraints from source

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} x_{ij,t} \leq Q_{i,t} \quad (4.31)$$

3) Demand constraints

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} y_k x_{ij,t} \geq D_{k,t} \quad (4.32)$$

4) Non – negativity constraints

$$x_{ij,t} \geq 0 \text{ (all } i \text{ and } j) \quad (4.33)$$

5) Risk constraints inherent from both crude sources and refinery vulnerabilities.

- crude sources risk constraints

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} R_i x_{ij,t} / \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} x_{ij,t} \leq R_t \quad (4.34)$$

- refinery vulnerability risk constraints

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} R_j y_k x_{ij,t} / \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} x_{ij,t} \leq R_t \quad (4.35)$$

6) Quality Constraints (using a number scale from 0 to 10 to represent the quality of crude oil – with 10 being the highest quality).

- Quality of crude constraints at each jth refinery will be

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} (ix_{ij,t}) / 2 \geq iq_{j,t} \quad (4.36)$$

Note: Oil is generally classified based on its density and sulphur content.

- Density- it can either be light crude or heavy crude. Light crude is more expensive because it requires less refining, while heavy crude is cheaper because it requires more refining.

- Sulphur content- Oil can either be sweet or sour crude. Sweet crude has a sulphur content of less than 0.5% by weight, making it easier to refine to meet environmental standards – so less expensive; while sour crude has sulphur content of more than 0.5% by weight, making it more expensive to refine.

Table F.1 in Appendix F shows the quality rating that we derived for various crude oil sources based on the above quality criteria.

4.4.2 Tank Unit Model

Tank is defined as a piece of equipment where the only two allowed operations are mixture and storage of the different feed streams. Only physical properties can be modified due to mixing. Tank farms for storing both crude and products are considered.

- Objective function; Minimize the total cost of storing both crude oil and products, while noting the level of risks and vulnerabilities at each tank farm for a time period t.

$$\text{Min } Z = \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} ((Z_{ijL} x_{ij,t}) + (Z_{ijkL} y_k x_{ij,t})) \quad (4.37)$$

- Constraints: If there are m refineries and n crude oil source, the problem reduces to the following constrained-maximum form:

1) Plant constraints at each refinery

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} x_{ij,t} \leq Q_{j,t} \quad (4.38)$$

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} y_k x_{ij,t} \leq D_{j,t} \quad (4.39)$$

2) Crude constraints from source

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} x_{ij,t} \leq Q_{i,t} \quad (4.40)$$

3) Demand constraints

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} y_k x_{ij,t} \geq D_{k,t} \quad (4.41)$$

4) Non – negativity constraints

$$x_{ij,t} \geq 0 \text{ (all } i \text{ and } j) \quad (4.42)$$

5) Risk constraints inherent from both crude and products storage points.

- crude storage points risk constraints

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} R_{ijL} x_{ij,t} / \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} x_{ij,t} \leq R_t \quad (4.43)$$

- products storage points risk constraints

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} R_{ijkL} y_k X_{ij,t} / \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} y_k X_{ij,t} \leq R_t \quad (4.44)$$

6) Storage farms capacity constraints

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} X_{ij,t} \leq Q_{s,t} \quad (4.45)$$

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} y_k X_{ij,t} \leq D_{s,t} \quad (4.46)$$

4.4.3 Pipeline Unit Model

Pipeline is defined as a piece of equipment that transports crude oil and products. Neither physical nor chemical properties are modified during transportation. As hypothesis, different petroleum types or products are never mixed when transported in pipelines, because a well-defined interface is assumed to exist between two different products or petroleum types. In other words, there is no property depletion due to direct contact between products or petroleum types. Therefore, the general framework for modeling a pipeline is to consider it as a group of units in parallel.

- Objective function; Minimize the total cost of transporting crude oil from sources to refineries, and then products from refineries to storage/distribution points/consumers. While, noting the level of risks and vulnerabilities on each route at time period t .

$$\text{Min } Z = \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} ((T_{ij} x_{ij,t}) - (T_{ijkl} y_k x_{ij,t})) \quad (4.47)$$

- Constraints: If there are m refineries and n crude oil source, the problem reduces to the following constrained-maximum form:

1) Plant constraints at each refinery

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} x_{ij,t} \leq Q_{j,t} \quad (4.48)$$

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} y_k x_{ij,t} \leq D_{j,t} \quad (4.49)$$

2) Crude constraints from source

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} x_{ij,t} \leq Q_{i,t} \quad (4.50)$$

3) Demand constraints

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} y_k x_{ij,t} \geq D_{k,t} \quad (4.51)$$

4) Non – negativity constraints

$$x_{ij,t} \geq 0 \quad (\text{all } i \text{ and } j) \quad (4.52)$$

5) Risk constraints inherent from both crude transportation from sources to refineries and products transportation from refineries to storage/outlet points at time period t.

- crude sources to refineries risk constraints

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} R_{ij} x_{ij,t} / \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} x_{ij,t} \leq R_t \quad (4.53)$$

- refineries to storage/outlet points risk constraints

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} R_{ijkL} y_k x_{ij,t} / \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} y_k x_{ij,t} \leq R_t \quad (4.54)$$

6) Pipeline capacity constraints

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} x_{ij,t} \leq Q_{p,t} \quad (4.55)$$

$$\sum_{i=1}^{i=m} \sum_{j=1}^{j=n} y_k x_{ij,t} \leq D_{p,t} \quad (4.56)$$

4.4.4 Oil and Gas Supply Chain Model

Models of the elements presented in the previous section take part in the set of constraints that compose the optimization problem of the whole complex. The optimization problem is then given as stated earlier in Section 2.1 (Oil and Gas Supply Chain). The objective function is defined in Equation 4.57 where the maximization of the revenue obtained by the product sales minus costs related to raw material, operation, inventory, transportation and storage is determined. The operating cost is dependent on the refinery/processing unit models, the transportation cost depends on the pipeline segment, while the storage cost is dependent on the tank model.

The objective of this work is to develop a risk based optimization model using the oil and gas refinery critical infrastructure supply chain operations (see figures 2.1, 2.2 and 2.3), to predict, manage and minimize the effects of the inherent risks and vulnerabilities of the different oil and gas supply chain routes.

- Objective function; Maximize the revenue obtained by the product sales minus costs related to raw material, operation, transportation and storage at time period t . The operation cost is dependent on the refinery/processing unit models, the transportation cost depends on the pipeline segment, while the storage cost is dependent on the tank model.

$$\text{Max } Z = \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} ((y_k x_{ij,t} r_{ijk}) - (p_{ij} x_{ij,t}) - (Z_{ijL} x_{ij,t}) + (Z_{ijkL} y_k x_{ij,t}) - (T_{ij} x_{ij,t}) - (T_{ijkl} y_k x_{ij,t})) \quad (4.57)$$

Subject to:

- Equations (4.29) - (4.36) to represent processing units at refineries,
- Equations (4.38) - (4.46) to represent crude oil and products tanks,

- Equations (4.48) - (4.56) to represent crude oil and products pipelines.

It must be clear that equation (4.12) is responsible for the connection between crude oil sources and refineries; equation (4.23) responsible for the connection from crude oil sources to storage tanks and petroleum products to storage tanks; while crude oil to pipelines and petroleum products to pipelines are connected through equation (4.33).

All the variables are as highlighted in the individual supply chain models above.

4.5 Model Based Vulnerability and Fault Tree Analysis (MBVA and FTA)

Models

4.5.1 MBVA Model

The MBVA model that will be used in this study will be the one developed by Lewis (2006). There, the author defined MBVA, as a comprehensive method of analysis that combines network, fault, event, and risk analysis into a single methodology for quantitatively analyzing a sector component such as a hub. In MBVA, hubs are identified, with hub vulnerabilities organized and quantified using a fault tree, all possible events being organized as an event tree, and then an optimal investment strategy computed that minimizes risk. MBVA gives the policy analyst a top-to-bottom tool for achieving critical infrastructure protection (CIP) under budgetary constraints.

The steps of MBVA are as follows:

- List assets – Take inventory
- Perform network analysis – identify hubs
- Model the hubs as a fault tree

- Analyze the fault tree model using an event tree
- Budget analysis – compute optimal resource allocation

The MBVA will be used to evaluate the energy sector critical units/nodes – like the crude source unit components. The reduction in vulnerability that will be obtained from the resource allocation by using the proposed MBVA being compared with the likely increase in cost of petroleum product as a result of the success of an imminent threat obtained from the LP model in Section 4.2 above in order to ascertain the benefits or otherwise of investing in the CIP.

These seem to be the most critical components, because of their concentration and capacities, furthermore, many of these critical components are wide open, easily accessed and therefore vulnerable to both symmetric and asymmetric attacks. Threats to these critical components will be analyzed based on likely vulnerability of each, before arriving at the vulnerability of the overall critical component/unit.

First, the network analysis of the chain will be carried out to determine if the network has a scale free structure, by obeying the power law, i.e., the number of nodes with degree K falling sharply as K is increased (i.e., high degree nodes with more than an average number of links). This is the first requirement that the network has to obey before we can carry out an MBVA modeling of the network.

The steps in carrying out the Network test are:

- Get the degrees of the node by counting the number of links connecting the nodes in the network.
- Get the frequency of nodes with a certain number of links, by counting the number of nodes with degree of 1, 2, 3, and so on, then divide these counts by the number of nodes in the entire network.

- Plot the node frequencies as a histogram starting with the frequency of nodes with 1 link, then 2 links, 3, and so on.
- If the resulting histogram has a shape, that shows the frequency counts declining as the number of links increases. The rate of decline approximates the curve, $(1/k)^p$, where p is greater than one, the network is a scale free network.

The vulnerabilities and damage/consequences, with the likelihood of an event scenario make up the risk triplets that will be analyzed to obtain the weighted risk/risk ratings in Section 4.2 above. So as the CIP are implemented, the vulnerability of the sector component will decrease, so also the consequences/damages and subsequently the risks associated with that sector component.

Vulnerability analysis (VA), involves complicated factors, such as the nature of the threat, the likelihood of successful attacks, and the interplay among components that make up the critical infrastructure sector. This sophistication requires a sophisticated approach involving probability, logic, and modeling. The predominant tool for constructing such models is the fault tree – logic and probability model of the infrastructure’s critical nodes, Figure (4.1) below shows the complete fault tree for the crude supply component of the energy sector.

A standard fault tree has three layers: the root representing the sector component/critical node; the intermediate component layer; and the threat. It is simply a model of the components of a critical node or sector organized as a hierarchy or tree-structured graph. The nodes in the tree are called components, logic gates (AND/OR), and threats. The intermediate component is any major asset of the sector, such as crude drilling, crude storage and crude shipment/transmission. The root of the fault tree is a special component/unit of that sector, e.g. crude supply; while a threat is any physical threat to a sector component. Threats are represented as terminal nodes in the tree-

structured fault tree. A fault occurs when a threat is activated – an attack- and successfully damages one or more components of the sector. The purpose of the fault tree is to model what happens to the sector component when a threat turns into a fault. A logic gate is a node in the fault tree that determines how faults propagate up the tree. They are diamond-shaped nodes in the fault tree, and can be an OR gate/an AND gate. In the case of an OR gate, the occurrence of one or more faults causes a fault to propagate up the tree, while in the case of an AND gate, all threats connected to the AND gate must occur for the fault to propagate up the tree. Faults initiated by one or more threat, work their way up the fault tree according to the branches and logic gates, with the sector component failure occurring, only when a fault reaches the root of the fault tree.

Therefore, a sector component failure is defined as or more faults that propagate all the way up to the root of the fault tree. The fault tree will be populated with vulnerability estimates, which are derived from records of past attacks or forced disruption of operations, maintenance history, component failure data, human errors, operation and engineering experience, and plant design documentation, e.t.c., to derive the overall sector component vulnerability.

MBVA is called “model-based” because we build a simple model of the sector components of interest. It, specifically, combines network analysis with fault tree modeling to derive vulnerability, risk, and resource allocation strategies that tell the decision maker how best to allocate resources.

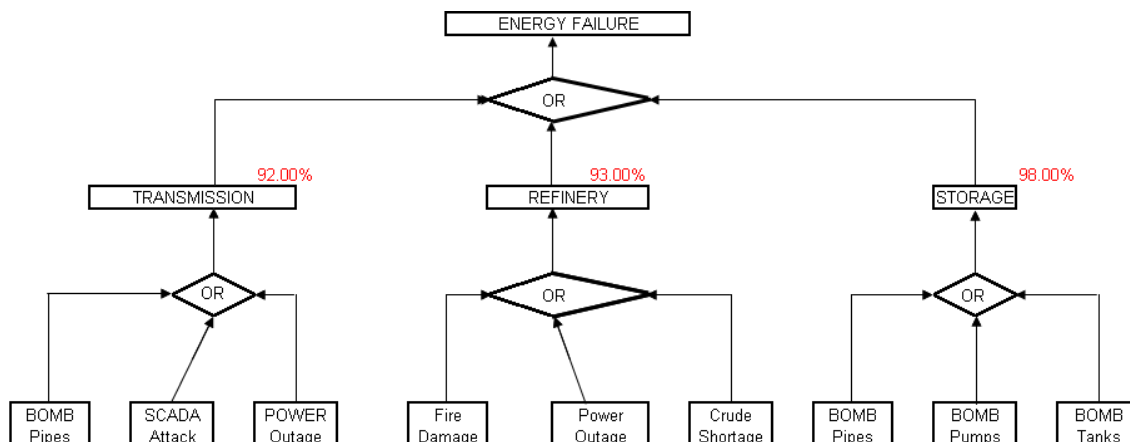


Figure 4.1 Crude source failure Fault Tree.

4.5.1.1 Crude Source Structure.

Some important bits that will play a major

part in subsequent analysis are enumerated below:

- US crude source come from both overseas and domestic sources.
- Crude vary in their quality and quantity.
- These crude sources component of the energy sector have varieties of risks and vulnerabilities inherent in their exploration/ drilling, shipping/transportation and storage.
- Its intermediate components are wellheads, transmission pipelines/ships and storage tanks.
- They are characterized by heavy concentrations-clusters-of these intermediate components.
- Its major vulnerabilities exist because of these clusters.
- These vulnerabilities are concentrated in three (3) intermediate components of the crude source component: drilling/exploration heads, large transmission pipelines, and large centralized storage facilities.
- Critical nodes of the wellheads intermediate components are vulnerable to these physical threats – fire damage, power outage and attacks; transmission pipelines are large volume clusters of pipelines that are vulnerable to such threats as bomb and SCADA attacks, and power outage; while that of the storage component are also large capacity storage farms located at both offshore and onshore points that are vulnerable to such threats like bomb attacks on pipes, pumps and tanks.

4.5.2 FTA Model

Fault Tree Analysis (FTA) is another technique for reliability and safety analysis. It is one of many symbolic "analytical logic techniques" found in operations research and in system reliability.

Fault Tree Diagram (FTD). Fault tree diagrams (or negative analytical trees) are logic block diagrams that display the state of a system (top event) in terms of the states of its components (basic events).

A FTD is built top-down and in term of events rather than blocks. It uses a graphic model of the pathways within a system that can lead to a foreseeable, undesirable loss event (or a failure). The pathways interconnect contributory events and conditions, using standard logic symbols (AND, OR etc). The basic constructs in a fault tree diagram are gates and events.

In this research, FTD was developed to analyze each source-demand pair and subsequently the entire supply chain risk using the calculated risk from likely events/activities that can likely affect the link, to determine whether any particular pair has failed or not. These calculated risks can either increase or decrease depending on the variation in the unfixed variables (i.e., the threat and probability of events scenarios) of our developed risk equation.

The AND/OR logic gates was used between any two source-demand pair, depending on whether respective pair has failed or not (OR for failure and AND for no failure). Any pair will be categorized as 'FAILED', if the analyzed fault tree risk for any pair is greater than a set threshold allowable risk.

Resource (\$\$) allocation were also apportioned from top to bottom of the developed FTD to each pair based on the analyzed fault tree risk to harden them against any threat scenario.

CHAPTER 5

SIMULATIONS AND ANALYSIS

5.1 Introduction

The risks based models in Chapter 4 will be used to simulate and analyze different scenarios in a real world oil and gas supply chain critical infrastructure system. The result will help to deduce and predict the impact of different risks and events in the sector, which will give professionals in this sector a better understanding of the effects of some of these analyzed events and activities, towards minimizing/eliminating instability in the oil and gas critical infrastructure by making the industry more resilient.

5.2 Events and Activities Risk Ratings Model Analysis

The risk, R_{ij} , of some events and activities that have impacted the oil and gas sector over the past century will be analyzed using the risk triplet, highlighted in Section 4.2.

5.2.1 Analysis

The threat scenario, e_i ($i = 1, 2 \dots m$), will be derived by assessing the protection vulnerability that is in place to prevent these events and activities taking place. For this analysis a minimal level of Critical Infrastructure Protection (CIP) in place will be assumed, as it is always better to assume a worst case scenario. Also, another consideration here will be the political climate – for cases of war or crisis in any region that has one of the source-demand nodes. For instance, since the average political condition in Nigeria over the past four decades is somewhat unstable, on the average, a high percentage of threat scenarios will be assumed, i.e., crisis in Nigeria, of 90%. While

the average threat of Hurricane in the Gulf coast area will be rated at 50% per hurricane season. Tables 5.1 and 5.2 below show the threat scenarios assumed for the rest events and activities.

The probability/vulnerability of this scenario (that is the overall vulnerability), $p_{ij}/V_T(c_j, e_i)$, measures the likelihood that a threat scenario will lead to consequences or damage. These figures are obtained by reviewing the figures in Chapter 3 to ascertain the frequency of occurrence of such event leading to those consequences. For instance, the Isreal – Arab war from history usually occurs every 1:20 years, therefore the probability will be 0.05. Tables 5.1 and 5.2 show the other analysis.

The damages/consequence, c_j ($j = 1, 2, \dots, n$), which measures the degree of loss that would be realized given that the specified initiating threat event resulted in a damage to the supply chain, will be derived by analyzing the effect of any event on the price of crude and products. These figures are obtained by analyzing Figures 3.1 – 3.16 in chapter 3 to ascertain the changes that occurred in the oil and gas network/chains from successful events/activities on their nodes/links in the past. For instance it was seen from Figure 3.1 that successful Israel-Arab war in the '70s led to a 400%!! Rise in crude prices, while a 50% successful hurricane (i.e., 50% knock down in production activity based on a hurricane) in the Gulf coast area of the US (a very critical node and link) will lead to a 20% increase in the price.

The three threat scenarios were then multiplied together to derive their risk, which was compared to the overall risk of all the analyzed events and activities at any one time, so as to derive the weighted risk, which will give their respective ratings. For instance, a successful hurricane in the Gulf coast area which has 20% damage and 50% likelihood of

threat scenario, but with a very high probability of occurrence of at least, 1:1year, ended up with the same rating-7, as that of a successful Israel-Arab war, despite the fact that it has a high consequences of 400% increase in the price of crude, but with a low probability of occurrence of 1:20years. Tables 5.1 and 5.2 below show the rest simulated results of the risk rating obtained with the developed risk model and spreadsheet.

