SUPPLY CHAIN NETWORK REDESIGN, CASE STUDY IN LUBRICATION INDUSTRY

BY

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Dedication

To my parents, who taught me how to stand up.

To everyone, who helped me to stay standing.

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ABSTRACT

Full Name : Khalid Saleh Al-Khodhairi

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Supply chain studies have been key areas for optimization across many sectors. However, with the changing landscape of geo-economic factors in the Middle East, coupled with increased complexities within the supply chain network and growing competitiveness amongst industries, optimization studies have naturally become more complex overtime. This thesis considers a case study for a major lubrication company in Saudi Arabia. The case study addresses a single-sourcing network redesign problem for a four-level supply chain consisting of suppliers, plants, distribution centers (DC's) and markets. The demand, land prices, and energy prices are uncertain parameters with DC-to-market dependent lead times. The objective is to determine the optimal number and locations of plants and DC's, the assignment of each plant-DC and DC-market, which minimizes the system-wide location, transportation, and inventory costs for each scenario. The problem is formulated as mixed integer nonlinear programming models (MINLP). Finally, a multi criteria decision-making approach is developed to decide the best warehouse type for the six different local markets.

ملخص الرسالة

الاسم الكامل: خالد صالح عبدالله الخضيري

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تصميم سلاسل الإمداد أصبح أكثر تعقيدا خلال العقد الماضي في الشرق الأوسط، مدفوعا بالعوامل الجيوإقتصادية. تعرض هذه الاطروحة دراسة حالة لشركة كبرى متخصصة في صناعة زيوت المحركات في المملكة العربية السعودية. تتناول دراسة الحالة إعادة تصميم سلسلة إمداد مكونة من أربعة مستويات: موردين، مصانع، مراكز توزيع وأسواق محلية مستهدفة، حيث شملت الدراسة أثر عدم التيقن في معدلات الطلب وأسعار الأراضي وأسعار الطاقة مع الأخذ مدة التوصيل من المصانع لمراكز التوزيع بالاعتبار. تهدف هذه الدراسة لتحديد أعداد ومواقع المصانع ومراكز التوزيع وحصص إمداد مراكز التوزيع من المصانع والحصة الأمثل لكل مركز توزيع للأسواق المحلية المستهدفة التي تحقق أجدى تكلفة لسلسلة الإمداد عبر تطوير نموذج رياضي باستخدام البرمجة الصحيحة المختلطة غير الخطية (MINLP). كما طورت الدراسة تحليل متعدد المعايير لاتخاذ القرار(MCDM) لتحديد نوع الفرع لكل سوق محلي مستهدف لستة مناطق مختلفة في المملكة العربية السعودية.

CHAPTER 1

INTRODUCTION

Company X is a global brand of industrial and automotive lubricants offering a wide range of oils, greases, and related products for most lubrication applications. Currently, Company X is outsourcing the product manufacturing to four different factories. However, Company X executive management is investigating to build a new factory in Saudi Arabia to make the products internally rather than outsourcing production.

The research objective is to consider Company X Supply Chain as a multi-echelon network and include cost factors as inventory, transportation, and operation. This is in order to determine whether the company continue with the outsourcing strategy or not. Consequently, determine the optimal number and location of the new factories, the capacity and location of distribution center(s), safety stock level, and optimal transportation network to maximize the profit and satisfy the market service level.

1.1 Lubrication Industry Overview

With a value of USD 118.89 billion, the lubricants industry is considered a major global industry that is both produced and consumed almost everywhere worldwide (Grand View Research., 2018). The lubricants industry is driven by its various applications such as industrial lubricants, automotive lubricants and construction lubricants. The major products of the industrial lubricants are process oils, metalworking oils and greases. While the common products in the automotive industry are gear oils, transmission fluids, brake fluids, greases and engine oils, which will be the focus of this thesis. There are many key players in the lubricants industry market such as Chevron, BP, Exxon Mobil, PetroChina, Total and Shell. The lubricants industry is projected for an incremental growth of 5.19 million tons by 2023 that is driven by automotive oils segment due to the increasing demand of automobiles in growing countries. Saudi Arabia is considered as a promising market for lubricants due to the high growth rates both in the industrial sector and population. The compound annual growth rate of Saudi lubricates market is expected to be 1.13% between 2018 and 2023. This growth is connected to the automotive and other transportation segment by factor of 60%. KSA lubricants overall business consumption is equivalent to almost 500 million liters a year; Company X lubricants contributes to 10% of that volume. The industry is highly competitive; therefore, supply chain design plays a vital role in the companies' quest for higher market shares.

1.2 Research Objectives

The objective of this work are to determine the optimal number and location of the new plant(s), the capacity and location of distribution center(s), optimal transportation network and safety stock level to maximize the profit and market service level.

1.3 Research Questions

The thesis addresses the next research questions for the lubrication company

1. Should Company X continue with the outsourcing strategy?
2. Do we need new plant(s)? If yes, where?

3. Do we need distribution centers? If yes, where?
4. What is the optimal transportation network?
5. What is the optimal strategic safety stock level in the different DCs in the supply chain?
6. What is the optimal local warehouse type?

1.4 Problem Statement

Let (x) be the lubricant factory (supply node) and (I) be the set of markets (Demand nodes). The objective is to determine where to locate the lubricant factory(s), how many DCs to locate, where to locate them, and which market to assign to each DC to minimize the total expected location, transportation and inventory costs, while ensuring a specific level of service. The possible Plant and DC locations are listed in Table 1.1.

Table 1.1: Supply Chain possible locations

Possible Plant Locations (x)	**Possible DC Locations (I)**	**Market Locations**
• Riyadh • Jeddah • Dammam • Yanbu	• Riyadh • Jeddah • Dammam • Yanbu	• Riyadh • Jeddah • Dammam • Buridah • Khamis Mushait • Tabuk

CHAPTER 2

LITERATURE REVIEW

Facility location models considered in the literature include several factors such as:

1. Commodity: Single or multiple
2. Model parameters: Deterministic or uncertain
3. DC capacity limitation: Capacitated or un-capacitated
4. Number of echelon: Single or multiple

The main models in the literature are listed below, based on the model parameters:

1. Deterministic Models:
    a. The Un-capacitated Facility Location Problem (UFLP)
    b. The Capacitated Facility Location Problem (CFLP)
    c. Multi–echelon, Multi-commodity Deterministic Model
2. Uncertain Models:
    a. Demand Uncertainty
        i. Location Model with Risk Pooling (LMRP) (The demand is stochastic with known distribution and each DC has (r,Q) as their inventory policy)
        ii. Stochastic Fixed Charge Location Model Problem (scenario-based model and probability of each scenario is known)
        iii. Robust Minimax Fixed Charge Location Problem(MFLP) (scenario-based model and probabilities of scenarios are unknown)

b. Supply Uncertainty

i. Reliable Fixed Charge Location Problem (RFLP) (probability of disruption is known, helps to identify back- up plans)

In the following section, the related literature to the thesis work is explored:

2.1 Un-capacitated Facility Location Problem Literature Review

The first facility location model was proposed by Balinski (1965) as Uncapacitated Facility Location Problem (UFLP). In the UFLP, only strategic decisions are taken with respect to which warehouses to open and the quantities that should be transported from each warehouse to each market. Sridharan (1995) extended the model by considering exogenous values for the maximum demand that can be supplied from each potential site. The model is deterministic, single commodity and single-period planning horizon. Clearly, these assumptions are not enough for most realistic facility location models. Therefore, the original model was extended extensively in the literature to consider more realistic settings as surveyed by Gendron et al. (2017) for models and relaxations for Two-Level Uncapacitated Facility Location with Single-Assignment.

2.2 Tri-Echelon Models Literature Review

Geoffrion and Graves (1974) is the seminal paper on multi-echelon facility location problems. It presents a three echelon (Plant-DC-Market) model. The paper considers location decisions only at DC echelon, while optimizing the product flow across the supply chain. The application used in the paper is in food industry, for a food chain with 14 different supply firms, 45 possible location for DCs and 17-commodity type for 121 market locations. The model is solved using Benders' partitioning procedure. Pirkul and

Jayaraman (1996) considered location decisions at both plant and DC echelons. However, the number of plants and DCs are fixed in advance. The model is solved using Lagrangian relaxation with a proposed heuristic that generates feasible solution effectively. The application used in the paper is in health-care industry. S. Park et al. (2010) proposed a model with uncertain demand and lead times.

2.3 Location Model with Risk Pooling (LMRP) Literature Review

Logistics literature considered location and inventory theories separately. Location theory literature considers the optimal location of plants, DCs and market and the product flow between them. Whereas, inventory theory studies the safety stock and replenishment plans at both DCs and market. Inventory costs was considered in location models by Baumol and Wolfe (1958) by adding the inventory cost term to UFLP objective function. Consequently, several integrated location-inventory models have appeared in the literature. Barahona and Jensen (1998) solved a location model with a fixed inventory cost. Moreover, Erlebacher and Meller (2000) formulated Continuous demand extension. Another location model was proposed by Teo et al. (2001) to include inventory costs without including the transportation costs. Thereafter, several joint location-inventory models were proposed. As LMRP is an NP-hard problem, many papers were focused in testing heuristics performance on the problem. Teo and Shu (2004) proposed multi-echelon joint location-inventory model and used column generation to solve the problem. Safety stock cost was incorporated by Nozick and Turnquist (2001).They studied the determination of optimal safety stock location, whether to be at plant or DC for multiple product types by introducing network design problem. Eskigun et al. (2005) introduced pipeline inventory costs in the location model based on the expected lead-time. Daskin et al. (2002) and Shen et al. (2003) introduced location model with risk pooling (LMRP) to incorporate inventory decision along with location decision in UFLP. The motivation was to include "risk pooling effects" to the model. LMRP keeps safety stock and utilizing Eppen (1979) results, who showed that the total expected safety stock in the centralized inventory strategy is significantly lower than the decentralized inventory strategy. Moreover, the multi commodity types extension was considered by Balcik (2003) and Shen (2005). Zhang et al. (2016) proposed a heterogeneous reliable location model with risk pooling under supply disruptions.

2.4 Location models under Financial Uncertainty

The uncertainty in the location models is not limited to demand uncertainty. Other uncertain parameters were considered in the literature such as supply disruption, cost of activity, lead-time and others as surveyed by K. Govindan et al. (2017). Financial related parameters such as cost of activities, selling price, buying price, tax, exchange, and interest rate were studied. The first model with financial uncertainty was proposed by (Alonso-Ayuso et al., 2003) who considered demand, product net profit, raw material cost as uncertain parameters. Several models addressed the financial uncertainty from different angles and for different objectives. The literature for more than two location layers are listed in Table 2.1.

Table 2.1: Financial Uncertainty Literature Review

	Reference	Number of location layers	Uncertain Parameters	Decision Variable	Uncertainty Type
1	Santoso et al. (2005)	3	• Demand • Supply • Transportation costs • Capacities	• Processing centers location • processing and finishing machines ‘procurement selection	Random parameters with known probability distribution
2	Schütz et al. (2009)	3	• Demand • Supply • Transportation Cost • Network Capacity	• Processing facility location • Inventory at processing facility • Demand allocation • Production level	Random parameters with known probability distribution
3	Xu et al. (2009)	3	• Demand • Supply • Transportation Cost	• Facility location • Allocation	Fuzzy decision-making
4	Hasani et al. (2015)	3	• Demand • Exchange rates • Tax rates • Import tariffs	• supplier selection • manufacturing site establishment • warehouse/distributor selection • collection/recovery facility establishment • tactical decisions	Random parameters with un-known probability distribution
5	Hasani and Khosrojerdi (2016)	3	• Demand • Procurement cost	• supplier selection • manufacturing site establishment, • warehouse/distributor selection • collection/recovery facility establishment • tactical decisions	Random parameters with a mix of un- known and known probability distribution