Table 5.1 Some Analyzed Long Term Events and Activities and their Calculated Risk Ratings using our Developed Spreadsheet and Risk Models

No. (1)	Events (2)	Consequences(%) (3)	Prob.(Yrs) (4)	Prob.(Yrs) in Decimal (4)	Threat (%) (5)	Calculated Risk (6) = {(3)(4)(5)}	Weighted Risk (7) = {(6)/(Σ of 6))*10}	Risk Ratings = (7) on scale of 1-10
1	Hurricane	20	1/1	1.00	50%	10.00	1.44	7
2	Demand growth	12	1/5	0.20	40%	0.96	0.14	3
3	Production increase/decrease	20	1/1	1.00	50%	10.00	1.44	7
4	Crisis in Nigeria	7	1/1	1.00	90%	6.30	0.91	5.5
5	Crisis in Iraq	50	1/3	0.33	50%	8.33	1.20	6
6	Crisis in Iran	67	1/5.5	0.18	70%	8.53	1.23	6
7	Crisis in Russia	20	1/10	0.10	50%	1.00	0.14	3
8	Crisis in Venezuela	37	1/10	0.10	50%	1.85	0.27	4
9	Economic crisis	30	1/8	0.13	85%	3.19	0.46	4
10	Pipeline attacks	1	1/1	1.00	70%	0.70	0.10	2
11	Israel - Arab war	400	1/20	0.05	50%	10.00	1.44	7
12	Offshore drilling	2	1/25	0.04	70%	0.06	0.01	1
13	Speculation	7	2/1	2.00	60%	8.40	1.21	6
14	Opening U.S. reserve.	5	1/10	0.10	10%	0.05	0.01	1
					Σ of Calculated Risk		69	

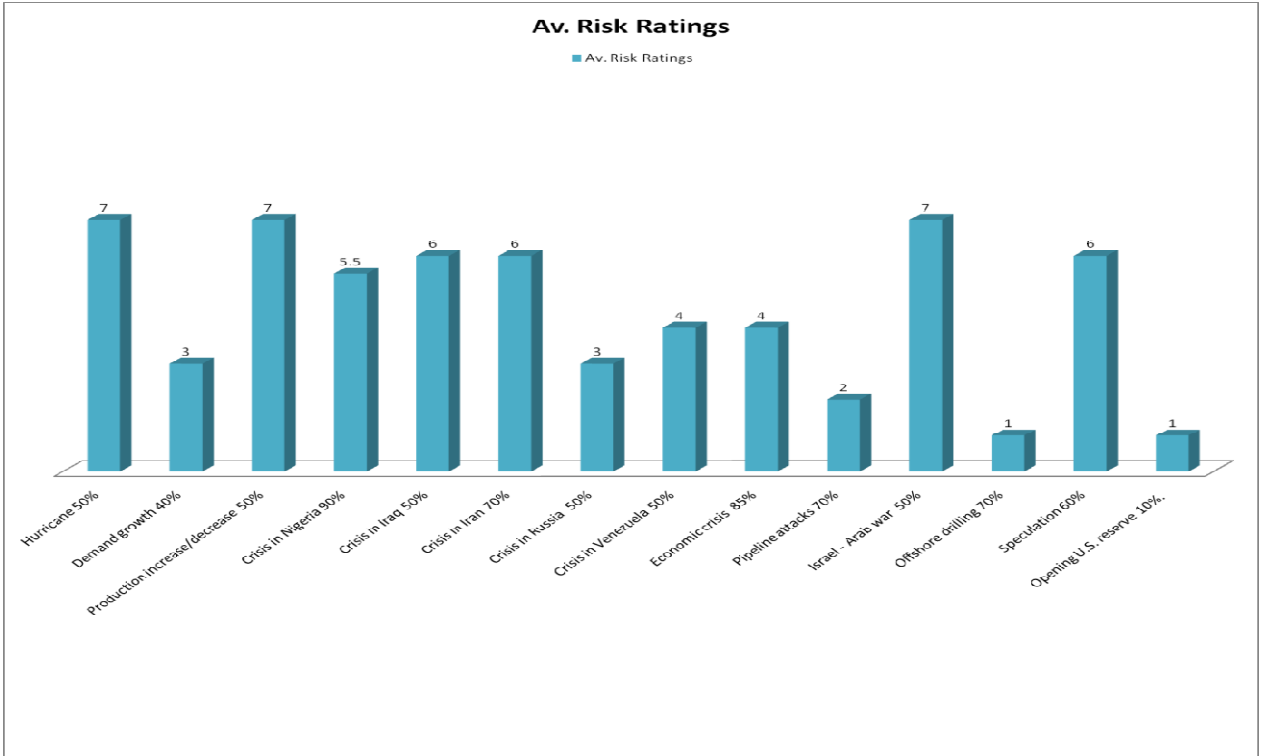


Figure 5.1 Bar chart showing some analyzed long term events vs. the calculated average risk ratings.

Table 5.2 Some Analyzed Short Term Events and Activities and their Calculated Risk Ratings using our Developed Spreadsheet and Risk Models

No. (1)	Events (2)	Consequences(%) (3)	Prob.(Yrs) (4)	Prob.(Yrs) in Decimal (4)	Threat (%) (5)	Calculated Risk (6) = {(3)(4)(5)}	Weighted Risk (7) = {((6)/(Σ of 6))*10}	Risk Ratings = (7) on scale of 1-10
1	Pipe leaks/breaks	167	1/10	0.10	80%	13.36	8.20	5
2	Redundancy failures	20	1/20	0.05	50%	0.50	0.31	3
3	Refinery fire/explosion	50	1/15	0.07	50%	1.67	1.02	4
4	Power outage	20	1/25	0.04	30%	0.24	0.15	2
5	Tank farms cracks/leaks	10	1/15	0.07	80%	0.53	0.33	3
					Σ of Calculated Risk	16		

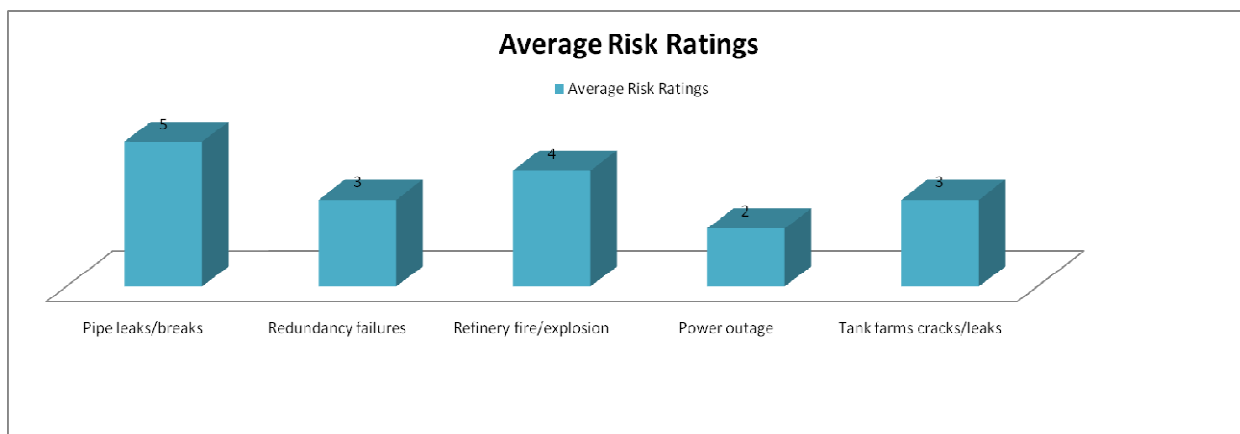


Figure 5.2 Bar chart showing some analyzed short term events Vs the calculated average risk ratings.

5.2.2 Summary and Conclusion

The analysis used to derive the risk ratings, which will be used in the analysis and simulations for the risk based models in this work, was derived using the prototypical expression for risk in the homeland security context, traditionally called the risk triplet scenarios. It can be deduced that the risk ratings were successfully derived by reviewing and analyzing the consequences and probability of occurrence of the events and activities in the nodes and links of the oil and gas supply chain/network. While the likelihood of the threat occurring, which can either go up or down, depends on the CIPs in place to prevent or protect these events, and, also the political or economic climate that exist at any one instance.

One of the limitations of this analysis is the tendency to base the analysis on the economical consequences of these events and activities, a future study might also try to look at other consequences as well.

5.3 Network Reliability Analysis Model Simulation

The case study to be simulated and analyzed using the network reliability model will be based on the real-world petroleum supply chain planning problem of Petrobras (Brazil), which was analyzed by Neiro et al. (2004) for the general modeling framework for the operational planning of petroleum supply chains. The study showed that Petrobras has 59 petroleum exploration sites among which 43 are offshore, 11 refineries that are located along the country's territory and a large number of facilities such as terminals and pipeline networks. Refinery sites are concentrated mainly in southern Brazil where seven sites are found, four of which represent 47% of the company's processing capacity. These refineries are located in the most important and strategic consumer markets. Therefore, the study addressed the supply chain of these four refineries, namely: REVAP, RPBC, REPLAN and RECAP (Figure 5.3). Five terminals compose the storage facilities, namely: SEBAT, SEGUA, CUBATAO, SCS and OSBRA; and a pipeline network for crude oil supply and another for product distribution compose the transportation facilities. The petroleum and product storage and distribution facilities were considered to be organized as detailed in Figures 5.4 and 5.5, respectively. Refineries are supplied with petroleum by two main pipeline branches. The OSVAT segment connects refineries REVAP and REPLAN to the SEBAT terminal, whereas the OSBAT segment connects refineries RPBC and RECAP to the same terminal. Terminals between extreme nodes are required in case intermediate storage is needed or pumping capacity is limited. Crude oil is acquired from a variety of suppliers and its properties strongly depend on supplier origin, which result in different petroleum types. Twenty petroleum types are considered to supply the complex.

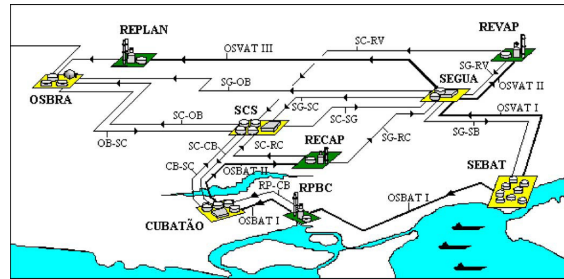


Figure 5.3 Supply chain—case study.

Source: Neiro et al. (2004).

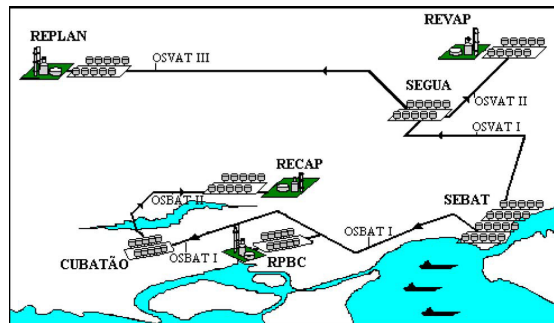


Figure 5.4 Crude oil supply—case study.

Source: Neiro et al. (2004).

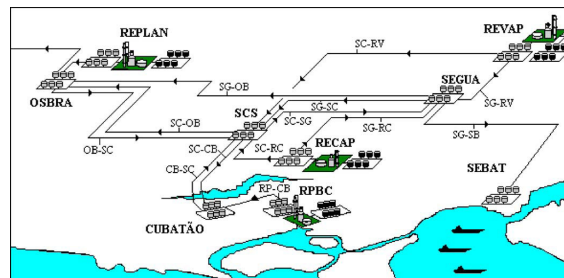


Figure 5.5 Products storage and distribution—case study.

Source: Neiro et al (2004).

The overall charge is supplied through SEBAT whereby it is then distributed to the terminals and refineries as described in the previous paragraph. Since petroleum types from different suppliers present distinct properties, every petroleum type is stored at an assigned petroleum tank that is also dedicated. Therefore, SEBAT holds twenty

petroleum tanks as shown in Figure 5.4. Ten oil types are potentially supplied to RECAP and the remaining ten are potential suppliers to REVAP, RPBC and REPLAN. Refineries and terminals also contain tank farm that store each of the petroleum types, according to Figure 5.4. The whole complex is able to provide 32 products to local markets. Six products may be also transferred to supply the demand from other regions. Transfer is accomplished by either vessels or pipelines. In case the former is selected, products are sent to the SEBAT or CUBATAO terminals, whereby products are shipped. In case of transfer through pipeline, products are sent to the OSBRA terminal, whereby they are pumped. Demands from other regions are imposed at the tanks of the transshipment terminals. In analogy to petroleum types, different products are also stored at dedicated tanks, so that every refinery and terminal contains a set of storage tanks for products. Figure 5.5 presents the two types of product tanks. The black tanks represent products that supply only the local market, whereas the gray tanks represent products that supply either market, local and from other regions.

5.3.1 Analysis

The supply chain is broken up into two chains for the analysis. The first is the crude oil supply, Figure 5.4, and the second is the products storage and distribution, Figure 5.5.

For convenience, in the first chain, the supply node, SEBAT, will henceforth be denoted as S1, while the demand nodes, REVAP, REPLAN, RPBC and RECAP will be denoted by D1, D2, D3 and D4. For the links, OSVAT I, OSVAT II, OSVAT III, OSBAT I (between S1 and D3), OSBAT I (between D3 and CUBATAO) and OSBAT II, will be denoted as P1, P2, P3, P4, P5 and P6 respectively.

In the case of the product storage and distribution, the supply nodes REPLAN, REVAP, RECAP and RPBC, will be denoted as S1, S2, S3 and S4, the demand nodes SEBAT, SEGUA, CUBATAO, SCS and OSBRA will be denoted as D1, D2, D3, D4 and D5, and for the links between $S2 \rightarrow D2$, $D2 \rightarrow D1$, $S2 \rightarrow D4$, $D2 \rightarrow D4$, $D5 \rightarrow \text{others}$, $S1 \rightarrow D5$, $D5 \rightarrow D4$, $D4 \rightarrow D5$, $D2 \rightarrow D5$, $D4 \rightarrow D2$, $S3 \rightarrow D2$, $S3 \rightarrow D4$, $D4 \rightarrow D3$, $D3 \rightarrow D4$, $S4 \rightarrow D3$, will be denoted as P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, P11, P12, P13, P14 and P15 hereinafter respectively.

For convenience also, assume that in the first chain only short term events and activities will likely affect them. Therefore, for OSVAT crude, assume that there is a major pipeline explosion, that normally takes weeks to repair, which from Table 5.2, has a risk rating of 2 on a 1 - 10 rating scale (i.e., 0.2), while for the OSBAT crude, the assumption is that there is a major fire at the storage farm, which normally takes months to repair. The rating for this from Table 5.2 is 5 (i.e., 0.5)

In the case of the product storage and distribution chain, the assumption is a long term event, like, sudden demand growth. Which carries a risk rating of 3 (0.3) on the risk ratings table, Table 5.1.

5.3.1.1 Minimum Cut-Set Analysis. Table 5.3 shows the demand, production/availability of the source-demand nodes of the crude oil SC network (Neiro et al. (2004)). While Table 5.4 shows the simulated arc flows of each link that connects a source demand pair, obtained using the optimization model for identification of the minimum cut-set of a source-demand pair, Equation 4.11 developed in Section 4.3, subject to constraints in Equations 4.12 to 4.15. Recall, that any link with a resultant arc flow

greater than zero is considered a minimum cut-set/critical link and must be preserved to maintain the network flow.

Table 5.3 Demands, Production/Availability at the Source-Demand nodes of the Crude Oil SC

Number	Nodes	Demand (m ³)	Production/ Availability(m ³)
1	REVAP	36,000	8,980
2	RBPC	35,500	6,763
3	RECAP	8,500	2,330
4	REPLAN	54,200	21,950
5	SEBAT	17,700	17,700
6	CUBATAO	26,563	10,600
7	SEGUA	36,000	35,403

Table 5.4 Arc Flow and Minimum Cut-Set Links Descriptions for the Crude oil SC Source-Demand Pairs

No.	Links	Arc Flows	Link Descriptions
1	P1	+10,200	Critical
2	P2	- 27,200	Non-Critical
3	P3	0	Neither
4	P4	+26,563	Critical
5	P5	-437	Non-Critical
6	P6	0	Neither

5.3.1.2 Reliability Analysis. The results of the reliability analysis without risks for crude oil supply chain in Table 5.5, show that aside from the (S1, D4) source – demand node pair, the three others are all critical nodes, with critical links too. (S1, D1) and (S1, D2) have a somewhat not too high reliability of 0.75, while, (S1, D3) have 0 reliability. This difference in reliability between these two critical nodes pair is because of the existence of a storage farm at SEGUA that can reduce the impact of failure in the critical links or nodes between the source and demand points. When risk is incorporated into the chain, the results in Table 5.8 shows a reduction in the reliability of the chains/links, with a 12% decrease in the reliability of (S1, D4) source – demand node pair.

The results of the reliability analysis without risks for the products storage and distribution supply chain in Table 5.6 shows that the existence of storage farms and many links between source-demand pairs not only increased the reliability, but will be crucial for oil and gas supply chain. In the case of pipe or critical nodes failure, the availability of these redundancies will preserve the supply chain. All the demand nodes are considered important so group demand and system demand reliability is not considered for the Petrobras supply chain. Fifteen of the twenty source-demand pair has a reliability value of over 0.9. The high reliability is a result of high redundancy and storage farms in the chain. When risks are incorporated in the chain, the reliabilities decreased, with five of the source-demand pair having a reliability of less than 0.8, Table 5.9.

The results of the reliability analysis without risks for individual demand nodes in Table 5.7 shows that D4 with the smallest reliability of 0.7220, followed by D1, with

0.7413. While with risks, D3 and D5 reliability dropped by 70%! While D1 and D2 dropped by approximately 10%, and D4 by 35%.

Table 5.5 Minimum Cut-Sets and Reliability Values for Source-Demand Pair for Crude Oil Supply Chain without Risks

(1) Number	(2) Node Pair	(3) Minimum Cut Set		(5) Reliability
		(3) Quantity	(4) Link Identification	
1	(S1,D1)	2	P1,P2	0.7500
2	(S1,D2)	2	P1,P3	0.7500
3	(S1,D3)	1	P4	0.0
4	(S1,D4)	3	P4,P5,P6	0.9630

Table 5.6 Minimum Cut-Sets and Reliability Value for Source-Demand Pair for Product Storage and Distribution Supply Chain without Risks

Number (1)	Node Pair (2)	Minimum Cut Set		Reliability (5)
		Quantity (3)	Link Identification (4)	
1	(S1,D1)	4	P6,P7,P10,P2	0.9961
2	(S1,D2)	3	P6,P7,P10	0.9630
3	(S1,D3)	3	P6,P7,P13	0.9630
4	(S1,D4)	2	P6,P7	0.7500
5	(S1,D5)	1	P6	0.0
6	(S2,D1)	4	P1,P3,P10,P2	0.9961
7	(S2,D2)	3	P1,P3,P10	0.9630
8	(S2,D3)	6	P1,P3,P4,P9,P7,P13	0.9999
9	(S2,D4)	5	P1,P3,P4,P9,P7	0.9997
10	(S2,D5)	5	P1,P3,P9,P4,P8	0.9997
11	(S3,D1)	2	P11,P2	0.7500
12	(S3,D2)	3	P11,P12,P10	0.9630
13	(S3,D3)	4	P12,P8,P7,P13	0.9961
14	(S3,D4)	3	P12,P11,P4	0.9630
15	(S3,D5)	5	P12,P11,P4,P9,P8	0.9997
16	(S4,D1)	4	P15,P14,P10,P2	0.9961
17	(S4,D2)	3	P15,P14,P10	0.9630
18	(S4,D3)	1	P15	0.0
19	(S4,D4)	2	P15,P14	0.7500
20	(S4,D5)	5	P15,P14,P8,P10,P9	0.9997

Table 5.7 Minimum Cut-Sets and Reliability Value for Individual Demand Nodes for Product Storage and Distribution Supply Chain with and without Risks

Demand Node (1)	Minimum Cut Set (2)	Reliability without risk (3)	Reliability with risk (4)
D1	P1,P2,P3,P6,P7,P10, P11,P14,P15	0.7413	0.6848
D2	P1,P3,P6,P7,P10, P11,P12,P14,P15	0.8600	0.7675
D3	P1,P3,P4,P6,P7,P8, P9,P12,P13,P15	0.9592	0.2772
D4	P1,P3,P4,P6,P7,P9, P11,P12,P14,P15	0.7220	0.4706
D5	P1,P3,P4,P8,P9,P10, P11,P12,P14,P15	0.9991	0.2976

Table 5.8 Minimum Cut-Sets and Reliability Values for Source-Demand Pair for Crude Oil Supply Chain with Risks

Number (1)	Node Pair (2)	Minimum Cut Set		Reliability (5)
		Quantity (3)	Link Identification (4)	
1	(S1,D1)	2	P1,P2	0.7100
2	(S1,D2)	2	P1,P3	0.7100
3	(S1,D3)	1	P4	-0.2
4	(S1,D4)	3	P4,P5,P6	0.8380

Table 5.9 Minimum Cut-Sets and Reliability Value for Source-Demand Pair for Product Storage and Distribution Supply Chain with risks

Number (1)	Node Pair (2)	Minimum Cut Set		Reliability (5)
		Quantity (3)	Link Identification (4)	
1	(S1,D1)	4	P6,P7,P10,P2	0.9880
2	(S1,D2)	3	P6,P7,P10	0.9360
3	(S1,D3)	3	P6,P7,P13	0.9360
4	(S1,D4)	2	P6,P7	0.7100
5	(S1,D5)	1	P6	-0.3
6	(S2,D1)	4	P1,P3,P10,P2	0.9880
7	(S2,D2)	3	P1,P3,P10	0.9360
8	(S2,D3)	6	P1,P3,P4,P9,P7,P13	0.9992
9	(S2,D4)	5	P1,P3,P4,P9,P7	0.9973
10	(S2,D5)	5	P1,P3,P9,P4,P8	0.9973
11	(S3,D1)	2	P11,P2	0.7100
12	(S3,D2)	3	P11,P12,P10	0.9360
13	(S3,D3)	4	P12,P8,P7,P13	0.9880
14	(S3,D4)	3	P12,P11,P4	0.9360
15	(S3,D5)	5	P12,P11,P4,P9,P8	0.9973
16	(S4,D1)	4	P15,P14,P10,P2	0.9880
17	(S4,D2)	3	P15,P14,P10	0.9360
18	(S4,D3)	1	P15	-0.3
19	(S4,D4)	2	P15,P14	0.7100
20	(S4,D5)	5	P15,P14,P8,P10,P9	0.9973

5.3.2 Summary and Conclusion

A methodology to analyze the reliability of the oil and gas networks/supply chains connectivity using the minimum cut-set method, and associated algorithms and simulation, to determine the impact of link failures as a result of risks associated with

certain events activities that affect the networks/supply chains was presented. The results of this analysis show that critical nodes/links in the network, which failure (i.e., its inability to meet up their output) will severely affect the supply chain network(s) can be identified using this method, and associated algorithms and simulation. The proposed algorithm for the identification of minimum cut-sets consists of the following four levels: (1) For source-demand pairs in the system; (2) for individual demand nodes; (3) for a group of demand nodes; and (4) for all demand nodes in the system. While the risk ratings are obtained using the risk triplet scenario: (1) the threat scenario; (2) the probability of the event scenario; and (3) consequences/ damages of a successful event scenario on the network. Though only the first level in the minimum cut-set method requires simulations, the remaining stages are achieved by combination of the result from the first stage. This ensures a reduction in the number of simulations needed to analyze the chain/network.

While the combination of the risk triplet scenario will yield the risk, from which the risk ratings from the weighted average was derived.

The Petrobas supply chain network reliability analyses results have shown that the method is applicable for analyzing an oil and gas networks/supply chain. Despite the fact that useful information on network reliability is obtained using connectivity analysis, it is worth noting that other useful analysis for the evaluation of the source-demand connectivity and reliability of the oil and gas networks/supply chain need to be studied, since this method is not sufficient.

5.4 LP Supply Chain Models Simulation

The real world supply chain of the Gulf coast area of the US petroleum supply chain will be simulated and analyzed here using our risk based LP model.

The petroleum supply chain in the US is divided into five (5) regions called Petroleum Administration for Defense Districts (PADDs). For our simulation, we will carry out several case studies using the five (5) largest refineries in the US that is located along the critical Gulf coast area of the US, which falls within the PADD 3 regions. The critical nature of this node makes it very important to simulate and analyze, in order to deduce the impacts of various risks and event scenarios on it.

These refineries are:

1. Exxon Mobil Corporation refinery, Baytown, TX. Refining capacity – 0.5mb/d
2. Exxon Mobil Corporation refinery, Baton Rouge, LA. Refining capacity – 0.44mb/d
3. BP PLC Corporation refinery, Texas city, TX. Refining capacity – 0.39mb/d
4. Exxon Mobil Corporation refinery, Beaumont, TX. Refining capacity – 0.3mb/d
5. PDV America Corporation (CITGO) refinery, Baytown, TX. Refining capacity– 0.29mb/d

Source: Lewis (2006)

This area forms a major network of refineries, pipelines and a major import port called LOOP i.e. Louisiana Offshore Oil Port, which accounts for almost 13% of the US total import of crude. Figure 5.6 below shows network of Gulf of Mexico oil fields refineries.

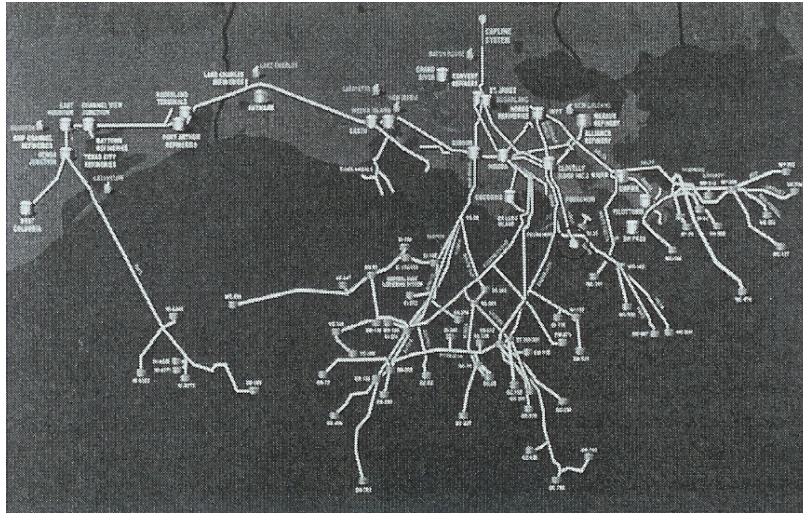


Figure 5.6 Gulf of Mexico Oil field and refineries (PADD 3) Network.

Source: Lewis (2006)

The Gulf of Mexico oil field region is made up of 152 refineries and the top five refineries in the US that is located along this critical region accounts for 11% of refined petroleum product in the US.

Information obtained from: EIA; Annual Refinery Report (April 25, 2010) indicates the following:

1. US Petroleum consumption: 19.5mb/d-top 5 accounts for 11% of these i.e.
 $2.1\text{mb/d} = \mathbf{D}_{k,t}$.
2. US crude oil imports: 9.7mb/ -top 5 refineries in Gulf coast gets 11% => about
 $1.1\text{mb/d} = \mathbf{Q}_{j,t}$.
3. Refineries capacity in the Gulf coast accounts for 8.1mb/d = $\mathbf{D}_{j,t}$.
4. Average storage capacity at the Gulf coast area of the US => 3.9mb/d = $\mathbf{Q}_{s,t}$ and $\mathbf{D}_{s,t}$.
5. Cost of storage: \$0.50/barrel = \mathbf{Z}_{ijl} and \mathbf{Z}_{ijk} .
6. Average pipeline (like the Transco pipeline) delivers: 2.2mb/d, also modest size
 Pipeline carries 720 tanker shipload/ day= 720 X 3,000b/d = 2.2mb/d => $\mathbf{Q}_{p,t}$ and $\mathbf{D}_{p,t}$.
7. Cost of transporting oil through a pipeline: \$0.85/barrel = \mathbf{T}_{ij} and \mathbf{T}_{ijk} .
8. Realization (\$/barrel) at j^{th} refinery's gate (i.e top 5 refineries in Gulf coast region) of the k^{th} product from the i^{th} crude i.e. \mathbf{r}_{ijk} :

Gasoline -	\$68.04/barrel
Kerosene -	\$71.03/barrel
Heating oil -	\$70.40/barrel
Residual fuel oil -	<u>\$60.97/barrel</u>

$$\sum r_{ijk}: \underline{\$270.44/\text{barrel}}$$

9. Net unit cost incurred in distilling 1 barrel of the i^{th} crude at the j^{th} refinery, i.e. p_{ij} :

Gasoline -	\$47.63/barrel
Kerosene -	\$49.72/barrel
Heating oil -	\$49.28/barrel
Residual fuel oil -	<u>\$42.68/barrel</u>

$$\sum p_{ij}: \underline{\$189.31/\text{barrel}}$$

10. For our illustrative example, we will consider only six (6) sources of crude to the top five refineries in the Gulf coast area:

Table 5.10 Quantity of Crude from some Sources to Refineries in the Gulf

<u>Source to Refineries</u>	<u>Qty of crude from source (b/d) (11% of the total crude from source): Q_i</u>
i. Canada (X_1)	215,160
ii. Iraq (X_2)	57,090
iii. Gulf coast (Local) (X_3)	296,890
iv. Other local sources (X_4)	247,610
v. Nigeria (X_5)	50,270
vi. Other international sources (X_6)	<u>456,720</u>
	$\sum Q_j: \underline{\mathbf{1,076,130\text{bpd}}}$

5.4.1 Analysis

A number of case studies were conducted to illustrate the main features and performance of the proposed optimization models. The case studies selected for analysis and discussion are listed in Tables 5.13 and 5.14. Results are compared to a base-case (Case-0), shown below, which is the solution of the LP model without the risk constraints. These case studies were carried out using the LINDO software for LP model simulations.

LINDO is a comprehensive tool designed to make building and solving Linear, Nonlinear (convex and nonconvex/Global), Quadratic, Quadratically Constrained, Second Order Cone, Stochastic, and Integer optimization models faster, easier and more efficient. It provides a completely integrated package that includes a powerful language for expressing optimization models, a full featured environment for building and editing problems, and a set of fast built-in solvers. It enables the easy creation of individual optimization applications, by allowing for easy plug-in and simulation of any developed mathematical programs using the power of the LINDO solvers. It also includes a number of significant enhancements and features that allows for more flexibility and functionality required in solving big or small, and simple or complex LP formulations. It includes dozens of routines to formulate, solve, query, and modify your LP problems.

The software helps in simulating the optimum objective function value of any LP model, while giving the programmer the values of its variables and the range of values at which optimum objective value will not be altered. This range of values allows for flexibility in carrying out the sensitivity analysis of the LP model, as was demonstrated in this study to achieve the best possible combination of the variables, subject to, demand, supply, capacity, quality, and risk and vulnerability constraints.

In a nutshell, LINDO is an interactive linear, quadratic, and integer programming system useful to a wide range of users. It can be used for the following:

- To solve interactive linear, quadratic, general integer and zero-one integer programming programs up to 500 rows and 1,000 columns.
- To perform sensitivity analysis and parametric programming.

See Appendixes A to D for the output of the simulation of the case studies, and also Tables 5.14 to 5.16 for the summary of the input and output obtained from the simulation, and the sensitivity analysis of different alternatives using LINDO solver.

The case studies will try to analyze the likely impact on the SC of scenarios like

1. Likely impact of multiple long term events (crisis in Nigeria and Iraq, and 50% successful hurricane in the Gulf coast), at different seasons of the year (i.e. Spring, Summer, Fall and Winter) with regards to their storage capacity for strategic and long term planning. See Tables 5.11 and 5.12 and Figures 5.7 and 5.8 for the average storage capacity in the Gulf coast region at different periods of the year.
2. Likely impacts of various short term events at the most critical season (i.e., the worst case scenario) of the year in regards to the average storage capacity at the Refineries; Storage farms; and Pipelines nodes of the SC, for tactical and short term planning. The critical season of the year with respect to the average daily storage capacity in the Gulf coast area from Figures 5.7 and 5.8, and Tables 5.11 and 5.12 is the fall season, with an average daily storage capacity of 3.7mb/d

Case-0 (Base Case): The chain is modeled with the average daily storage capacity, and, without the risk constraints to obtain the optimum value based on demand and supply forces by using the analyzed data from EIA (April 25, 2010).

$$\mathbf{Max Z} = (((\sum(y_k x_{ij}) (r_{ijk})) - (\sum p_{ij} x_{ij})) - ((\sum(Z_{ijL} x_{ij})) + (\sum Z_{ijkL} y_k x_{ij})) - ((\sum(T_{ij} x_{ij})) - (\sum T_{ijkl} y_k x_{ij}))))$$

$$\text{i.e., } Z = 75X_1 + 75X_2 + 75X_3 + 75X_4 + 75X_5 + 75X_6$$

Subject to;

1) Plant constraints at the refinery

$$\sum x_{ij} \leq Q_j$$

$$\text{i.e., } X_1 + X_2 + X_3 + X_4 + X_5 + X_6 \leq 1,076,130$$

$$\sum y_k x_{ij} \leq D_j$$

$$\text{i.e., } 0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 \leq 8,100,000$$

2) Crude constraints from sources

$$\sum x_{ij} \leq Q_i$$

$$\text{i.e., } X_1 \leq 215,160$$

$$X_2 \leq 57,090$$

$$X_3 \leq 296,890$$

$$X_4 \leq 247,610$$

$$X_5 \leq 50,270$$

$$X_6 \leq 456,720$$

3) Demand constraints

$$\sum y_k x_{ij} \geq D_k$$

$$\text{i.e., } 0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 \leq 2,144,780$$

4) Storage farms capacity constraints

$$\sum x_{ij} \leq Q_s$$

$$\text{i.e., } X_1 + X_2 + X_3 + X_4 + X_5 + X_6 \leq 3,940,067$$

$$\sum y_k x_{ij} \leq D_s$$

$$\text{i.e., } 0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 \leq 3,940,067$$

5) Pipeline capacity constraints

$$\sum x_{ij} \leq Q_p$$

$$\text{i.e. } X_1 + X_2 + X_3 + X_4 + X_5 + X_6 \leq 2,261,905$$

$$\sum y_k x_{ij} \leq D_p$$

$$\text{i.e. } 0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 \leq 2,261,905$$

6) Quality of the crude constraints

$$\Sigma(ix_{ij})/2 \geq iq_j$$

Note: The quality ratings obtained from our crude quality analysis in Table F.1 of Appendix F was used, which are Nigeria and Iraq - **8**; Canada and other international sources - **7**; Gulf coast area and other local sources - **5**. While using **7** as the minimum allowable quality ratings for all the nodes.

Substituting and simplifying the equation will give:

$$7X_1 + 8X_2 + 5X_3 + 5X_4 + 8X_5 + 7X_6 \geq 14$$

7) Non – negativity constraints

$$x_{ij} \geq 0$$

$$\text{i.e. } X_1, X_2, X_3, X_4, X_5, X_6 \geq 0$$

Each of the rest cases (Case-1 to Case-3) represents different scenarios highlighted above. The case studies are compared in terms of percentage drop/rise in petroleum products production as a result of the various scenarios, with respect to the base case (Case-0), as shown in Table 5.13 below.

Case-1: Here, the chain is modeled for strategic and long term planning, by using all the data in Case-0, with the daily average storage capacity and assuming a multiple long term threat scenario from crisis in Nigeria, Iraq, and 50% successful hurricane in the Gulf coast area. The average expected risk ratings of these events on the supply chain obtained in Section 5.1, and highlighted in Table 5.1 and Figure 5.1 will be used in simulating the likely impact on the energy sector. A risk rating of 1 for Canada was also used, because

of its low vulnerability; and ratings of 2 and 3 for other local and international sources. While the maximum allowable risk ratings for all nodes was 5.

Case-2: Here, the chain is modeled for strategic and long term planning, by using all the data in Case-1, but with different average daily storing capacity across the four seasons of the year. First, it will be modeled with the average daily storing capacity, and subsequently by varying the storing capacity, based on the data in Table 5.12 and Figure 5.7 showing the average daily storage capacity in the Gulf coast area across the four (4) seasons of the year, in order to simulate the impact of multiple threat scenarios across various seasons of the year. The cases to be considered here are:

- **Case 2(a):** during the spring season
- **Case 2(b):** during the summer season
- **Case 2(c):** during the fall season, and
- **Case 2(d):** during the winter season

Case-3: Here, the chain is modeled for tactical and short term planning, by using all the data in Case-1, but varying the short term events risks on the three critical nodes of the SC during the most critical season of the year in terms of average daily storage capacity (which was identified as Fall, based on the data obtained from EIA website). That is, modeling with the daily average storage capacity during the fall season of the year and assuming a short term threat scenario on the three critical nodes of the supply chain (i.e. Refining, Transportation/Pipeline and Storage units). The average expected risk ratings of these short term events on the supply chain obtained in Section 5.1, and highlighted in Table 5.2 and Figure 5.2, which shows refinery fire explosion having a rating of 4 (in a scale of 1-10, with 10 being the maximum), tank farm leaks/cracks with a rating of 3,

while pipeline leaks/breaks has a risk rating of 5, will be used in simulating the likely impact on the energy sector. While the maximum allowable risk ratings for all nodes was 5, except when analyzing threat scenarios in the pipeline units, where a maximum allowable risk rating of 6 will be used. The cases to be considered here are:

- **Case 3(a):** refinery fire explosion during the fall season
- **Case 3(b):** tank farm cracks/leaks during the fall season
- **Case 3(c):** pipeline leaks/breaks during the fall season, and

Case-4: The worst case scenarios for long term and short term risk scenarios obtained in cases 2 and 3 by introducing some capacity expansion and redundancies, in other to show what if scenarios will be simulated and analyzed.