2.5 Local Warehouse type using Analytical Hierarchy Process (AHP)

The publications in Analytical Hierarchy Process (AHP) field are intensive since Saaty (1980) introduced it, as it is the most widely used method in MCDM problems. The literature contributions are mainly classified in two directions. The first is applying AHP in a new application as surveyed by Vaidya et al. (2006), which listed and categorized 150 publications by application area. The second direction is to extend AHP method, such group decision making with AHP by Saaty (1989) and fuzzy AHP in Kuo et al. (1999) paper. Furthermore, other papers integrated AHP with other methods like AHP-TOPSIS method in Prakash et al. (2015), AHP-PROMETHEE by Macharis et al. (2004), AHP-SVM-TOPSOS by Putra (2016) and many other method extensions.

Multi Criteria Decision Making (MCDM) was applied for warehouse location selection. Korpela & Lehmusvaara (1999) proposed a customer oriented approach to warehouse network evaluation and design using AHP. E Boltürk et al. (2016) Multi-attribute warehouse location selection in humanitarian logistics using hesitant fuzzy AHP. Warehouse site selection was studied by Korpela &Tuominen (1996) using AHP. Korpela et al. (2007) also proposed AHP and DEA methodologies to address the problem. Erkan & Can (2014) also proposed MCDM model for warehouse tactical decision for selecting the best warehouse data collecting system by using AHP and FAHP methods.

CHAPTER 3

DATA COLLECTION AND ANALYSIS

In this chapter, case study's data are collected and analyzed. Demand historical data per region are collected and analyzed to derive conclusive demand forecasting. Then, current supply cost is calculated. Finally, potential DC's and lubrication Plant's costs are calculated based on a market research.

3.1 Demand Historical Data

The data used in the case study are obtained from Company X for the period from January 2016 up to end of October 2018. The Summary statistics for each region demand (in liters) data is shown in Table 3.1.

Table 3.1: Summary statistics for each region demand (liters) in monthly basis

Region/Statistic	Mean	Standard Deviation	COV	Minimum	Maximum
Buridah	1,840,462	223,555	0.121	627,432	3,279,060
Jeddah	10,407,700	1,023,290	0.098	6,871,356	16,277,604
Khamis Mushait	3,495,526	144,509	0.041	2,877,000	4,775,532
Dammam	6,881,546	347,819	0.051	4,997,052	8,680,416
Riyadh	13,786,150	1,291,412	0.094	4,908,528	18,444,624
Tabuk	1,749,434	152,839	0.087	959,064	2,896,512

Normality test was conducted for the data for each region and the results are listed in the Table 3.2:

Table 3.2: Normality Test Results

Region	P-Value	Normality Test Result
Buridah	0.474	Pass
Jeddah	<0.005	Fail
Khamis Mushait	<0.005	Fail
Dammam	0.214	Pass
Riyadh	0.033	Fail
Tabuk	<0.005	Fail

Buridah and Dammam passed the normality test based on the P-value, while the others did not. Note that the average demand during the lead time for the cities considered is of very high order while the coefficient of variation is at most 0.121, as shown in Table 3.1. Therefore, the assumption that the demand is normally distributed in the optimization models will have a negligible impact on the result as extensively examined by Tyworth and O'Neill (1997) and further discussed by Silver et al. (2016).

The demand product mix is listed in Table 3.3. A nighty nine percent of the product mix is almost equally between "10W-30" and "20W-50" products. As a result, the demand was aggregated as a single product.

Table 3.3: Product Mix

Product Mix	
Product	Sales %
5W-20	0.01000%
5W-30	0.00200%
5W-40	0.00500%
5W-50	0.00013%
10W-20	0.02200%
10W-30	49.63000%
10W-40	0.03000%
10W-50	0.00600%
10W-60	0.02000%
20W-20	0.01200%
20W-30	0.00060%
20W-40	0.00080%
20W-50	50.26147%

3.2 Current Supply Chain Network Cost

The existing network setup of Company X Lubricants distribution in Saudi Arabia will be evaluated with the determination of its associated cost to be used as a reference for the proposed enhancement in the network. The products are bottled in 1-liter units and transported in boxes. First; supply and demand volume need to be converted to number of delivery trips using the volume-delivery conversion factor (truckload = 20092 liters). The below table show the outcome of this exercise.

Table 3.4: Annual Supply and Demand Volume (Liters) and Delivery Trips Split

	Cities	Allocated Volume-Liters	No. of Truck Loads
Demand	Jeddah	10,407,700	518
	Riyadh	13,786,150	686
	Dammam	6,881,547	343
	Buridah	1,840,462	92
	Khamis	3,495,526	174
	Tabuk	1,749,435	87
Supply	**Cities**	**Allocated Volume-Liters**	**No. of Truck Loads**
	Supplier A (Yanbu)	15,280,061	760
	Supplier B (Jeddah)	11,460,046	570
	Supplier C (Dubai)	7,640,031	380
	Supplier D (Europe)	3,820,016	190

In addition to above, the truck transportation cost between all possible scenarios/combinations were obtained from Company X contracted logistics company and listed in Table 3.5. It is worth to mention that Transportation Costs between cities are based on the local available logistics companies, distance, volume and fleet routes, resulting in non-symmetric prices between cities (i.e. SAR 456 for Jeddah to Riyadh's shipment, SAR 760 for Riyadh to Jeddah's shipment). The existing Company X Lubricants transportation network cost is shown in Table 3.6.