Table 5.11 5yrs Average Monthly Stocks at Storage Tanks(X 1,000 Barrels) in the Gulf Coast Area (PADD III Region) of the US

Month	5yrs Average Monthly Stocks at Storage Tanks (X 1,000 Barrels)
January	3,974,483
February	4,345,857
March	4,142,387
April	4,459,567
May	4,169,839
June	4,129,767
July	3,915,097
August	3,717,097
September	3,878,600
October	3,661,323
November	3,592,367
December	3,294,065

Source: EIA; Annual Refinery Report (04/25/10)

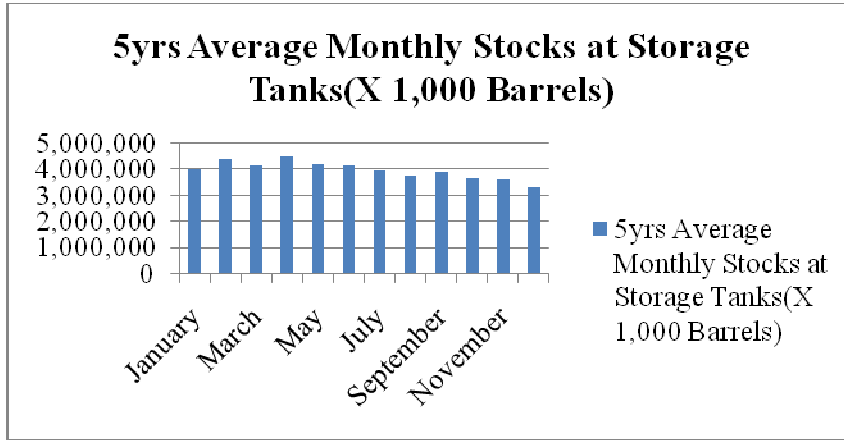


Figure 5.7 5yrs average monthly stocks at storage tanks (X 1,000 barrels) in the Gulf coast area (PADD III Region) of the US.

Source: EIA; Annual Refinery Report (04/25/10)

Table 5.12 5yrs Average Seasonal Stocks at Storage Tanks(X 1,000 Barrels) in the Gulf Coast Area (PADD III Region) of the US

Month	5yrs Average Seasonal Stocks at Storage Tanks(X 1,000 Barrels)
Spring	4,257,264
Summer	3,920,772
Fall	3,710,763
Winter	3,871,468

Source: EIA; Annual Refinery Report (04/25/10)

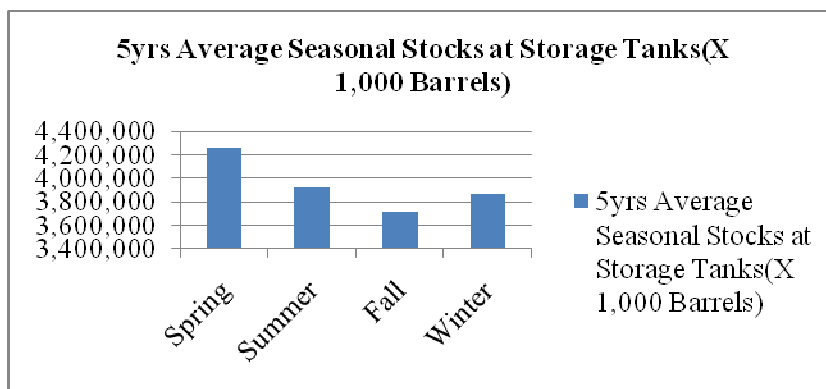


Figure 5.8 5yrs average seasonal stocks at storage tanks (X 1,000 barrels) in the Gulf coast area (PADD III Region) of the US.

Source: EIA; Annual Refinery Report (04/25/10).

Table 5.13 Likely Impact of various Long and Short Term Risk Scenarios on Prices of Petroleum Products

Cases	Loss/Drop in Production (%)
Case-0 (Base case – no risk)	0
Case-1 (all data in Case-0 + average risk ratings of all nodes)	30
Case-2 Long term risk scenarios at various seasons average daily storage capacities:	18
(a) Spring	
(b) Summer	30
(c) Fall	35
(d) Winter	30
Case-3 Short term risk scenarios on the critical units of the SC during the most critical season(w.r.t. average storing capacity)	35
(a) Refineries (fall)	
(b) Tanks (fall)	38
(c) Pipelines (fall)	39
Cases	Increase/Rise in production (%)
Case-4 worst case long and short term risk scenario with an added capacity expansion and redundancies in the SC network).	18
(a) Tank capacity expansion - Long term (Fall season)	
(b) Redundancy in pipeline – Short term (Fall season)	17

See also Appendixes A to D for the LP models formulation and LINDO output for the simulated and analyzed cases above.

Sensitivity analysis of the risk based LP output was also carried out in this study as enumerated in Tables 5 to 5, in order to show the decisions and managerial insights that a policy maker can make based on the current output, Allowable Increase/Decrease (AI/AD), expected output based on risks and crude quality, and the required output for stability. Some of these observations and insights were:

- A consistent decline in the AI in output from other international sources below its current output. This observation supports our earlier analyzed risk rating, which showed crude sources like Nigeria and Iraq being classified as critical, based on their risk ratings.
- A consistent increase towards INFINITY for the AI for other local sources above its current output. This can be translated as showing that there are needs to not only explore other local sources of crude oil within the US, but to also encourage investment into alternative sources of energy. This is presently being put forward by the Obama administration, which studies has shown will reduce the dependence on foreign oil by at least 35% by year 2030, in addition to creating seventeen thousand jobs, while also reducing carbon emission by 80% in 2050.
- In all the five cases analyzed, only in one instant-case 2(a), that there was an AI in the supply of about 50% in the Gulf coast, with the rest cases showing a consistent in AI below the present output. This can be used to support the argument against exploring more deep water drilling because of the catastrophic nature of any threat situation, as highlighted in the BP oil spill in the Gulf of Mexico that occurred from 20th of April – 15th of July, 2010.
- That despite showing a consistent drop in the expected output from the crisis prone crude sources (Iraq and Nigeria) used in this study, the AI also shows an allowance of at least double of the present supply. This can be interpreted as showing that achieving more political stability in these countries will help in minimizing the instability in the oil and gas SC.
- That due to stability political stability in Canada, there is an allowance to increase the crude supply from this source to almost INFINITY, but despite this, the required output for stability keep showing a sharp decline. This can be surmised as being a result of low quality rating of Canadian crude.

Table 5.14 Sensitivity Analysis Summary for Case 2(a) – Spring Season

Variables	Risk Rating	Quality Rating	Current Output	Expected Output Drop	Allowable Increase	Allowable Decrease	Required Output for Stability
X1-Canada	1	7	2.98	0.00	INFINITY	2.98	1.29
X2-Iraq	6	8	0.40	0.40	2.14	0.36	0.40
X3-Gulf	7	5	1.80	1.80	2.14	0.36	1.80
X4-Local	2	5	2.50	2.14	INFINITY	0.36	2.50
X5-Nigeria	5.5	8	0.22	0.22	2.14	0.22	0.22
X6-Abroad	3	7	4.60	4.60	2.14	0.36	4.60

Table 5.15 Sensitivity Analysis Summary for Cases 2(b) and (d) – Summer and Winter Seasons.

Variables	Risk Rating	Quality Rating	Current Output	Expected Output Drop	Allowable Increase	Allowable Decrease	Required Output for Stability
X1-Canada	1	7	2.20	0.00	INFINITY	2.20	0.00
X2-Iraq	6	8	0.40	0.40	1.36	0.40	0.60
X3-Gulf	7	5	1.80	1.80	1.36	1.14	3.00
X4-Local	2	5	2.50	1.36	INFINITY	1.14	2.19
X5-Nigeria	5.50	8	0.22	0.22	1.36	0.22	0.50
X6-Abroad	3	7	4.60	4.60	1.36	1.14	4.60

Table 5.16 Sensitivity Analysis Summary for Case 2(c) – Fall Season

Variables	Risk Rating	Quality Rating	Current Output	Expected Output Drop	Allowable Increase	Allowable Decrease	Required Output for Stability
X1-Canada	1	7	2.62	0.00	INFINITY	2.62	1.63
X2-Iraq	6	8	0.40	0.00	0.94	0.40	0.00
X3-Gulf	7	5	1.80	1.80	0.94	1.56	1.80
X4-Local	2	5	2.50	2.50	INFINITY	1.56	2.50
X5-Nigeria	5.5	8	0.22	0.22	0.94	0.22	0.22
X6-Abroad	3	7	4.60	3.44	0.94	1.56	4.60

See also Appendix B for the LINDO output of the sensitivity analysis.

5.4.2 Summary and Conclusion

A methodology to analyze the effects of certain risk scenarios on the oil and gas networks/supply chains connectivity using the LP models, and associated simulations was presented. The results of this analysis show that crisis or events that successfully impact the critical nodes/links in the network, which can lead to failure (i.e. its inability to meet up their output) of the chain, can be modeled to know the dollar cost of their impact on the consumers using the LP models, and associated simulations.

Some of the limitations of this study is in the assumptions that most times the causes of price increase in the oil and gas sector to be as a result of one event, while in some instances it could be as a result of multiple events that were not included in the risk analysis.

5.5 MBVA and FTA Model Simulation

5.5.1 MBVA Model Simulation

MBVA gives the policy analyst a top-to-bottom tool for achieving critical infrastructure protection (CIP) under budgetary constraints. For this simulation, the Gulf of Mexico refineries, which fall within the highly critical PADD 3 regions of the US will be used. The critical nature of this node makes it very important to simulate and analyze optimum reduction in risk and vulnerabilities of this critical node, at an optimum cost. Optimum here means that point where further investment or allocation of money for any CIP will not be wise based on the Cost Benefit Analysis (CBA) of Budget vs. Risk Reduction, and Budget vs. Vulnerability Reduction.

The reduction in vulnerability and subsequently risk that will be obtained from the resource allocation at the Gulf coast refineries using the proposed MBVA will also be compared with the likely drop in petroleum product production based on various simulations of the Gulf coast refineries using the LP model in Section 5.4 above in order to ascertain the benefits or otherwise of investing in the CIP.

Network analysis of these oil field network shows that it has a scale free structure [see figure 5.9] below. It obeys a near-perfect power law with $p = 1.179$.

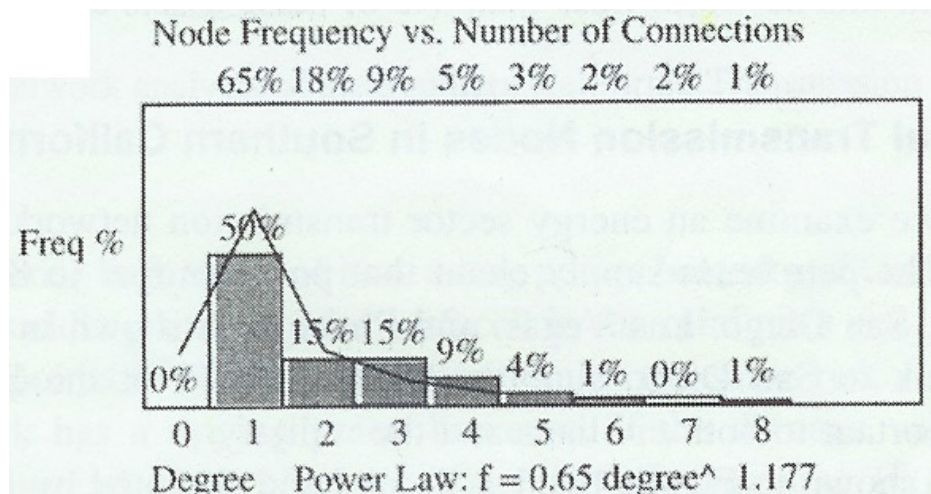


Figure 5.9 Node frequency histogram and power law ($p=1.79$) fit for the network of the Gulf of Mexico oil fields and refineries.

The fault tree to be used in this analysis will be a standard fault tree – i.e. having three layers: the root of the fault tree will be Energy failure; while the components will be; Transmission/Pipeline, Refinery and Storage; and the threats will be: for Transmission/Pipelines – bomb pipes, SCADA attack and power outage; for Refinery – fire damage, power outage and crude shortage; for Storage – bomb pipes, bomb pumps and bomb tanks. The logic gates to be used will be the OR logic gates. The reason for using this logic gate is that failure of any component of this Gulf coast refinery fault tree will lead to the failure of the entire system.

MBVA Analysis and Results. For the refinery at Gulf Coast Region.

i. Refineries - Processing

- Potential causes of damage
- Fire Damage – assume 80% vulnerability
- Crude Shortage – assume 50% vulnerability
- Power Outage – assume 30% vulnerability
- Cost of refinery is about = \$1B

- PADD 3 Region Produces 11% of national refined product, approximately
 $2.2\text{M bpd} \times 42 = 92.4\text{Mgpd}$
- 1 barrel = 42 gallons
- Profit $\Rightarrow \$2.04 - \$1.50 = \$0.54$
- Damage $\Rightarrow 92\text{M barrels} \times \$0.54 = \$48\text{ M}$
- Break even
- 5 years at an estimated inflow of $\$290\text{M/yr.} \times 5 = \text{over } \1B
- Most refineries are already running on a positive NPV since they are older than 5 years.
- Assumption: Only cost of damage is that of lost revenue.
- Damage (D) for refinery = $\$48\text{M}$
- Cost to protect refinery $\Rightarrow 70\%$ of D = $\$34\text{M}$

ii. Pipelines- Transmissions

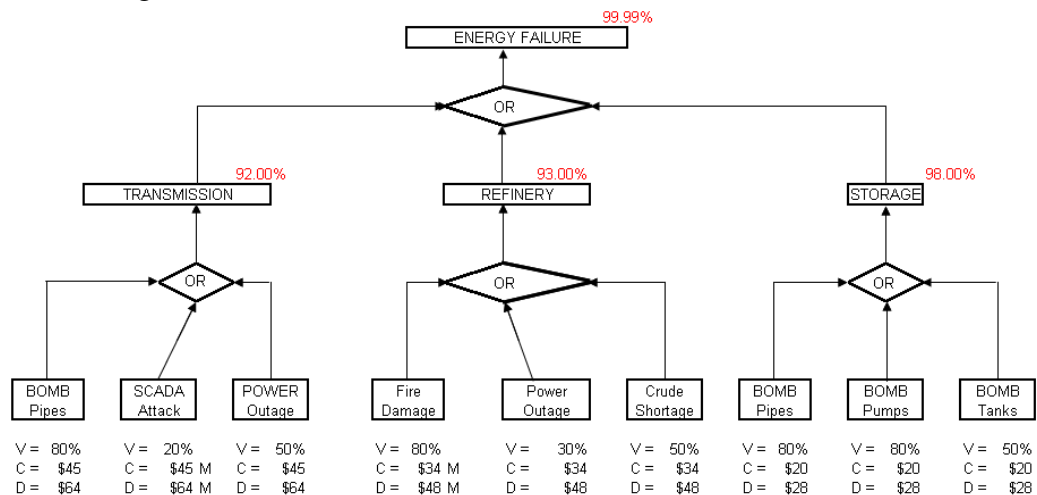
- Potential causes for damage
- Bomb Pipes - assume 80% vulnerability
- SCADA attack - assume 20% vulnerability
- Power Outage - assume 50% vulnerability
- Pipeline repair near Phoenix, AZ took approx. 29 days to repair.
- 5500 mile Transcontinental Pipeline (Transco) delivers 95M gallons per day to the East Coast.
- A spill in March 28, 1993 led to an estimated cost to Colonial Oil Pipeline owners of Transcontinental, $\$34\text{M}$ and cost for environmental protection of approx. $\$30\text{M}$.
- D (pipeline) = $\$64\text{M}$
- C (pipeline) = $70\% \times D = \$45\text{M}$

iii. Storage

- Potential causes for damage
- Bomb Pipes - assume 80% vulnerability
- Bomb Pumps - assume 80% vulnerability
- Bomb Tanks - assume 50% vulnerability
- Average storing capacity of a storage tank is 823,850 barrels of petroleum
- $823,850 \times \$2.04 \times 17 = \$28,571,118$
- $D(\text{pipeline}) = \$28\text{M}$
- $C(\text{pipeline}) = 70\% \times D = \20M

iv. Assumptions

- For this simulation a high vulnerability (80%) will be assumed, because it is rather easy to damage the Gulf coast energy supply chain because of its obvious concentrations and open access of its components.
- The result of the fault tree failure analysis using the above computations, indicate that the Gulf coast area refineries have a very high vulnerability of 99%, see Figure 5.6 below.



Please note all monetary values are in MILLIONS.

Figure 5.10 Gulf coast refineries energy failure fault tree.

The energy failure risk summary using the fault tree analysis indicates thus:

- Top 3, Max. Risk Events
- Risk Max₁ = \$8.831
- Transmission Bomb Pipe + Transmission Power Outage + Refinery Fire Damage + Refinery Crude Shortage + Storage Bomb Pipes + Storage Bomb Pumps + Storage Bomb Tanks.
- Risk Max₂ = \$8.028
- Transmission Bomb Pipe + Transmission Power Outage + Refinery Fire Damage + Refinery Crude Shortage + Storage Bomb Pipes + Storage Bomb Pumps.
- Risk Max₃ = \$7.455
- Transmission Bomb Pipe + Transmission Power Outage + Refinery Fire Damage + Storage Bomb Pipes + Storage Bomb Pumps + Storage Bomb Tanks.
- Bottom 3, Min. Risk Events
- Risk Min₁ = \$0.000
- No Faults
- Risk Min₂ = \$0.001
- Transmission SCADA Attack + Refinery Power Outage
- Risk Min₃ = \$0.002
- 7 Events

FTplus software for budget/resource allocation using MBVA was used to simulate the Gulf coast area refineries. The allocation can be done with three different strategies:

1. Manual allocation strategy
2. Rank order allocation strategy, and
3. Apportioned allocation strategy

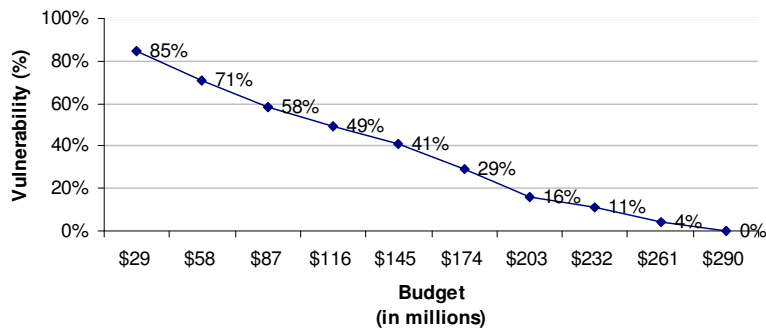


Figure 5.11 Vulnerability vs. Budget.

The results obtained were analyzed below:

Table 5.17 Budget vs. Vulnerability Reduction

Budget (x \$1m)	229	558	887	1116	1145	1174	2203	2232	2261	2290
Vulnerability (%)	885	771	558	449	441	229	116	111	44	00

See also Appendix E for the various results obtained using the FT plus software for the three different resource allocation strategies.

5.5.2 FTA Model Simulation

In this research, a Fault Tree Diagram (FTD) to analyze each source-demand pair and subsequently the entire supply chain risk of the Petrobras (Brazil) crude oil supply chain, which was already studied in Section 5.3, using the calculated risk from likely short term events/activities that can likely affect the link, to determine whether any particular pair has failed or not was developed. These calculated risks can either increase or decrease depending on the variation in the unfixed variables (i.e., the threat and probability of events scenarios) of the developed risk equation.

The AND/OR logic gates was used between any two source-demand pair, depending on whether respective pair has failed or not (OR for failure, and, AND for no -

failure). Any pair is categorized as 'FAILED', if the analyzed fault tree risk for any pair is greater than a set threshold allowable risk.

Resource (\$\$) allocation were also apportioned from top to bottom of the developed FTD to each pair based on the analyzed fault tree risk to harden them against any threat scenario.

Let the assumptions be, that in this crude oil SC chain, only short term events and activities will likely affect them. Therefore, for OSVAT crude, let the assumption be that there is a major pipeline explosion, that normally takes weeks to repair, which from Table 5.2, has a risk rating of 2 on a 1 - 10 rating scale (i.e., 0.2), while for the OSBAT crude, let it be assumed that there is a major fire at the storage farm, which normally takes months to repair. The rating for this from Table 5.2 is 5 (i.e., 0.5)

5.5.2.1 FTD Analysis.

The FTD analysis for the crude oil SC network using the calculated risk of the likely events that was assumed to affect each source-demand pair in the case study, shows that if the threshold allowable risk for failure of each source-demand pair was set not to be less than 1 (i.e., <1 , on a scale of 1 to 10, with 10 being the highest). From the FT analysis in Figure 5.12, it was found out that the pairs S1,D3, and, S1,D2, are the critical pairs that will be in a failure mode if the events were to occur without adequate hardening/protection mechanism in place. So in analyzing the whole SC network FTD, the OR logic will be used for these two source-demand pairs. The total network failure percentage was obtained as 60%, but note that in Figure 5.13, it shows that the failure percentage will drop to less than 1% if an extra transportation redundancy was introduced for the S1, D3 pair, which will switch these pair from a

failure mode to a safe mode, and so, the AND logic for analyzing the pair in the Fault Tree Analysis of the entire network will be used.

5.5.2.2 Resource Point Allocation Analysis.

If a budget of 100 available

Resource points is assumed, and this is to be allocated by Network Analysis(NA) (Lewis, 2006), using the developed FTD (Figure 5.12), working from top to bottom of the tree, the result of the resource allocation shown in Table 5.15 and 5.16 below will be obtained.

The results show that the highest allocation of 70 Resource points will be allocated to S1, D3 pair. This coincides with the earlier analysis that introducing a redundancy in this pair will lower the failure probability of the entire network.

Note: that despite the fact that the impending analyzed threat scenarios does not put the earlier simulated critical links in Section 5.3 using the min. cut-set equations (i.e., P1 and P4) the resource allocation using the Network Analysis (NA) from Table 5.15 below, allows for more resources to be allocated by default to these two pairs.

Table 5.18 Resource Points Allocation for each Source-Demand Pair in the Crude oil SC using Network Analysis.

No	Pair	Analyzed Risk	Sharing Percentage (%)	Resource Point Allocation
1	S1,D1	0.04	6	6
2	S1,D2	0.04	6	6
3	S1,D3	0.5	70	70
4	S1,D4	0.125	18	18
			$\Sigma = 0.705$	$\Sigma = 100$

Table 5.19 Resource Points Allocation for each link of a Source-Demand Pair in the Crude oil SC using Network Analysis.

Pair	Available Resource Point	Link	Analyzed Risk	Sharing (%)	Resource Allocation
S1,D1	6	P1	0.2	50	3
		P2	0.2	50	3
S1,D2	6	P1	0.2	50	3
		P3	0.2	50	3
S1,D3	70	P4	0.5	100	70
S1,D4	18	P4	0.5	33	6
		P5	0.5	33	6
		P6	0.5	33	6
				$\Sigma = 100$	

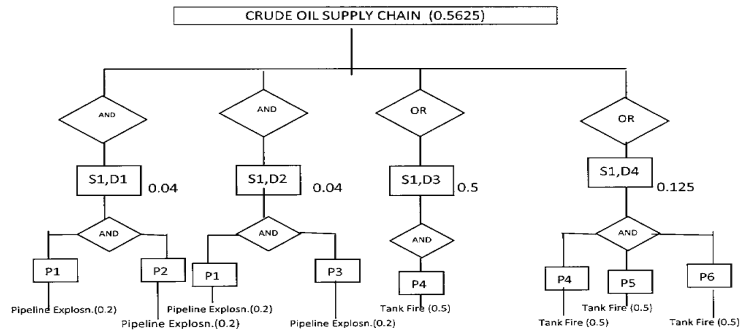


FIGURE 7: Petrobas (Brazil) Crude oil network SC Fault Tree Analysis without redundancy

Figure 5.12 Petrobas (Brazil) crude oil network SC Fault Tree Analysis without redundancy using our developed tree.

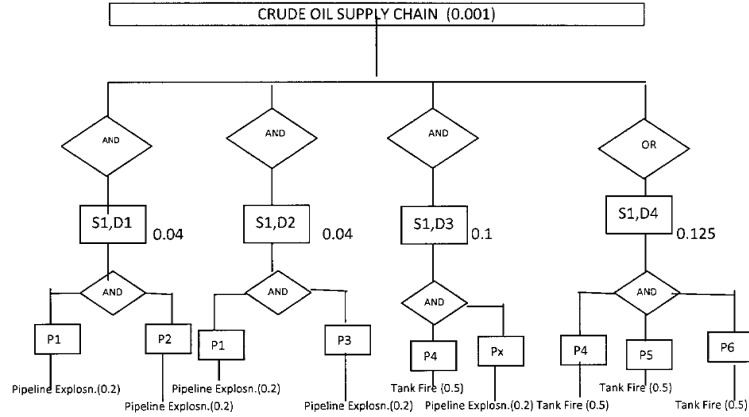


FIGURE 8 : Petrobras (Brazil) Crude oil network SC Fault Tree Analysis with a redundancy pipeline for (S1,D4) pair

Figure 5.13 Petrobras (Brazil) crude oil network SC Fault Tree Analysis with a redundancy pipeline for (S1, D4) using our developed tree.

5.5.3 Summary and Conclusion

A methodology to analyze the vulnerability and reliability of a typical oil and gas network supply chain when impacted by likely threat scenarios was presented. These threat scenarios that affect the supply chain network often lead to a negative impact on the entire energy sector. These analyses will help stakeholders in the sector to predict, plan, manage and mitigate against any likely threat scenarios which will likely impact the SC network.

5.5.3.1 MBVA. The result of the simulation and analysis of the Gulf coast area SC shows that the optimum budget allocation for any CIP in a typical oil and gas SC will be in the region of \$203million. Based on Table 5.14 and figure 5.11, the study deduced that at that point of investment the CBA shows an appreciable increase, while beyond that the increase in CBA is somewhat minimal.

5.5.3.2 FTA. The combination of the risk triplet scenario will yield the risk, from which the risk and the risk ratings for short term events were derived. These calculated risk, together with the developed FTD will successfully enable anyone to determine whether each source-demand pair can be said to have failed or not from the likely impact of these threat scenarios, and also to obtain the optimum resource allocation to harden any source-demand pair in the network.

5.5.4 Limitations

- Lack of sector expertise
- Since there are no major incidences of failure in the energy SC, most of the assumptions of cost and damage are not quite precise and might lead to misleading assumptions.
- These FTA and MBVA only focused on damage from the sector failure from economic perspective, whereas a more accurate damage would have involved other losses.
- Historically accidental incidents in the Energy SC have taken only a few lives and cost a mere \$33million per year.
- The Question then is: Why be concerned?
- Answer: Given that it is easy to damage the energy SC, and very difficult to fix, what damage might a clever and malicious attacker do? It may be time to change strategies!

5.6 Comparisons of Models Performances

In this study, three risk based models were developed and simulated. The models are:

- The risk rating model.
- The risk based Supply Chain Model – these models comprises of two models:
 - Risk based network reliability analysis SCM.

- Risk based Linear Programming SCM.
- The Model Based Vulnerability Analysis (MBVA) and The Fault Tree Analysis (FTA) models.

Table 5.20 Comparisons of Models Performances.

Risk rating Model	Risk based Supply Chain Models		MBVA and FTA Models
	Reliability Analysis SC Model	LP SC Model	
This model is used to derive the risk ratings from some events, activities and threats that will most likely impact the oil and gas SC. The results we obtained showed that events like Israel-Arab war, successful hurricane in the Gulf coast area of the US, and production increase or decrease have a risk rating of 7 on a scale of 10.	This model enabled us to determine the critical nodes/links in the network, which if impacted by any of the events and activities we derived their ratings above will lead to failure (i.e., its inability to meet up their output) of the supply chain. The model went further to help us to not only determine these critical nodes/links, but also helped us to derive the drop in the overall network reliability, based on the successful impact of any of these threats.	This model is used to determine the loss of production and subsequently increase in price of petroleum products because of any successful threat on the critical nodes of the SC	These models which we proposed in this study will help to determine the optimum investment in any CIP, i.e., to see what \$X investment will lead to a cost beneficial reduction in the risk and vulnerability of the sector, side-by-side, the loss of reliability of the SC, and also the increase in product prices as a result of any successful threat impacting the SC.

5.7 Limitations of the Models

Though the models developed in this study has shown that; the risk ratings of some events, activities and threats that can affect the oil and gas SCM can be derived using the risk rating models; while, the risk based LP SCM will enable experts to forecast, manage and minimize the likely impacts of different risk scenarios on the SC; then, the risk based network reliability analysis model using the minimum cut-set method, and its associated

algorithms and simulations have shown that the impact of link failures as a result of risks associated with certain events, activities, and threats that can affect the SC can be determined, while also determining the critical nodes/links in the network; and lastly, the MBVA has shown that the possible CIP that can be used to protect the SC, viz-a-viz, the reduction of the risks and vulnerabilities, and subsequently the CBA of the Resource allocation vs. the risks and vulnerability reduction can be obtained. There are also some inherent limitations to these models which we will discuss below:

The major limitation to the events and activities risk ratings model is that the analysis was based on the economical consequences of these events and activities. A future study might also try to look at other consequences as well.

The limitation for the risk based LP SCM, is in the assumptions that most times the causes of price fluctuations in the industry to be as a result of one or two events, while in some instances it could be as result of multiple events that were not included in the risk analysis.

Despite the fact that useful information on network reliability was obtained using the risk based reliability analysis model, it is worth noting that an amendment to the model to look at cost that is involved when these identified critical nodes/links fail will also be encouraged. Though, in this research, the trend of analyzing the cost benefits of either protecting or including redundancies to the chain was initiated, or, simply do nothing, it is recommended that more studies in this area need to be encouraged.

Some of the limitations of the MBVA and FTA models are:

- Lack of sector expertise.
- Since there are no major incidences of failure in the energy SC, most of the assumptions of cost and damage are not quite precise and might lead to misleading assumptions.
- The models only focused on damage to the sector from economic perspective, whereas a more accurate damage would involve other losses.
- Historically accidental incidents in the energy SC have taken only a few lives and cost a mere \$33million per year. So, why be concerned? Given that it is easy to damage the energy SC, the question is, 'what damage might a clever and malicious attacker do? It may be time to change strategies.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

In conclusion, this research has helped to develop various risk based models, which were used to simulate and analyze different threat scenarios that can impact the oil and gas supply chain critical infrastructure. This will enable scholars, researchers, government and private stakeholders in the industry to better understand and plan for the protection and response action that could be taken in tackling some of the risks that could impact the industry, viz-a-viz, their optimum goal. It also went further to look at the cost benefits of some of the Critical Infrastructure Protection (CIP) that can be used to minimize the effect of various risk scenarios on the energy sector in particular and the economy in general.

First a risk model was developed and used to derive the risk rating for events, activities or threats that will most likely impact the oil and gas supply chain (SC). The events were categorized as either short term or long term events (with short term events lasting only a few days, while long term events last weeks).

The study showed that for any events, activities or threats that will likely impact the oil and gas SC critical infrastructure, the following risk rating categorization, on a scale of 1-10 (with 10 being the maximum), will be followed after analysis:

- A risk rating of 7-10 will be categorized as **very critical**.
- A risk rating of 3-7 will be categorized as **critical**.
- A risk rating of 1-3 will be categorized as **less critical**.

While, the following categorization will be used for analyzing the duration of occurrence of events, threats, or activities:

For long term events, threats, or activities (with duration in weeks):

- Duration of 7-10 weeks will be categorized as **very severe**.
- Duration of 3-7 weeks will be categorized as **severe**.
- Duration of 1-3 weeks will be categorized as **less severe**.

For short term events, threats, or activities (with duration in days):

- Duration of 7-10 days will be categorized as **very severe**.
- Duration of 3-7 days will be categorized as **severe**.
- Duration of 1-3 days will be categorized as **less severe**.

The study also showed that events like the Israel-Arab war, successful hurricanes in the Gulf coast area of the US, and the increase or decrease in production have a risk rating of 7.

With these risk ratings, a risk based network reliability analysis model using the minimum cut-set method and its associated risk based algorithms and simulations was developed. The model enabled the study to determine the critical nodes/links in the network, which if impacted by any of the events and activities analyzed above, will lead to failure of the supply chain (i.e., its inability to meet up to its output). The model went further to not only determine the critical nodes/links, but also to derive the drop in the overall network reliability, based on the successful impact of any of these threats. Some of the results obtained showed that if a short term event, like a major pipeline explosion that will affect the transportation of crude to the RECAP and CUBATAO refineries in the

Petrobras of Brazil SC, with an assumed risk rating of 2 occurs, it will lead to a 12% drop in production.

The risk based LP Supply Chain Model (SCM) which was developed and used in this study, to analyze the supply chain (SC) for strategic/long term and tactical/short term planning, was able to establish likely impacts of different risk scenarios on a generalized oil and gas SC network, like the Gulf coast area SC. The average expected risk ratings obtained above was used as one of the constraints in simulating the different risk scenarios, and to forecast their likely impacts, in other to come up with alternative ways that can be used to manage/minimize risks. The study showed that for a generalized oil and gas SC, a very critical (in terms of long term/globalised risk ratings), and a very severe (in terms of duration in weeks) event/threat/activity - like crisis in the crude source points, will likely cause the following:

- 18% drop/loss in the production at this SC, with a likely price increase of 15% in product prices. This will occur in the regions that are dependent on the supply from this SC during the spring season, with an average daily stock of about 4.2 million (x 1,000 bpd).
- 30% drop/loss in production at this SC, with a likely price increase of 22.4% in product prices. This will occur in the regions that are dependent on the supply from this SC during the summer season, with an average daily stock of about 3.9 million (x1, 000 bpd).
- 35% drop/loss in production at this SC, with a likely price increase of 26% in product prices. This will occur in the regions that are dependent on the supply from this SC during the fall season (the most critical season) with an average daily stock of about 3.7 million (x 1,000 bpd).
- 30% drop/loss in production at this SC, with a likely price increase of 22.4% in product prices. This will occur in the regions that are dependent on the supply from this SC during the winter season, with an average daily stock of about 3.9 million (x 1,000 bpd).

The study also showed that a very critical and very severe short term/localized event/threat/activity - like a refinery explosion/fire, tank leak/crack, or pipeline fire/attack, occurring on this SC during the fall season (most critical in terms of average daily stock), will likely cause the following:

- In an event like a refinery explosion, a 35% loss/drop in productivity, with a likely product price increase of about 26% will occur in the areas that are dependent on this SC.
- In an event like a tank farm leak/crack, a 38% loss/drop in productivity, with a likely product price increase of about 28% will occur in the areas that are dependent on this SC.
- In an event like a pipeline leak/break, a 39% loss/drop in productivity, with a likely product price increase of about 29% will occur in the areas that are dependent on this SC.

Introducing a 15% tank capacity expansion and a 15% redundancy in pipeline will lead to an 18% and 17% rise in productivity respectively, during the fall season, and will go a long way in buffering any risk scenario.

The Fault Tree Analysis (FTA) and Model Based Vulnerability Analysis (MBVA) were carried out on the SC in this study, to determine whether each source-demand pair analyzed, failed or not, due to the likely impact of any event, activity or threat scenario analyzed above. The analysis was also carried out to show how scarce resources can be allocated for optimum result in protecting the oil and gas SC nodes/links from failure. Using the SC of the Gulf coast area as a case study, the result showed that investing \$29, \$58, \$87, \$116, \$145, \$174, and, \$203 (optimum budget), and \$232 million, towards a Critical Infrastructure Protection (CIP) in the area, will likely lower the vulnerability to 85%, 71%, 58%, 49%, 41%, 29%, 16%, and, 11% respectively, and prevent the potential for a huge price increase on the consumers in particular, and the economy in general.

This study was able to show that both the risk based minimum cut-set model and its associated algorithms and simulation, and the risk based LP SC model developed in this study to derive the reliability or the critical nodes/links in the network, with the associated drop in production, will enable experts in the industry to determine the optimum investment that is needed to provide CIP to the SC network. This optimum investment is obtained by using the MBVA and FTA models that was proposed in this study to see what investment in dollars will lead to a cost beneficial reduction in the risk and vulnerability of the sector. This will be compared side-by-side, the loss of reliability, reduction in vulnerabilities and risks, and the drop in the production of the SC.

The impact of various threat scenarios using the developed model was analyzed on a real world oil and gas supply chain. First, as a generalized SC, using the risk based LP SC model to simulate the Gulf coast area SC, because of its critical nature. Then, on a site specific SC, using the risk based network reliability model to simulate the Petrobras of Brazil SC. Thereafter, the Gulf coast area SC using the MBVA, and also the Petrobras (Brazil) SC using the FTA, were simulated, to determine the optimum budget allocation for any proposed CIP. This was done side-by-side the CBA of any reduction in risk and vulnerability, and the likely loss in revenue from a drop in production of the SC.