Table 3.5: Transportation Costs (SAR) between Supply and Demand Cities in KSA Network

Cities	Dammam	Riyadh	Jeddah	Yanbu	Tabuk	Buridah	Khamis
Dammam	X	360	1080	1200	1400	600	1200
Riyadh	360	X	760	880	1040	280	880
Jeddah	648	456	X	280	840	680	520
Yanbu	720	528	168	X	520	800	840
Tabuk	1400	1040	840	520	X	800	1320
Buridah	600	280	680	600	800	X	1200
Khamis	1200	880	520	840	1320	1200	X

Hence, the existing Company X Lubricants distribution network costs SR 3,113,384 on annual basis. The blending outsourcing cost is estimated to be SAR 0.17 per liter. Therefore, annual blending outsourcing cost for the current demand level is SAR 6,487,339.40.The total annual supply chain cost is SAR 9,600,723.40.

Table 3.6: Transportation Cost (SAR) Calculation

Source	Destination	No. Truck Loads	Transportation Unit Cost	Total Annual Transportation Cost
APSCO	Riyadh	105	456	47880
	Dammam	343	648	222264
	Khamis	122	520	63440
Fuchs	Riyadh	760	528	401280
MELUBCO	Jeddah	380	3800	1444000
Supplier A (Europe)	Jeddah	190	4200	798000
Jeddah	Khamis	52	390	20280
Riyadh	Buridah	92	280	25760
	Tabuk	87	1040	90480
Current total Transportation Cost (SAR)				3,113,384

3.3 Potential Distribution Center's Cost

As mentioned in the Introduction section, Riyadh, Jeddah, Dammam and Yanbu are potential locations to locate the distribution center(s), if needed. Distribution Center's Cost are estimated through field survey in the four cities. The estimated costs are listed in Table 3.7. Set up cost includes layout, equipment, and systems. Operational cost includes utilities, insurance, license, and labors. Costs are obtained from the company's financial team. Prices uncertainty will be discussed in section 3.7.

Table 3.7: Annual DC’s Cost (SAR) calculation

DC	Annual Rent per m^2	Annual Rent (2000 m^2)	Set up Cost	Annual Operational Cost	Total Annual Cost(SAR)
Riyadh	166	332,000	239,000	385,710	956,710
Jeddah	145	290,000	239,000	385,710	914,710
Dammam	122	244,000	239,000	385,710	868,710
Yanbu	105	210,000	239,000	385,710	834,710

3.4 Potential Lubrication Blending Plant’s Cost

Company X is considering four locations for the potential plant(s). Location determination depends on the plant(s) and sourcing costs.

3.4.1 Lubrication Blending Plant’s cost per region

Lubrication Blending Plant’s cost mainly consists of rent, set up cost, Equipment, Operational and financing cost. The intended potential locations have “Ready Factories” offered by The Saudi Authority for Industrial Cities and Technology Zones, (MODON), which is located in the industrial city of each region considered in the case study. The set-up cost is to modify the factory set up to accommodate the specific operational needs, including piping and instrumentation. Equipment’s are the main cost, including blenders, pigging units, drum decanters, filling lines and thermic fluid heaters. Operational costs include utilities, insurance, license and labors costs. The plant will be financed by local banks with 8 % interest rate. Cost break down for each region is listed in Table 3.8.

Table 3.8: Annual Plant's Cost (SAR) calculation

Plant	Rent	Set Up	Equipment	Operational Cost	Financing Cost	Total Annual Cost
Riyadh	450,000	72,000	2,000,000	1,192,000	297,120	4,011,120
Jeddah	300,000	72,000	2,000,000	1,192,000	285,120	3,849,120
Dammam	180,000	72,000	2,000,000	1,192,000	275,520	3,719,520
Yanbu	150,000	72,000	2,000,000	1,192,000	273,120	3,687,120

3.4.2 Raw Material Sourcing's Cost

Automotive lubricant is produced from base oil and special additives, representing 90% and 10% of the lubricant raw materials respectively. Company X would procure the base oil from Saudi Aramco Base Oil Company (Luberef), located in Yanbu, Saudi Arabia. While, it procures the additives for the automotive lubricant from Europe. Raw material volume and sources are listed in Table 3.9.The raw material transportation cost for a truckload to each plant's potential location is listed in Table 3.10.

Table 3.9: Raw Material Sources and Annual Volume (Liters)

Raw Material	Source	Pick up Location	Volume (Liters)	Volume (Truck Loads)
Lube Oil	Luberef	Yanbu	34,344,735	1,710
Additive	Supplier A (Europe)	Jeddah	3,816,082	190

Table 3.10: Raw Material Transportation Cost (SAR)

Raw Material	Dammam	Riyadh	Jeddah	Yanbu
Lube Oil	720	528	168	0
Additive	4,848	4,656	4,200	4,480
Total Cost	1,132.8	940.8	571.2	448

3.5 Additional Initial Investment

The estimated additional required investment if the company decides to abandon the current outsourcing strategy and establish a blending facility is SAR 3.1 million. It is attributed mainly to technology transfer and marketing.

3.6 Costs Uncertainty

Saudi market is one of the fastest growing markets in the Middle East, resulting in regulations and prices uncertainty. Real states' prices, utilities' prices and Labor market's regulation are subject to high uncertainty levels.

As shown in Figure 3.1, Real states' price index dropped from 94.8 in January 2016 to 80.4 in January 2019 as published by Saudi General Authority for Statistics (2019). The drop is attributed to several economic and political factors. The future performance of the index is uncertain. Some market experts are optimistic and forecasted higher price index due to the positive economic outlook, expected government reforms and demographic demand (FALCOM, 2019). On the other hand, other market experts anticipated further decline due to demand supply imbalance and declining rents as projected by FALCOM (2019). In order to address the uncertainty, future predictions were explored from the accuracy perspective and found that Gross Domestic Product (GDP) has been the most rigorous index. As a result, Real states' price index was examined against Saudi Arabia's GDP in Figure 3.2 Saudi General Authority for Statistics (2019). The correlation coefficient is -0.24, which indicates low correlation based on Raithel (2008). Alternatively, three chief economists in various organizations in Saudi Arabia were interviewed for estimating the subjective uncertainty of real state future predictions. The results are listed in Table 3.11; the average of the expert's estimation is used for this thesis. There are three scenarios considered: Optimistic Scenario, Base Scenario, and Pessimistic Scenario.