A recent practical case that highlights the importance of this study which aims at minimizing and managing risks in the oil and gas SC critical infrastructure was the Deepwater Horizon oil spill (also referred to as the BP oil spill/the BP oil disaster/the Macondo blow out). This occurred from the 20th of April – 15th of July, 2010, due to a wellhead blow out at the Gulf of Mexico near Mississippi River Delta of the US. The explosion which led to thirteen deaths, and a spill of almost 5 million barrels, with a total

economic loss that was put at over \$30 billion, clearly demonstrates the need for an adequate, and cost beneficial CIP to be put in place in the oil and gas SC. This can be done by using the models and steps highlighted in this study.

6.2 Recommendations

There are many recommendations that can be put forward in this research that will enable experts to manage, minimize/eliminate instability in the oil and gas critical infrastructure SC, and make them more resilient. However, whatever choice is made, these research have developed an easy-to-use risk based SC models that will enable executives, risk/supply chain/production managers, transportation and logistics personnel, suppliers and regulators, academicians and students, and the general public determine the economic implications of their decisions.

Some of the Critical Infrastructure Protection techniques which will be recommended for the protection of the critical nodes and links of the oil and gas SC critical infrastructure include:

- Increasing system redundancy.
- Deploying state - of - the - art surveillance equipment.
- Deploying aerial and ground patrols.
- Fortifying supply chain systems against cyber-security breaches.

The most effective way however, to address the scourge of sabotage is to confront terrorists wherever they are. This is already being done by most countries as part of the global war on terror.

The most obvious way to increase supply chain nodes/links security is the use of patrols and the creation of buffer zones along the critical nodes/links into which unauthorized personnel are prohibited from entering. In Iraq, close to 14,000 security guards have been deployed along the pipelines and other critical nodes. But ground patrols are only effective to a certain degree, especially in areas of inclement weather and forbidding terrain.

Another way that will be recommended to reduce supply chain sabotage is by paying tribes and powerful warlords to protect the critical nodes/links on their territory. This method was tried in Iraq with limited success, and is also being implemented right now in Nigeria – where the leader of the most powerful ethnic militia group was recently released from detention as a bargain for a halt in the oil and gas supply chain network vandalization.

Technology could also play an important role in the effort to secure critical nodes/links. Sophisticated surveillance systems to enhance infrastructure security can be deployed in critical locations. New technologies for seismic sensing of underground vibrations can provide early warning when saboteurs approach the protected area. Such systems may be expensive, but by making possible the remote monitoring of much of the supply chain network, governments can eliminate the need for large numbers of troops and instead rely on smaller numbers of rapid – response teams.

Such systems can also be complemented by air surveillance. As a result of progress in high - resolution remote sensing and image processing technology, it is now possible to deploy small and medium – size Unmanned Aerial Vehicles (UAVs) and unmanned helicopters for nodes/links inspection purposes. These UAVs can stay in the

air up to 30 hours at medium – to – low altitudes, and can send images to a central control station where they can be reviewed by security teams. Some defense contractors are developing UAVs mounted with automatic weapons to be used against saboteurs.

Unfortunately, many of the countries where such technologies would be most effective, like Nigeria, are too poor to afford them. Under such circumstances governments and pipeline operators that cannot prevent attacks altogether should invest in mechanisms to minimize the damage attacks can cause. The cheapest and most effective way to protect an existing nodes/links is to prevent easy access by surrounding it with walls and fences. New pipelines should be buried. While this may substantially increase construction cost, in areas where saboteurs are known to operate the investment will quickly pay for itself.

New technologies can fortify pipes with external carbon fiber wrap that can mitigate the effects of explosive devices. Equally important is to shorten the lead time between the attack and the repair. The quicker it takes to repair the damage, the lower the cost of the disruption. Pipeline saboteurs often target pipelines at critical junctions or hit custom – made parts that take longer to replace. To reduce the lead time, pipeline operators should be equipped with sufficient inventories of spare parts.

It is important to also realize that none of the approaches discussed here is likely to put an end to the problem. As long as oil and gas continue to be essential to the functioning of the world's economy, its nodes/links sabotage is likely to remain one of the industry's risks. No matter what remedy is applied; it will add a surcharge to the price of a barrel. So, it is important that experts use the work that was done in this research as a

guide in making the most economic and beneficial decision in making the industry more resilient.

APPENDIX A

LINDO SOFTWARE OUTPUT FOR BASE CASE

Simulations of the gulf coast oil sc using the average daily storage capacity of their tank farms and without any risk constraints using the developed risk based LP models and Lindo software to obtain the base optimum value.

Note: that the description of the variables and constraints are shown and described in Section 4.4, while the values and their derivations are shown and explained in Section 5.4 also. While the summary of the inputs and outputs are shown in the sensitivity analysis summary of the cases in Tables 5.14 to 5.16.

(1) Base Case – Case 0 LP model.

$$\text{Max } 75X1 + 75X2 + 75X3 + 75X4 + 75X5 + 75X6$$

Subject to:

$$X1 + X2 + X3 + X4 + X5 + X6 < 10.8$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 81$$

$$X1 < 2.2$$

$$X2 < 0.6$$

$$X3 < 3$$

$$X4 < 2.5$$

$$X5 < 0.5$$

$$X6 < 4.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 21.5$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 39$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 39$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 22.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 22.6$$

$$7X1 + 8X2 + 5X3 + 5X4 + 8X5 + 7X6 < 14$$

- **Lindo output for Base Case (showing an objective function value of 810×10^5).**

LP OPTIMUM FOUND AT STEP 5

OBJECTIVE FUNCTION VALUE

1) 810.0000

VARIABLE	VALUE	REDUCED COST
X1	0.000000	0.000000
X2	0.600000	0.000000
X3	3.000000	0.000000
X4	2.100000	0.000000
X5	0.500000	0.000000
X6	4.600000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	75.000000
3)	70.307999	0.000000
4)	2.200000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	0.400000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	10.808000	0.000000
11)	28.200001	0.000000
12)	28.308001	0.000000
13)	11.800000	0.000000
14)	11.908000	0.000000
15)	52.500000	0.000000

NO. ITERATIONS= 5

APPENDIX B

LINDO OUTPUT FOR LONG TERM EVENTS

Simulations of multiple long term events on the gulf coast oil sc across various storing capacities for the four (4) seasons of the year using the developed risk based LP models and Lindo software.

Note: that the description of the variables and constraints are shown and described in Section 4.4, while the values and their derivations are shown and explained in Section 5.4 also. While the summary of the inputs and outputs are shown in the sensitivity analysis summary of the cases in Tables 5.14 to 5.16.

(2) Cases 1 and 2 (b and d) LP – average storage of 3.9mb/d (same with summer and winter Storage, i.e. cases (2(b) and 2(d)).

$$\text{Max } 75X1 + 75X2 + 75X3 + 75X4 + 75X5 + 75X6$$

Subject to:

$$X1 + X2 + X3 + X4 + X5 + X6 < 8.38$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 81$$

$$X1 < 2.2$$

$$X2 < 0.4$$

$$X3 < 1.8$$

$$X4 < 2.5$$

$$X5 < 0.22$$

$$X6 < 4.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 21.5$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 39$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 39$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 22.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 22.6$$

$$7X1 + 8X2 + 5X3 + 5X4 + 8X5 + 7X6 > 14$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-2.97X1 - 2.97X2 - 2.97X3 - 2.97X4 - 2.97X5 - 2.97X6 < 0$$

$$-4X1 - 4X2 - 4X3 - 4X4 - 4X5 - 4X6 < 0$$

$$-3.96X1 - 3.96X2 - 3.96X3 - 3.96X4 - 3.96X5 - 3.96X6 < 0$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-3.96X1 - 3.96X2 - 3.96X3 - 3.96X4 - 3.96X5 - 3.96X6 < 0$$

- **LINDO output for cases 1 and 2 (b and d) (showing approximately 22.4% drop in objective function in comparison with the base case).**

LP OPTIMUM FOUND AT STEP 7

OBJECTIVE FUNCTION VALUE

1) 628.5000

VARIABLE	VALUE	REDUCED COST
X1	0.000000	0.000000
X2	0.400000	0.000000
X3	1.800000	0.000000
X4	1.360000	0.000000
X5	0.220000	0.000000
X6	4.600000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	75.000000
3)	72.703796	0.000000
4)	2.200000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	1.140000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	13.203800	0.000000
11)	30.620001	0.000000
12)	30.703800	0.000000
13)	14.220000	0.000000
14)	14.303800	0.000000
15)	38.959999	0.000000
16)	18.170000	0.000000
17)	24.888599	0.000000
18)	33.520000	0.000000
19)	33.184799	0.000000
20)	18.170000	0.000000
21)	33.184799	0.000000

NO. ITERATIONS= 7

Cases 2 (b) & (d) (Summer & Winter) Sensitivity Analysis

RANGES IN WHICH THE BASIS IS UNCHANGED:

OBJ COEFFICIENT RANGES			
VARIABLE	CURRENT	ALLOWABLE	ALLOWABLE
	COEF	INCREASE	DECREASE
X1	75.000000	0.000000	INFINITY
X2	75.000000	INFINITY	0.000000
X3	75.000000	INFINITY	0.000000
X4	75.000000	0.000000	0.000000
X5	75.000000	INFINITY	0.000000
X6	75.000000	INFINITY	0.000000

RIGHTHAND SIDE RANGES			
ROW	CURRENT	ALLOWABLE	ALLOWABLE
	RHS	INCREASE	DECREASE
2	8.380000	1.140000	1.360000
3	81.000000	INFINITY	72.703796
4	2.200000	INFINITY	2.200000
5	0.400000	1.360000	0.400000
6	1.800000	1.360000	1.140000
7	2.500000	INFINITY	1.140000
8	0.220000	1.360000	0.220000
9	4.600000	1.360000	1.140000
10	21.500000	INFINITY	13.203800
11	39.000000	INFINITY	30.620001
12	39.000000	INFINITY	30.703800
13	22.600000	INFINITY	14.220000
14	22.600000	INFINITY	14.303800
15	14.000000	38.959999	INFINITY
16	0.000000	INFINITY	18.170000
17	0.000000	INFINITY	24.888599
18	0.000000	INFINITY	33.520000
19	0.000000	INFINITY	33.184799
20	0.000000	INFINITY	18.170000
21	0.000000	INFINITY	33.184799

- Amended LP for cases 1 and 2 (b and d) (with 30% increase in projected output).

$$\text{Max } 75X1 + 75X2 + 75X3 + 75X4 + 75X5 + 75X6$$

Subject to:

$$X1 + X2 + X3 + X4 + X5 + X6 < 10.89$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 81$$

$$X1 < 4.71$$

$$X_2 < 0.6$$

$$X_3 < 3$$

$$X_4 < 2.5$$

$$X_5 < 0.5$$

$$X_6 < 4.6$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 21.5$$

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 39$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 39$$

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 22.6$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 22.6$$

$$7X_1 + 8X_2 + 5X_3 + 5X_4 + 8X_5 + 7X_6 > 14$$

$$-4X_1 + X_2 - 3X_3 - 3X_4 + 0.5X_5 - 2X_6 < 0$$

$$-2.97X_1 - 2.97X_2 - 2.97X_3 - 2.97X_4 - 2.97X_5 - 2.97X_6 < 0$$

$$-4X_1 - 4X_2 - 4X_3 - 4X_4 - 4X_5 - 4X_6 < 0$$

$$-3.96X_1 - 3.96X_2 - 3.96X_3 - 3.96X_4 - 3.96X_5 - 3.96X_6 < 0$$

$$-4X_1 + X_2 - 3X_3 - 3X_4 + 0.5X_5 - 2X_6 < 0$$

$$-3.96X_1 - 3.96X_2 - 3.96X_3 - 3.96X_4 - 3.96X_5 - 3.96X_6 < 0$$

- **LP output for cases 1 and 2 (b and d) amended (showing same objective function with base case when output is increased by approx. 30%).**

LP OPTIMUM FOUND AT STEP 0

OBJECTIVE FUNCTION VALUE

1) 816.7500

VARIABLE	VALUE	REDUCED COST
X1	0.000000	0.000000
X2	0.600000	0.000000
X3	3.000000	0.000000
X4	2.190000	0.000000
X5	0.500000	0.000000
X6	4.600000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	75.000000
3)	70.218903	0.000000
4)	4.710000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	0.310000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000

10)	10.718900	0.000000
11)	28.110001	0.000000
12)	28.218901	0.000000
13)	11.710000	0.000000
14)	11.818900	0.000000
15)	52.950001	0.000000
16)	23.920000	0.000000
17)	32.343300	0.000000
18)	43.560001	0.000000
19)	43.124401	0.000000
20)	23.920000	0.000000
21)	43.124401	0.000000

NO. ITERATIONS= 0

(3) Case 2(a) LP – spring season (with average daily storage capacity of 4.3mb/d).

Max $75X_1 + 75X_2 + 75X_3 + 75X_4 + 75X_5 + 75X_6$

Subject to:

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 9.16$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 81$$

$$X_1 < 2.98$$

$$X_2 < 0.4$$

$$X_3 < 1.8$$

$$X_4 < 2.5$$

$$X_5 < 0.22$$

$$X_6 < 4.6$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 21.5$$

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 43$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 43$$

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 22.6$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 22.6$$

$$7X_1 + 8X_2 + 5X_3 + 5X_4 + 8X_5 + 7X_6 > 14$$

$$-4X_1 + X_2 - 3X_3 - 3X_4 + 0.5X_5 - 2X_6 < 0$$

$$-2.97X_1 - 2.97X_2 - 2.97X_3 - 2.97X_4 - 2.97X_5 - 2.97X_6 < 0$$

$$-4X_1 - 4X_2 - 4X_3 - 4X_4 - 4X_5 - 4X_6 < 0$$

$$-3.96X_1 - 3.96X_2 - 3.96X_3 - 3.96X_4 - 3.96X_5 - 3.96X_6 < 0$$

$$-4X_1 + X_2 - 3X_3 - 3X_4 + 0.5X_5 - 2X_6 < 0$$

$$-3.96X_1 - 3.96X_2 - 3.96X_3 - 3.96X_4 - 3.96X_5 - 3.96X_6 < 0$$

Case 2(a) LINDO output (showing about 15% drop in the objective function).

LP OPTIMUM FOUND AT STEP 0

OBJECTIVE FUNCTION VALUE

1) 687.0000

VARIABLE	VALUE	REDUCED COST
X1	0.000000	0.000000
X2	0.400000	0.000000
X3	1.800000	0.000000
X4	2.140000	0.000000
X5	0.220000	0.000000
X6	4.600000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	75.000000
3)	71.931602	0.000000
4)	2.980000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	0.360000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	12.431600	0.000000
11)	33.840000	0.000000
12)	33.931599	0.000000
13)	13.440000	0.000000
14)	13.531600	0.000000
15)	42.860001	0.000000
16)	20.510000	0.000000
17)	27.205200	0.000000
18)	36.639999	0.000000
19)	36.273602	0.000000
20)	20.510000	0.000000
21)	36.273602	0.000000

NO. ITERATIONS= 0

Case 2 (a) (spring season) Sensitivity Analysis

RANGES IN WHICH THE BASIS IS UNCHANGED:

VARIABLE	OBJ COEFFICIENT RANGES		
	CURRENT COEF	ALLOWABLE INCREASE	ALLOWABLE DECREASE
X1	75.000000	0.000000	INFINITY

X2	75.000000	INFINITY	0.000000
X3	75.000000	INFINITY	0.000000
X4	75.000000	0.000000	0.000000
X5	75.000000	INFINITY	0.000000
X6	75.000000	INFINITY	0.000000

ROW	RIGHTHAND SIDE RANGES		
	CURRENT RHS	ALLOWABLE INCREASE	ALLOWABLE DECREASE
2	9.160000	0.360000	2.140000
3	81.000000	INFINITY	71.931602
4	2.980000	INFINITY	2.980000
5	0.400000	2.140000	0.360000
6	1.800000	2.140000	0.360000
7	2.500000	INFINITY	0.360000
8	0.220000	2.140000	0.220000
9	4.600000	2.140000	0.360000
10	21.500000	INFINITY	12.431600
11	43.000000	INFINITY	33.840000
12	43.000000	INFINITY	33.931599
13	22.600000	INFINITY	13.440000
14	22.600000	INFINITY	13.531600
15	14.000000	42.860001	INFINITY
16	0.000000	INFINITY	20.510000
17	0.000000	INFINITY	27.205200
18	0.000000	INFINITY	36.639999
19	0.000000	INFINITY	36.273602
20	0.000000	INFINITY	20.510000
21	0.000000	INFINITY	36.273602

- **Amended LP for case 2(a) (with 18% increase in projected output).**

$$\text{Max } 75X1 + 75X2 + 75X3 + 75X4 + 75X5 + 75X6$$

Subject to:

$$X1 + X2 + X3 + X4 + X5 + X6 < 10.81$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 81$$

$$X1 < 4.63$$

$$X2 < 0.4$$

$$X3 < 1.8$$

$$X4 < 2.5$$

$$X5 < 0.22$$

$$X6 < 4.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 21.5$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 43$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 43$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 22.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 22.6$$

$$7X1 + 8X2 + 5X3 + 5X4 + 8X5 + 7X6 > 14$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-2.97X1 - 2.97X2 - 2.97X3 - 2.97X4 - 2.97X5 - 2.97X6 < 0$$

$$-4X1 - 4X2 - 4X3 - 4X4 - 4X5 - 4X6 < 0$$

$$-3.96X1 - 3.96X2 - 3.96X3 - 3.96X4 - 3.96X5 - 3.96X6 < 0$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-3.96X1 - 3.96X2 - 3.96X3 - 3.96X4 - 3.96X5 - 3.96X6 < 0$$

- **LP output for case 2(a) amended (showing same objective function with base case when output is increased by approximately 18%).**

LP OPTIMUM FOUND AT STEP 0

OBJECTIVE FUNCTION VALUE

1) 810.7500

VARIABLE	VALUE	REDUCED COST
X1	1.290000	0.000000
X2	0.400000	0.000000
X3	1.800000	0.000000
X4	2.500000	0.000000
X5	0.220000	0.000000
X6	4.600000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	75.000000
3)	70.298103	0.000000
4)	3.340000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	0.000000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	10.798100	0.000000
11)	32.189999	0.000000
12)	32.298100	0.000000
13)	11.790000	0.000000
14)	11.898100	0.000000
15)	53.689999	0.000000
16)	26.750000	0.000000

17)	32.105701	0.000000
18)	43.240002	0.000000
19)	42.807598	0.000000
20)	26.750000	0.000000
21)	42.807598	0.000000

NO. ITERATIONS= 0

(4) Case 2(c) LP – fall season (with average daily storage capacity of 3.7mb/d).