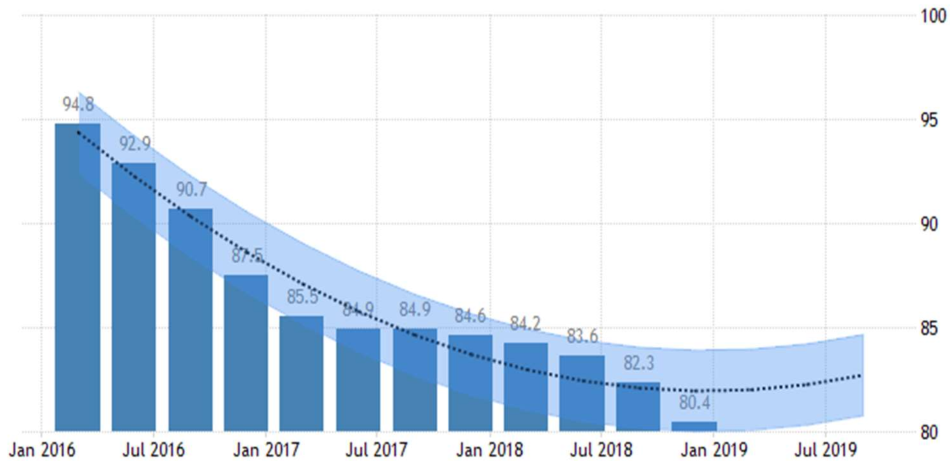

Figure 3.1: Saudi Real states' price index Trend

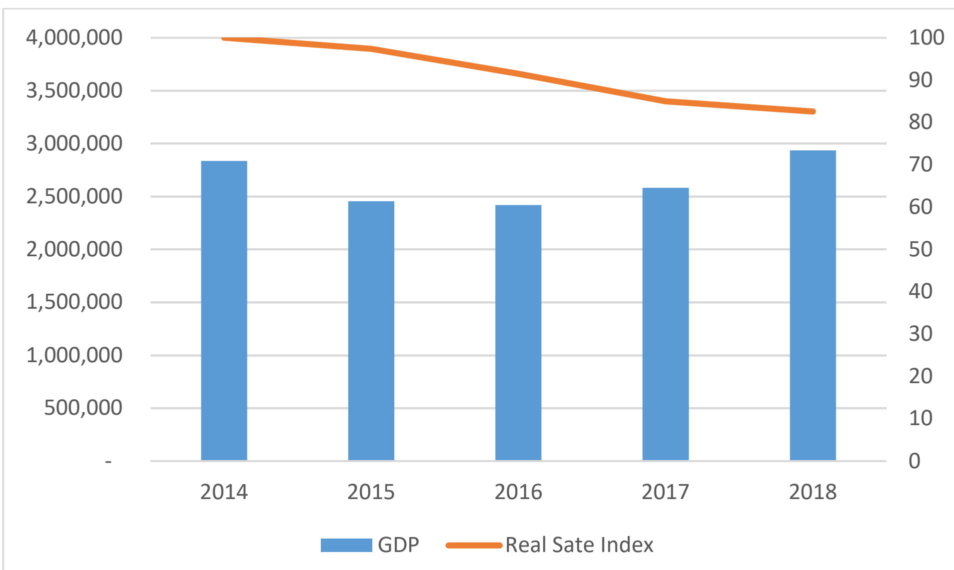

Figure 3.2: GDP (SAR) vs Real State Index

Table 3.11: Real Estate Uncertainty' Estimation

	Optimistic Scenario	Base Scenario	Pessimistic Scenario
	%15 Probability	%70 Probability	%15 Probability
Expert 1	40% Decrease	12 % Increase	15 % Increase
Expert 2	20% Decrease	8 % Increase	25 % Increase
Expert 3	15 % Decrease	18% Increase	27% Increase
Average	25 % Decrease	1.67% Increase	19% Increase

Saudi Energy prices had several reforms during the past few years, as shown in Figure 3.3 (Apicorp research, 2018). The reforms methodology was not published, increasing the uncertainty of future prices. “Fuel prices are reviewed regularly, but there is no intention to increase other energy prices in 2019” Saudi Finance Minister (Reuters, 2019). The statement raised the speculation of the future prices, as the prices are dependent on the country strategy not on the international energy prices. As transportation cost is a crucial element on location models, Oil price was examined against Saudi Arabia’s GDP in Figure 3.4. The correlation coefficient is 0.67, which indicates moderate correlation based on. Alternatively, three chief economists were interviewed for estimating the subjective uncertainty. The results are listed in Table 3.12; the average of the expert’s estimation is used for this thesis.

Product	Unit	2015	2016	Increase	2018	Increase
Natural Gas	($/mmbtu)	0.75	1.25	67%	Unchanged	0
Ethane	($/mmbtu)	0.75	1.75	133%	Unchanged	0%
Gasoline - High Grade	($/litre)	0.16	0.24	50%	0.544	127%
Gasoline - Low Grade	($/litre)	0.12	0.2	67%	0.365	83%
Diesel Transport	($/litre)	0.07	0.12	79%	Unchanged	0%
Diesel Industry	($/barrel)	9.11	14.1	55%	16.15	15%
Arab Light Crude	($/barrel)	4.24	6.35	50%	Unchanged	0%
Arab Heavy Crude	($/barrel)	2.67	4.4	65%	Unchanged	0%
Kerosene	($/barrel)	23.00	25.7	12%	Unchanged	0%

Source: Apicorp research

Figure 3.3: Saudi Energy prices Trend

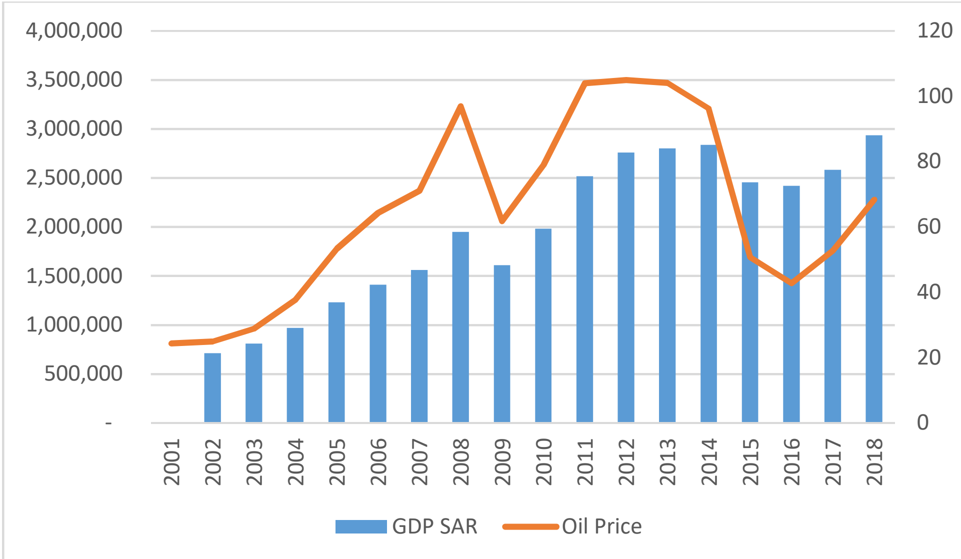

Figure 3.4: GDP vs Oil Price

Table 3.12: Energy Prices uncertainty' estimation

	Optimistic Scenario	Base Scenario	Pessimistic Scenario
	%15 Probability	%70 Probability	%15 Probability
Expert 1	No change	5 % Increase	10 % Increase
Expert 2	No change	10 % Increase	14 % Increase
Expert 3	5 % Decrease	8% Increase	20% Increase
Average	1.67 % Decrease	7.67% Increase	14.67 % Increase

Saudi Labor market had several reforms to nationalize the Labor Market and reduce the unemployment rate. National Transformation Program unemployment target is 9% by 2010, while Ministry of Labor and Social Development's target is 10.5% by 2022 as shown in Figure 3.5 (Jadwa, 2018). Similar inconsistent targets for Saudization targets, which was 100% for 12 retail sectors as announced in January 2018, then reduced to 70% in September 2018 (Argaam, 2018). Expat tax was introduced in 2017 and increases every year until it reached SAR 800 per expat along with expat dependent tax. Many speculations were discussed about the unemployment, as 700,000 expats left the country during 2017, while Saudi unemployment figures actually rose to 12.9 percent (Al-Maeena, 2018). The labor market uncertainty is neither discussed nor included in the location models as it is affecting all the potential locations equally.

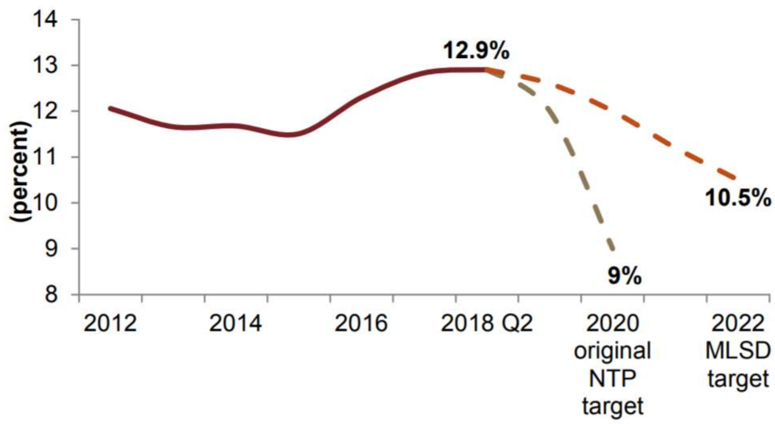

Figure 3.5: Various Official Unemployment Target

CHAPTER 4

DETERMINISTIC MODELS

In this chapter, the problem will be modeled assuming known and deterministic demand with reliable supply. Furthermore, Un–capacitated fixed–charge location model adopted from Snyder & Shen (2011) to find the optimal distribution center(s) “DC”. Snyder & Shen (2011) explained the problem in details. In the beginning, we will consider a single echelon consisting of DC’s supplying the market. Lastly, Mixed Integer Linear Program (MILP) Multi-echelon model is developed to find the optimal location for the production plant(s), distribution center(s) “DC”, optimal plant-DC assignment and DC-Markets assignment. The implementation of mathematical models is done in MILP open solver.

4.1 Un–capacitated fixed–charge location Model

In this section, the problem is considered as an un–capacitated fixed–charge (UFLP) location problem. The model’s assumptions and notations are listed and defined. Then, the problem is described by a mathematical model. Finally, the model is applied to the lubrication company considered in this thesis.

4.1.1 Assumptions

The model is constrained by the following assumptions:

- Supply is reliable
- Demand is both known and deterministic

- Two echelons with DC's and Market
- Demand and supply are considered in annual basis
- Single period
- Single Product
- The market can be supplied by multiple DC's
- The DC's are un-capacitated

4.1.2 Notation

Indices

$\{1, .., J\}$: the set of potential DC's location

$\{1, .., I\}$: The set of markets

Parameters

f_j : Fixed annual cost to have a DC in location j

c_{ij} : Cost to transport one unit of demand from DC in location j to market i

h_i : Market i's Demand

Decision Variables

x_j : equal to 1, if a DC is open in location j, and zero otherwise

y_{ij} : the demand fraction of market's i shipped from DC at location j

4.1.3 Formulation

The first step is to develop the objective function using the above notations. Obviously, the objective function is to minimize the total annual cost.