Max $75X_1 + 75X_2 + 75X_3 + 75X_4 + 75X_5 + 75X_6$

Subject to

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 7.96$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 81$$

$$X_1 < 2.62$$

$$X_2 < 0.4$$

$$X_3 < 1.8$$

$$X_4 < 2.5$$

$$X_5 < 0.22$$

$$X_6 < 4.6$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 21.5$$

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 43$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 43$$

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 22.6$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 22.6$$

$$7X_1 + 8X_2 + 5X_3 + 5X_4 + 8X_5 + 7X_6 > 14$$

$$-4X_1 + X_2 - 3X_3 - 3X_4 + 0.5X_5 - 2X_6 < 0$$

$$-2.97X_1 - 2.97X_2 - 2.97X_3 - 2.97X_4 - 2.97X_5 - 2.97X_6 < 0$$

$$-4X_1 - 4X_2 - 4X_3 - 4X_4 - 4X_5 - 4X_6 < 0$$

$$-3.96X_1 - 3.96X_2 - 3.96X_3 - 3.96X_4 - 3.96X_5 - 3.96X_6 < 0$$

$$-4X_1 + X_2 - 3X_3 - 3X_4 + 0.5X_5 - 2X_6 < 0$$

$$-3.96X_1 - 3.96X_2 - 3.96X_3 - 3.96X_4 - 3.96X_5 - 3.96X_6 < 0$$

- **Case 2(c) LINDO output (showing about 26% drop in the objective function value).**

LP OPTIMUM FOUND AT STEP 2

OBJECTIVE FUNCTION VALUE

1) 597.0000

VARIABLE	VALUE	REDUCED COST
X1	0.000000	0.000000
X2	0.000000	0.000000

X3	1.800000	0.000000
X4	2.500000	0.000000
X5	0.220000	0.000000
X6	3.440000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	75.000000
3)	73.119598	0.000000
4)	2.620000	0.000000
5)	0.400000	0.000000
6)	0.000000	0.000000
7)	0.000000	0.000000
8)	0.000000	0.000000
9)	1.160000	0.000000
10)	13.619600	0.000000
11)	35.040001	0.000000
12)	35.119598	0.000000
13)	14.640000	0.000000
14)	14.719600	0.000000
15)	33.340000	0.000000
16)	19.670000	0.000000
17)	23.641199	0.000000
18)	31.840000	0.000000
19)	31.521601	0.000000
20)	19.670000	0.000000
21)	31.521601	0.000000

NO. ITERATIONS= 2

Case 2(c) (Fall Season) Sensitivity Analysis

RANGES IN WHICH THE BASIS IS UNCHANGED:

VARIABLE	OBJ COEFFICIENT RANGES		
	CURRENT COEF	ALLOWABLE INCREASE	ALLOWABLE DECREASE
X1	75.000000	0.000000	INFINITY
X2	75.000000	INFINITY	0.000000
X3	75.000000	INFINITY	0.000000
X4	75.000000	0.000000	0.000000
X5	75.000000	INFINITY	0.000000
X6	75.000000	INFINITY	0.000000

ROW	RIGHTHAND SIDE RANGES		
	CURRENT	ALLOWABLE	ALLOWABLE

	RHS	INCREASE	DECREASE
2	7.960000	1.560000	0.940000
3	81.000000	INFINITY	73.119598
4	2.620000	INFINITY	2.620000
5	0.400000	0.940000	0.400000
6	1.800000	0.940000	1.560000
7	2.500000	INFINITY	1.560000
8	0.220000	0.940000	0.220000
9	4.600000	0.940000	1.560000
10	21.500000	INFINITY	13.619600
11	43.000000	INFINITY	35.040001
12	43.000000	INFINITY	35.119598
13	22.600000	INFINITY	14.640000
14	22.600000	INFINITY	14.719600
15	14.000000	36.860001	INFINITY
16	0.000000	INFINITY	16.910000
17	0.000000	INFINITY	23.641199
18	0.000000	INFINITY	31.840000
19	0.000000	INFINITY	31.521601
20	0.000000	INFINITY	16.910000
21	0.000000	INFINITY	31.521601

- **Amended LP for case 2(c) (with 35% increase in projected output).**

$$\text{Max } 75X_1 + 75X_2 + 75X_3 + 75X_4 + 75X_5 + 75X_6$$

Subject to:

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 10.75$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 81$$

$$X_1 < 5.41$$

$$X_2 < 0.4$$

$$X_3 < 1.8$$

$$X_4 < 2.5$$

$$X_5 < 0.22$$

$$X_6 < 4.6$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 21.5$$

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 43$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 43$$

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 22.6$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 22.6$$

$$7X_1 + 8X_2 + 5X_3 + 5X_4 + 8X_5 + 7X_6 > 14$$

$$-4X_1 + X_2 - 3X_3 - 3X_4 + 0.5X_5 - 2X_6 < 0$$

$$-2.97X_1 - 2.97X_2 - 2.97X_3 - 2.97X_4 - 2.97X_5 - 2.97X_6 < 0$$

$$-4X_1 - 4X_2 - 4X_3 - 4X_4 - 4X_5 - 4X_6 < 0$$

$$-3.96X_1 - 3.96X_2 - 3.96X_3 - 3.96X_4 - 3.96X_5 - 3.96X_6 < 0$$

$$-4X_1 + X_2 - 3X_3 - 3X_4 + 0.5X_5 - 2X_6 < 0$$

$$-3.96X_1 - 3.96X_2 - 3.96X_3 - 3.96X_4 - 3.96X_5 - 3.96X_6 < 0$$

- **LP output for case 2(c) amended (showing same objective function with base case when output is increased by approximately 35%).**

LP OPTIMUM FOUND AT STEP 0

OBJECTIVE FUNCTION VALUE

1) 806.2500

VARIABLE	VALUE	REDUCED COST
X1	1.630000	0.000000
X2	0.000000	0.000000
X3	1.800000	0.000000
X4	2.500000	0.000000
X5	0.220000	0.000000
X6	4.600000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	75.000000
3)	70.357498	0.000000
4)	3.780000	0.000000
5)	0.400000	0.000000
6)	0.000000	0.000000
7)	0.000000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	10.857500	0.000000
11)	32.250000	0.000000
12)	32.357498	0.000000
13)	11.850000	0.000000
14)	11.957500	0.000000
15)	52.869999	0.000000
16)	28.510000	0.000000
17)	31.927500	0.000000
18)	43.000000	0.000000
19)	42.570000	0.000000
20)	28.510000	0.000000
21)	42.570000	0.000000

NO. ITERATIONS= 0

APPENDIX C

LINDO OUTPUT FOR SHORT TERM EVENTS

Simulations of short term events on the gulf coast area sc during the most critical storage time of the year (i.e. the fall season): using the developed risk based LP models and Lindo software.

Note: that the description of the variables and constraints are shown and described in Section 4.4, while the values and their derivations are shown and explained in Section 5.4 also. While the summary of the inputs and outputs are shown in the sensitivity analysis summary of the cases in Tables 5.14 to 5.16.

(1) Case 3(a): LP model for a refinery fire/explosion in the Gulf coast area SC during the fall season (the most critical storage capacity season of the year).

$$\text{Max } 75X1 + 75X2 + 75X3 + 75X4 + 75X5 + 75X6$$

Subject to:

$$X1 + X2 + X3 + X4 + X5 + X6 < 7.96$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 81$$

$$X1 < 2.62$$

$$X2 < 0.4$$

$$X3 < 1.8$$

$$X4 < 2.5$$

$$X5 < 0.22$$

$$X6 < 4.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 21.5$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 37$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 37$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 22.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 22.6$$

$$7X1 + 8X2 + 5X3 + 5X4 + 8X5 + 7X6 > 14$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-0.99X1 - 0.99X2 - 0.99X3 - 0.99X4 - 0.99X5 - 0.99X6 < 0$$

$$-4X1 - 4X2 - 4X3 - 4X4 - 4X5 - 4X6 < 0$$

$$-3.96X1 - 3.96X2 - 3.96X3 - 3.96X4 - 3.96X5 - 3.96X6 < 0$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-3.96X1 - 3.96X2 - 3.96X3 - 3.96X4 - 3.96X5 - 3.96X6 < 0$$

LINDO output for case 3(a) – showing 26% drop in objective function in comparison with the base case.

LP OPTIMUM FOUND AT STEP 7

OBJECTIVE FUNCTION VALUE

1) 597.0000

VARIABLE	VALUE	REDUCED COST
X1	0.000000	0.000000
X2	0.400000	0.000000
X3	1.800000	0.000000
X4	0.940000	0.000000
X5	0.220000	0.000000
X6	4.600000	0.000000
ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	75.000000
3)	73.119598	0.000000
4)	2.620000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	1.560000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000

10)	13.619600	0.000000
11)	35.040001	0.000000
12)	35.119598	0.000000
13)	14.640000	0.000000
14)	14.719600	0.000000
15)	36.860001	0.000000
16)	16.910000	0.000000
17)	7.880400	0.000000
18)	31.840000	0.000000
19)	31.521601	0.000000
20)	16.910000	0.000000
21)	31.521601	0.000000

NO. ITERATIONS= 7

- **Amended LP for case 3(a) (with 35% increase in projected output).**

$$\text{Max } 75X_1 + 75X_2 + 75X_3 + 75X_4 + 75X_5 + 75X_6$$

Subject to

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 10.75$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 81$$

$$X_1 < 5.41$$

$$X_2 < 0.4$$

$$X_3 < 1.8$$

$$X_4 < 2.5$$

$$X_5 < 0.22$$

$$X_6 < 4.6$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 21.5$$

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 37$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 37$$

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 22.6$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 22.6$$

$$7X_1 + 8X_2 + 5X_3 + 5X_4 + 8X_5 + 7X_6 > 14$$

$$-4X_1 + X_2 - 3X_3 - 3X_4 + 0.5X_5 - 2X_6 < 0$$

$$-0.99X_1 - 0.99X_2 - 0.99X_3 - 0.99X_4 - 0.99X_5 - 0.99X_6 < 0$$

$$-4X_1 - 4X_2 - 4X_3 - 4X_4 - 4X_5 - 4X_6 < 0$$

$$-3.96X_1 - 3.96X_2 - 3.96X_3 - 3.96X_4 - 3.96X_5 - 3.96X_6 < 0$$

$$-4X_1 + X_2 - 3X_3 - 3X_4 + 0.5X_5 - 2X_6 < 0$$

$$-3.96X_1 - 3.96X_2 - 3.96X_3 - 3.96X_4 - 3.96X_5 - 3.96X_6 < 0$$

LINDO output for case 3(a) amended (shows same objective function with base case when production is increased by 35%).

LP OPTIMUM FOUND AT STEP 1

OBJECTIVE FUNCTION VALUE

1) 806.2500

VARIABLE	VALUE	REDUCED COST
X1	1.230000	0.000000

X2	0.400000	0.000000
X3	1.800000	0.000000
X4	2.500000	0.000000
X5	0.220000	0.000000
X6	4.600000	0.000000
ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	75.000000
3)	70.357498	0.000000
4)	4.180000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	0.000000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	10.857500	0.000000
11)	32.250000	0.000000
12)	32.357498	0.000000
13)	11.850000	0.000000
14)	11.957500	0.000000
15)	53.270000	0.000000
16)	26.510000	0.000000
17)	10.642500	0.000000
18)	43.000000	0.000000

19)	42.570000	0.000000
20)	26.510000	0.000000
21)	42.570000	0.000000

NO. ITERATIONS= 1

(2) Case 3(b): LP model for a tank farm leak/crack in the Gulf coast area SC during the fall season (the most critical storage capacity season of the year).

$$\text{Max } 75X1 + 75X2 + 75X3 + 75X4 + 75X5 + 75X6$$

Subject to

$$X1 + X2 + X3 + X4 + X5 + X6 < 7.96$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 81$$

$$X1 < 2.62$$

$$X2 < 0.4$$

$$X3 < 1.8$$

$$X4 < 2.5$$

$$X5 < 0.22$$

$$X6 < 4.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 21.5$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 37$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 37$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 22.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 22.6$$

$$7X1 + 8X2 + 5X3 + 5X4 + 8X5 + 7X6 > 14$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-2.97X1 - 2.97X2 - 2.97X3 - 2.97X4 - 2.97X5 - 2.97X6 < 0$$

$$-4X1 - 4X2 - 4X3 - 4X4 - 4X5 - 4X6 < 0$$

$$-1.98X1 - 1.98X2 - 1.98X3 - 1.98X4 - 1.98X5 - 1.98X6 < 0$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-3.96X1 - 3.96X2 - 3.96X3 - 3.96X4 - 3.96X5 - 3.96X6 < 0$$

LINDO output for case 3(b) – showing 28% drop in objective function in comparison with the base case.

LP OPTIMUM FOUND AT STEP 0

OBJECTIVE FUNCTION VALUE

1) 585.0000

VARIABLE	VALUE	REDUCED COST
X1	0.000000	0.000000
X2	0.400000	0.000000
X3	1.800000	0.000000
X4	0.780000	0.000000
X5	0.220000	0.000000
X6	4.600000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	75.000000
3)	73.278000	0.000000
4)	2.460000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	1.720000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	13.778000	0.000000
11)	29.200001	0.000000

12)	29.278000	0.000000
13)	14.800000	0.000000
14)	14.878000	0.000000
15)	36.060001	0.000000
16)	16.430000	0.000000
17)	23.166000	0.000000
18)	31.200001	0.000000
19)	15.444000	0.000000
20)	16.430000	0.000000
21)	30.888000	0.000000

NO. ITERATIONS= 0

- **Amended LP for Case 3(b) (with 38% increase in projected output).**

Max $75X_1 + 75X_2 + 75X_3 + 75X_4 + 75X_5 + 75X_6$

Subject to

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 10.92$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 81$$

$$X_1 < 5.58$$

$$X_2 < 0.4$$

$$X_3 < 1.8$$

$$X_4 < 2.5$$

$$X_5 < 0.22$$

$$X_6 < 4.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 21.5$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 37$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 37$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 22.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 22.6$$

$$7X1 + 8X2 + 5X3 + 5X4 + 8X5 + 7X6 > 14$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-2.97X1 - 2.97X2 - 2.97X3 - 2.97X4 - 2.97X5 - 2.97X6 < 0$$

$$-4X1 - 4X2 - 4X3 - 4X4 - 4X5 - 4X6 < 0$$

$$-1.98X1 - 1.98X2 - 1.98X3 - 1.98X4 - 1.98X5 - 1.98X6 < 0$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-3.96X1 - 3.96X2 - 3.96X3 - 3.96X4 - 3.96X5 - 3.96X6 < 0$$

LINDO output for case 3(b) amended (shows same objective function with base case when production is increased by 38%).

LP OPTIMUM FOUND AT STEP 1

OBJECTIVE FUNCTION VALUE

1) 807.0000

VARIABLE	VALUE	REDUCED COST
X1	1.240000	0.000000
X2	0.400000	0.000000
X3	1.800000	0.000000

X4	2.500000	0.000000
X5	0.220000	0.000000
X6	4.600000	0.000000
ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	75.000000
3)	70.347603	0.000000
4)	4.180000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	0.000000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	10.847600	0.000000
11)	26.240000	0.000000
12)	26.347601	0.000000
13)	11.840000	0.000000
14)	11.947600	0.000000
15)	53.340000	0.000000
16)	26.549999	0.000000
17)	31.957199	0.000000
18)	43.040001	0.000000
19)	21.304800	0.000000
20)	26.549999	0.000000

21) 42.609600 0.000000

NO. ITERATIONS= 1

(3) Case 3(c): LP model for a pipe leak/break in the Gulf coast area SC during the fall season (the most critical storage capacity season of the year).

$$\text{Max } 75X1 + 75X2 + 75X3 + 75X4 + 75X5 + 75X6$$

Subject to

$$X1 + X2 + X3 + X4 + X5 + X6 < 7.96$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 81$$

$$X1 < 2.62$$

$$X2 < 0.4$$

$$X3 < 1.8$$

$$X4 < 2.5$$

$$X5 < 0.22$$

$$X6 < 4.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 21.5$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 37$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 37$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 22.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 22.6$$

$$7X1 + 8X2 + 5X3 + 5X4 + 8X5 + 7X6 > 14$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-2.97X1 - 2.97X2 - 2.97X3 - 2.97X4 - 2.97X5 - 2.97X6 < 0$$

$$-4X1 - 4X2 - 4X3 - 4X4 - 4X5 - 4X6 < 0$$

$$-3.96X1 - 3.96X2 - 3.96X3 - 3.96X4 - 3.96X5 - 3.96X6 < 0$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-0.99X1 - 0.99X2 - 0.99X3 - 0.99X4 - 0.99X5 - 0.99X6 < 0$$

LINDO output for case 3(c) – showing 29% drop in objective function in comparison with the base case.

LP OPTIMUM FOUND AT STEP 7

OBJECTIVE FUNCTION VALUE

1) 573.0000

VARIABLE	VALUE	REDUCED COST
----------	-------	--------------

X1	0.000000	0.000000
X2	0.400000	0.000000
X3	1.800000	0.000000
X4	0.620000	0.000000
X5	0.220000	0.000000
X6	4.600000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
-----	------------------	-------------

2)	0.000000	75.000000
3)	73.436401	0.000000
4)	2.300000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	1.880000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	13.936400	0.000000
11)	35.360001	0.000000
12)	35.436401	0.000000
13)	14.960000	0.000000
14)	15.036400	0.000000
15)	35.259998	0.000000

16)	15.950000	0.000000
17)	22.690800	0.000000
18)	30.559999	0.000000
19)	30.254400	0.000000
20)	15.950000	0.000000
21)	7.563600	0.000000

NO. ITERATIONS= 7

- **Amended LP for Case 3(c) (with 39% increase in projected output).**

$$\text{Max } 75X_1 + 75X_2 + 75X_3 + 75X_4 + 75X_5 + 75X_6$$

Subject to

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 10.62$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 81$$

$$X_1 < 5.28$$

$$X_2 < 0.4$$

$$X_3 < 1.8$$

$$X_4 < 2.5$$

$$X_5 < 0.22$$

$$X_6 < 4.6$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 21.5$$

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 37$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 37$$

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 22.6$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 22.6$$

$$7X_1 + 8X_2 + 5X_3 + 5X_4 + 8X_5 + 7X_6 > 14$$

$$-4X_1 + X_2 - 3X_3 - 3X_4 + 0.5X_5 - 2X_6 < 0$$

$$-2.97X_1 - 2.97X_2 - 2.97X_3 - 2.97X_4 - 2.97X_5 - 2.97X_6 < 0$$

$$-4X_1 - 4X_2 - 4X_3 - 4X_4 - 4X_5 - 4X_6 < 0$$

$$-3.96X_1 - 3.96X_2 - 3.96X_3 - 3.96X_4 - 3.96X_5 - 3.96X_6 < 0$$

$$-4X_1 + X_2 - 3X_3 - 3X_4 + 0.5X_5 - 2X_6 < 0$$

$$-0.99X_1 - 0.99X_2 - 0.99X_3 - 0.99X_4 - 0.99X_5 - 0.99X_6 < 0$$

LINDO output for case 3(c) amended (shows same objective function with base case when production is increased by 39.5%).