Total cost = Fixed Cost + Transportation Cost

Fixed Cost $=\sum_{j\in J} f_j x_j$, Transportation Cost = $\sum_{i\in I}\sum_{j\in J} h_i c_{ij} y_{ij}$

Total Cost $= \sum_{j\in J} f_j x_j + \sum_{i\in I}\sum_{j\in J} h_i c_{ij} y_{ij}$

With the following constraints:

$$\sum_{j\in J} y_{ij} = 1, \text{ for all } i \in I \tag{4.1}$$

$$y_{ij} \le x_j, \text{ for all } i \in I, j \in J \tag{4.2}$$

$$y_{ij} \ge 0 \text{ for all } i \in I, j \in J \tag{4.3}$$

$$x_j = 0 \text{ or } 1 \text{ for all } j \in J \tag{4.4}$$

The first constraint is commonly known as assignment constraints, which guarantees that all markets will be fully served. The second constraint is to ensure market are assigned to an open distribution center. The third constraint is non-negativity constraint. The last constraint is binary constraint. The model is shown below:

$$\text{Minimize} \quad \sum_{j\in J} f_j x_j + \sum_{i\in I}\sum_{j\in J} h_i c_{ij} y_{ij} \tag{4.5}$$

$$\text{Subject to} \quad \sum_{j\in J} y_{ij} = 1, \text{ for all } i \in I \tag{4.6}$$

$$y_{ij} \leq x_j, \text{ for all } i \in I, j \in J \tag{4.7}$$

$$y_{ij} \geq 0 \text{ for all } i \in I, j \in J \tag{4.8}$$

$$x_j = 0 \text{ or } 1 \text{ for all } j \in J \tag{4.9}$$

4.1.4 Results

Using MILP open solver, the UFLP result is to open one distribution center at Riyadh out of the four potential DC's locations at Riyadh, Jeddah, Dammam and Yanbu, with the DC-market assignment shown in Table 4.1:

Table 4.1: DC-Markets' allocation (Truck Loads)

		Market					
		Riyadh	Jeddah	Dammam	Buridah	Khamis	Tabuk
DC	Riyadh	686	518	343	92	174	87

The optimal objective function is SAR 1,092,800, with markets' single sourcing from Riyadh's DC. The solution is justified as Riyadh has the highest demand and it is a strategic location as it is in the center of all the markets considered.

4.2 Multi–echelon deterministic Model

In this section, the problem is extended to consider optimal location for the production plant(s), distribution center(s) "DC", optimal plant-DC assignment and DC-Markets assignment (Snyder & Shen, 2011). The model is extended to include the supplier layer in the optimization to be the fourth layer along with plants, distribution centers, and markets layers. The assumptions and notations are listed and defined. Then, the problem is described by a mathematical model. Finally, the model is applied to the lubrication company considered in this thesis.

4.2.1 Assumptions

The model is constrained by the following assumptions:

- Supply is reliable, no stock outs
- Demand is deterministic
- Four echelons with Suppliers, Plants, DC's and Markets
- Demand and supply are considered in annual basis
- Single period
- Single Product
- The markets can be supplied by multiple DC's
- The DC's can be supplied by multiple Plants
- The Plants and DC's are un-capacitated, as the company has not established either yet.

4.2.2 Notations

Indices

$\{1,..,K\}$: the set of potential Plants' location

$\{1,..,J\}$: the set of potential DC's location

$\{1,..,I\}$: The set of markets

Parameters

f_j : Fixed annual cost to have a DC in location j.

g_k : Fixed annual cost to have a Plant in location k.

r_k : Cost to transport one unit of raw material to plant k (see Table 3.8)

c_{ij} : Cost to transport one unit of demand from DC in location j to market i

d_{jk} : Cost to transport one unit of demand from plant in location k to DC at location j

h_i : Market's i annual demand

M :Big number

Decision Variables

x_j : equal to 1, if a DC is opened in location j, and zero otherwise

z_k : equal to 1, if a plant is opened at location k, and zero otherwise

y_{ij} : the fraction of Market's i demand shipped from DC at location j

w_{jk} : the fraction of DC's j demand shipped from plant at location k

4.2.3 Formulation

The first step is to develop the objective function using the above notations. Obviously, the objective function is to minimize the annual total cost.

Total cost = Fixed Cost + Transportation Cost + Raw material procurement Cost

Fixed Cost $= \sum_{j \in J} f_j x_j + \sum_{k \in K} g_k z_k$,

Transportation Cost = $\sum_{j \in J} \sum_{k \in K} r_k w_{jk} + \sum_{j \in J} \sum_{i \in I} c_{ij} y_{ij} + \sum_{k \in K} \sum_{j \in J} d_{jk} w_{jk}$

$$\text{Total Cost} = \sum_{j \in J} f_j x_j + \sum_{k \in K} g_k z_k + \sum_{j \in J} \sum_{k \in K} r_k w_{jk} + \sum_{j \in J} \sum_{i \in I} c_{ij} y_{ij} + \sum_{k \in K} \sum_{j \in J} d_{jk} w_{jk}$$

With the following constraints:

$$\sum_{j \in J} y_{ij} = h_i, \text{ for all } i \in I \tag{4.10}$$

$$\sum_{k \in K} w_{jk} = \sum_{i \in I} y_{ij}, \text{ for all } j \in J \tag{4.11}$$

$$\sum_{j \in J} w_{jk} \leq M z_k, \text{ for all } k \in K \tag{4.12}$$

$$\sum_{i \in I} y_{ij} \leq M x_j, \text{ for all } j \in J \tag{4.13}$$

$$y_{ij} \geq 0 \text{ for all } i \in I, j \in J \tag{4.14}$$

$$w_{jk} \geq 0 \text{ for all } j \in J, k \in K \tag{4.15}$$

$$x_j = 0 \text{ or } 1 \text{ for all } j \in J \tag{4.16}$$

$$z_k = 0 \text{ or } 1 \text{ for all } k \in K \tag{4.17}$$

The first constraint is commonly known as assignment constraints, which guarantees that all markets will be fully served. The second constraint is to ensure that the supply and demand for the distribution center is the same. The following two constraints are to ensure markets and DCs are assigned to opened DCs and plants. Constraints (4.14) and (4.15) are to ensure non-negative for DC's and plant's assignments. The last two constraints are binary for opening plants or DCs.