LP OPTIMUM FOUND AT STEP 1

OBJECTIVE FUNCTION VALUE

1) 806.5000

VARIABLE	VALUE	REDUCED COST
----------	-------	--------------

X1	1.100000	0.000000
----	----------	----------

X2	0.400000	0.000000
----	----------	----------

X3	1.800000	0.000000
----	----------	----------

X4	2.500000	0.000000
----	----------	----------

X5	0.220000	0.000000
----	----------	----------

X6	4.600000	0.000000
----	----------	----------

ROW	SLACK OR SURPLUS	DUAL PRICES
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2)	0.000000	75.000000
----	----------	-----------

3)	70.486198	0.000000
----	-----------	----------

4)	4.180000	0.000000
----	----------	----------

5)	0.000000	0.000000
----	----------	----------

6)	0.000000	0.000000
----	----------	----------

7)	0.000000	0.000000
----	----------	----------

8)	0.000000	0.000000
----	----------	----------

9)	0.000000	0.000000
----	----------	----------

10)	10.986200	0.000000
11)	32.380001	0.000000
12)	32.486198	0.000000
13)	11.980000	0.000000
14)	12.086200	0.000000
15)	52.360001	0.000000
16)	25.990000	0.000000
17)	31.541401	0.000000
18)	42.480000	0.000000
19)	42.055199	0.000000
20)	25.990000	0.000000
21)	10.513800	0.000000

NO. ITERATIONS= 1

APPENDIX D

LINDO OUTPUT FOR LONG and SHORT TERM EVENTS WITH CIPs

Simulations of long term and short term events on the gulf coast area sc after incorporating capacity expansion and redundancies as a means of minimizing the impact of threats on the sc network: using the developed risk based LP models and Lindo software.

Note: the description of the variables and constraints are shown and described in Section 4.4, while the values and their derivations are shown and explained in Section 5.4 also.

(1) Case 4(a) LP – 16% capacity expansion of the daily average storage capacity during the fall season (most critical-based on initial results) to minimize the impact of multiple long term risk scenarios on the SC network.

$$\text{Max } 75X1 + 75X2 + 75X3 + 75X4 + 75X5 + 75X6$$

Subject to

$$X1 + X2 + X3 + X4 + X5 + X6 < 9.16$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 81$$

$$X1 < 2.98$$

$$X2 < 0.4$$

$$X3 < 1.8$$

$$X4 < 2.5$$

$$X5 < 0.22$$

$$X6 < 4.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 21.5$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 43$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 43$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 22.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 22.6$$

$$7X1 + 8X2 + 5X3 + 5X4 + 8X5 + 7X6 > 14$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-2.97X1 - 2.97X2 - 2.97X3 - 2.97X4 - 2.97X5 - 2.97X6 < 0$$

$$-4X1 - 4X2 - 4X3 - 4X4 - 4X5 - 4X6 < 0$$

$$-1.98X1 - 1.98X2 - 1.98X3 - 1.98X4 - 1.98X5 - 1.98X6 < 0$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-3.96X1 - 3.96X2 - 3.96X3 - 3.96X4 - 3.96X5 - 3.96X6 < 0$$

Case 4(a) LINDO output (showing about 15% drop in the objective function in comparison to the Base case).

LP OPTIMUM FOUND AT STEP 0

OBJECTIVE FUNCTION VALUE

1) 687.0000

VARIABLE	VALUE	REDUCED COST
X1	0.000000	0.000000
X2	0.400000	0.000000
X3	1.800000	0.000000
X4	2.140000	0.000000
X5	0.220000	0.000000
X6	4.600000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	75.000000
3)	71.931602	0.000000
4)	2.980000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	0.360000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	12.431600	0.000000
11)	33.840000	0.000000
12)	33.931599	0.000000
13)	13.440000	0.000000
14)	13.531600	0.000000
15)	42.860001	0.000000
16)	20.510000	0.000000
17)	27.205200	0.000000
18)	36.639999	0.000000
19)	36.273602	0.000000
20)	20.510000	0.000000
21)	36.273602	0.000000

NO. ITERATIONS= 0

- **Amended LP for Case 4(a) (with 18% increase in projected output).**

$$\text{Max } 75X_1 + 75X_2 + 75X_3 + 75X_4 + 75X_5 + 75X_6$$

Subject to

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 10.81$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 81$$

$$X_1 < 4.63$$

$$X_2 < 0.4$$

$$X3 < 1.8$$

$$X4 < 2.5$$

$$X5 < 0.22$$

$$X6 < 4.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 21.5$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 43$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 43$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 22.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 22.6$$

$$7X1 + 8X2 + 5X3 + 5X4 + 8X5 + 7X6 > 14$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-2.97X1 - 2.97X2 - 2.97X3 - 2.97X4 - 2.97X5 - 2.97X6 < 0$$

$$-4X1 - 4X2 - 4X3 - 4X4 - 4X5 - 4X6 < 0$$

$$-1.98X1 - 1.98X2 - 1.98X3 - 1.98X4 - 1.98X5 - 1.98X6 < 0$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-3.96X1 - 3.96X2 - 3.96X3 - 3.96X4 - 3.96X5 - 3.96X6 < 0$$

- **LINDO output for case 4(a) amended (showing same objective function with base case when output is increased by approximately 18%).**

LP OPTIMUM FOUND AT STEP 0

OBJECTIVE FUNCTION VALUE

1) 810.7500

VARIABLE	VALUE	REDUCED COST
X1	1.290000	0.000000
X2	0.400000	0.000000
X3	1.800000	0.000000
X4	2.500000	0.000000
X5	0.220000	0.000000
X6	4.600000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	75.000000
3)	70.298103	0.000000
4)	3.340000	0.000000
5)	0.000000	0.000000
6)	0.000000	0.000000
7)	0.000000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	10.798100	0.000000

11)	32.189999	0.000000
12)	32.298100	0.000000
13)	11.790000	0.000000
14)	11.898100	0.000000
15)	53.689999	0.000000
16)	26.750000	0.000000
17)	32.105701	0.000000
18)	43.240002	0.000000
19)	42.807598	0.000000
20)	26.750000	0.000000
21)	42.807598	0.000000

NO. ITERATIONS= 0

(2) Case 4(b) LP – 20% Redundancy on the daily average pipeline capacity in the Gulf coast area pipelines to minimize the impact of short term risk scenario (leaks/cracks) on the SC network.

Max $75X_1 + 75X_2 + 75X_3 + 75X_4 + 75X_5 + 75X_6$

Subject to

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 9.17$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 81$$

$$X_1 < 3.83$$

$$X_2 < 0.4$$

$$X_3 < 1.8$$

$$X_4 < 2.5$$

$$X_5 < 0.22$$

$$X_6 < 4.6$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 21.5$$

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 37$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 37$$

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 < 27.12$$

$$0.99X_1 + 0.99X_2 + 0.99X_3 + 0.99X_4 + 0.99X_5 + 0.99X_6 < 27.12$$

$$7X_1 + 8X_2 + 5X_3 + 5X_4 + 8X_5 + 7X_6 > 14$$

$$-4X_1 + X_2 - 3X_3 - 3X_4 + 0.5X_5 - 2X_6 < 0$$

$$-2.97X_1 - 2.97X_2 - 2.97X_3 - 2.97X_4 - 2.97X_5 - 2.97X_6 < 0$$

$$-4X_1 - 4X_2 - 4X_3 - 4X_4 - 4X_5 - 4X_6 < 0$$

$$-3.96X_1 - 3.96X_2 - 3.96X_3 - 3.96X_4 - 3.96X_5 - 3.96X_6 < 0$$

$$-4X_1 + X_2 - 3X_3 - 3X_4 + 0.5X_5 - 2X_6 < 0$$

$$-0.99X_1 - 0.99X_2 - 0.99X_3 - 0.99X_4 - 0.99X_5 - 0.99X_6 < 0$$

Case 4(b) LINDO output (showing about 15% drop in the objective function in comparison to the base case).

LP OPTIMUM FOUND AT STEP 1

OBJECTIVE FUNCTION VALUE

1) 687.7500

VARIABLE	VALUE	REDUCED COST
X1	0.050000	0.000000
X2	0.000000	0.000000
X3	1.800000	0.000000
X4	2.500000	0.000000
X5	0.220000	0.000000
X6	4.600000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	75.000000
3)	71.921700	0.000000
4)	3.780000	0.000000
5)	0.400000	0.000000
6)	0.000000	0.000000
7)	0.000000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	12.421700	0.000000
11)	27.830000	0.000000
12)	27.921700	0.000000
13)	17.950001	0.000000
14)	18.041700	0.000000
15)	41.810001	0.000000
16)	22.190001	0.000000
17)	27.234900	0.000000
18)	36.680000	0.000000
19)	36.313202	0.000000
20)	22.190001	0.000000
21)	9.078300	0.000000

NO. ITERATIONS= 1

- **Amended LP for Case 4(b) (with 17% increase in projected output).**

Max $75X_1 + 75X_2 + 75X_3 + 75X_4 + 75X_5 + 75X_6$

Subject to

$$X1 + X2 + X3 + X4 + X5 + X6 < 10.73$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 81$$

$$X1 < 5.39$$

$$X2 < 0.4$$

$$X3 < 1.8$$

$$X4 < 2.5$$

$$X5 < 0.22$$

$$X6 < 4.6$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 21.5$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 37$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 37$$

$$X1 + X2 + X3 + X4 + X5 + X6 < 31.73$$

$$0.99X1 + 0.99X2 + 0.99X3 + 0.99X4 + 0.99X5 + 0.99X6 < 31.73$$

$$7X1 + 8X2 + 5X3 + 5X4 + 8X5 + 7X6 > 14$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-2.97X1 - 2.97X2 - 2.97X3 - 2.97X4 - 2.97X5 - 2.97X6 < 0$$

$$-4X1 - 4X2 - 4X3 - 4X4 - 4X5 - 4X6 < 0$$

$$-3.96X1 - 3.96X2 - 3.96X3 - 3.96X4 - 3.96X5 - 3.96X6 < 0$$

$$-4X1 + X2 - 3X3 - 3X4 + 0.5X5 - 2X6 < 0$$

$$-0.99X1 - 0.99X2 - 0.99X3 - 0.99X4 - 0.99X5 - 0.99X6 < 0$$

- **LINDO output for Case 4(b) Amended (Showing same objective function with Base case when output is increased by approximately 17%).**

LP OPTIMUM FOUND AT STEP 0

OBJECTIVE FUNCTION VALUE

1) 804.7500

VARIABLE	VALUE	REDUCED COST
X1	1.610000	0.000000
X2	0.000000	0.000000
X3	1.800000	0.000000
X4	2.500000	0.000000
X5	0.220000	0.000000
X6	4.600000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
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2)	0.000000	75.000000
3)	70.377296	0.000000
4)	3.780000	0.000000
5)	0.400000	0.000000
6)	0.000000	0.000000
7)	0.000000	0.000000
8)	0.000000	0.000000
9)	0.000000	0.000000
10)	10.877300	0.000000
11)	26.270000	0.000000
12)	26.377300	0.000000
13)	21.000000	0.000000
14)	21.107300	0.000000
15)	52.730000	0.000000
16)	28.430000	0.000000
17)	31.868099	0.000000
18)	42.919998	0.000000
19)	42.490799	0.000000
20)	28.430000	0.000000
21)	10.622700	0.000000

NO. ITERATIONS= 0

APPENDIX E

FTPLUS SOFTWARE RESULTS FOR MBVA RESOURCE ALLOCATION

Note: the description of the vulnerabilities and damages used are shown and described in Section 4.5, while the values and their derivations are shown and explained in Section 5.5 also.

Figures E.1 to E.3 show resource/allocation strategies using FT Plus.

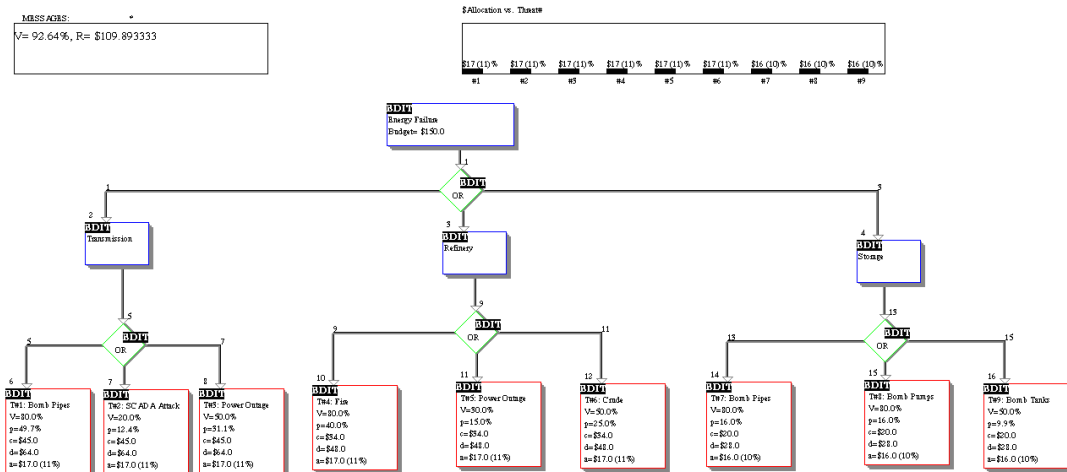


Figure E.1 Resource allocation for Gulf coast area oil and gas SC using manual allocation strategy.

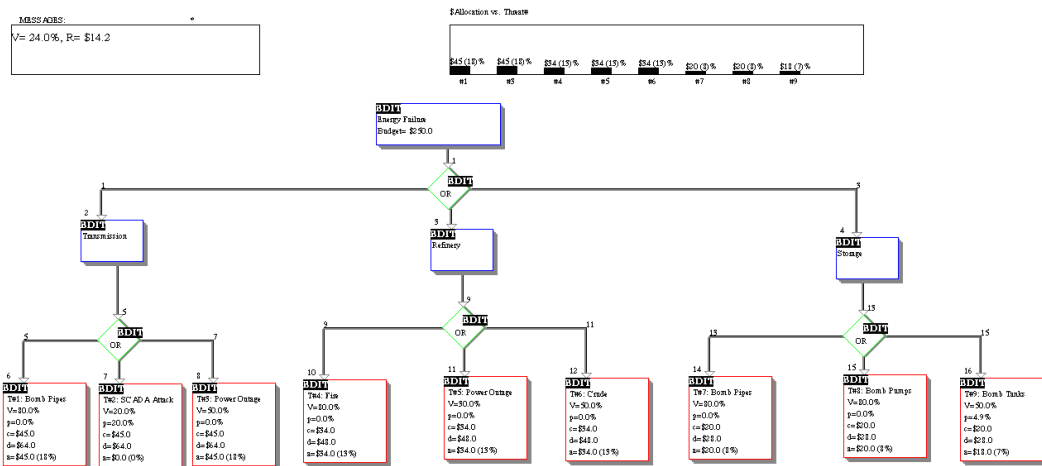


Figure E.2 Resource allocation for Gulf coast area oil and gas SC using rank order allocation strategy.

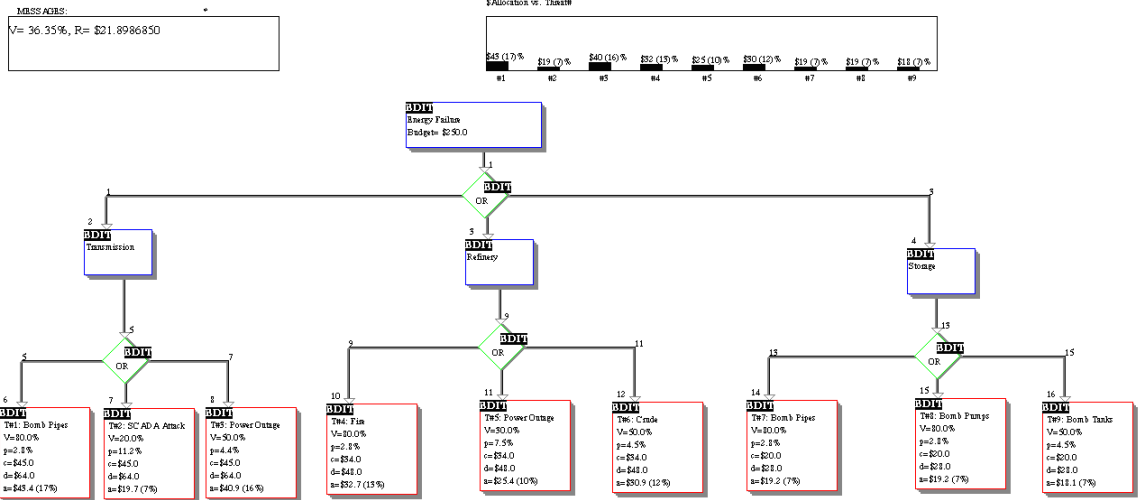


Figure E.3 Resource allocation for Gulf coast area oil and gas SC using apportioned allocation strategy.

APPENDIX F

ANALYZED QUALITY RATINGS OF CRUDE OIL IMPORTS TO THE US

Table F.1 show the quality rating obtained for crude oil imported into the US, using both density and sulphur content criterias. It is in a number scale of 1 – 10, with 10 being the highest).

Note: Oil is generally classified based on its density and sulphur content.

- Density- it can either be light crude or heavy crude. Light crude is more expensive because it requires less refining, while heavy crude is cheaper because it requires more refining.
- Sulphur content- Oil can either be sweet or sour crude. Sweet crude has a sulphur content of less than 0.5% by weight, making it easier to refine to meet environmental standards – so less expensive; while sour crude has sulphur content of more than 0.5% by weight, making it more expensive to refine.

Table F.1 below shows the quality ratings that were derived for various crude oil sources based on the above quality criteria.

Table F.1 US Crude Oil Imports (in 1,000 BPD) and their Quality Ratings

Country	Feb-09	Jan - 09	YTD 2009	Feb - 08	YTD 2008	Qlty. Ratings
CANADA	1,913	1,946	1,930	1,920	1,933	7
MEXICO	1,219	1,299	1,261	1,231	1,214	7
S/ARABIA	1,135	1,337	1,241	1,614	1,544	8
VENEZUELA	962	1,172	1,072	945	1,043	8
ANGOLA	671	527	595	341	458	8
IRAQ	519	568	545	780	658	8
NIGERIA	457	488	473	982	1,075	8
BRAZIL	365	397	382	169	169	7
KUWAIT	251	225	237	261	249	8
ECUADOR	243	272	258	169	209	8
COLOMBIA	225	225	225	220	194	7
EQ. GUINEA	167	118	141	69	53	8
ALGERIA	142	359	256	191	281	8
RUSSIA	139	157	149	80	47	6
CHAD	101	79	90	89	103	6
TOTAL	8,509	9,169	8,854	9,061	9,230	

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