The mathematical model is shown below:

Minimize $$\sum_{j\in J} f_j x_j + \sum_{k\in K} g_k z_k + \sum_{j\in J}\sum_{k\in K} r_k w_{jk} + \sum_{j\in J}\sum_{i\in I} c_{ij} y_{ij} + \sum_{k\in K}\sum_{j\in J} d_{jk} w_{jk} \qquad (4.18)$$

Subject to $$\sum_{j\in J} y_{ij} = h_i, \text{ for all } i \in I \qquad (4.19)$$

$$\sum_{k\in K} w_{jk} = \sum_{i\in I} y_{ij}, \text{ for all } j \in J \qquad (4.20)$$

$$\sum_{j\in J} w_{jk} \leq Mz_k, \text{ for all } k \in K \qquad (4.21)$$

$$\sum_{i\in I} y_{ij} \leq Mx_j, \text{ for all } j \in J \qquad (4.22)$$

$$y_{ij} \geq 0 \text{ for all } i \in I, j \in J \qquad (4.23)$$

$$w_{jk} \geq 0 \text{ for all } j \in J, k \in K \qquad (4.24)$$

$$x_j = 0 \text{ or } 1 \text{ for all } j \in J \qquad (4.25)$$

$$z_k = 0 \text{ or } 1 \text{ for all } k \in K \qquad (4.26)$$

4.2.4 Results

Using MILP open solver, the result is to open one plant at Yanbu out of the four potential Plant's locations at Riyadh, Jeddah, Dammam and Yanbu, and one distribution center at Yanbu out of the four potential DC's locations at Riyadh, Jeddah, Dammam and Yanbu, with the DC-market assignment shown in Table 4.2:

Table 4.2: DC-Markets' allocation (Truck Loads)

		Market					
		Riyadh	Jeddah	Dammam	Buridah	Khamis	Tabuk
DC	Yanbu	686	518	343	92	174	87

The optimal objective function is SAR 6,391,222 annually; the cost is mainly attributed to plant fixed cost of SAR 3.687 million, which is 58% of the total cost.

4.3 Conclusion

In this chapter, two deterministic models were developed to address the location problem. The first model objective is to select the optimal DC location only. The solution was to open a DC in Riyadh with optimal objective function value of SAR 1,092,800. While the second model objective is to select the optimal location for the production plant(s), distribution center(s) “DC”, optimal plant-DC assignment and DC-Markets assignment. The optimal plant location is Yanbu and optimal DC location is Yanbu, which serves as the single source to all the markets.

CHAPTER 5

MODELS WITH UNCERTAINTY

In this chapter, the problem is modeled assuming stochastic demand with reliable supply. Furthermore, Location Model with Risk Pooling (LMRP) is utilized to find the optimal distribution center(s) "DC" location with known plant(s) supplying the distribution center as discussed by Snyder et al. (2011). Then, Multi-echelon model is developed to find the optimal location for the production plant(s), distribution center(s) "DC", optimal plant-DC assignment and DC-Markets assignment with known and stochastic demand with robust supply. Finally, the model is extended to include land price, energy price uncertainty, these lead to uncertain set-up fixed cost and transportation cost. The numerical results are conducted using MS Excel/open solver and the optimal results are shown in detail.

5.1 Location Model with Risk Pooling (LMRP)

In this section, the problem is considered as a Location Model with Risk Pooling (LMRP) adopted from Snyder & Shen (2011). The assumptions and notations used by the model are listed and defined. Then, the problem is described mathematically. Finally, the model is applied to the lubrication company.

5.1.1 Assumptions

The model is constrained by the following assumptions:

- Supply is reliable, no stock outs
- Demand is stochastic with known distribution
- Three echelons with Plant, DC's and Market
- Demand and supply are considered on daily basis
- DC's has continuous review (r,Q) inventory policy, where r is the reorder point and Q is the order quantity
- Single period
- Single Product
- The markets can be supplied by single DC's
- Single sourcing policy for the DC's
- The DC's are un-capacitated

5.1.2 Notations

Indices

{1,.., J}: the set of potential DC's location

{1,.., I}: The set of markets

Parameters

f_j: fixed daily cost to open a DC at site j

K_j: fixed cost for DC at location j to place an order from plant

c_j: cost/unit for items ordered by DC j from the plant

h_j: holding cost/unit/day at DC j

L_j: lead time for orders placed by DC j to the plant in days

d_{ij}: outbound transportation cost/unit from DC j to market i

μ_i: mean daily market demand at market i

σ_i^2: daily market demand variance at market i

α: desired service level, the fraction of DC order cycles during which no stock out occurs

Decision Variables

x_j: equal to 1, if a DC in set in location j and zero otherwise

y_{ij}: equal to 1, if market i is served by DC j and zero otherwise

5.1.3 Formulation

The first step is to develop the objective function using the above notations. Obviously, the objective function is to minimize the total cost.

Total cost = Fixed Cost + Purchase and transportation cost from the plant+ Transportation cost from DCs to markets + Cycle cost+ Safety stock cost, as mentioned in Nahmias, S. (2009) as following:

Fixed Cost $=\sum_{j\in J} f_j x_j$,

Purchase and transportation cost from the plant $=\sum_{j\in I} c_j \sum_{i\in I} \mu_i y_{ij}$,

Transportation cost from DCs to market: $\sum_{j\in J} \sum_{i\in I} \mu_i d_{ij} y_{ij}$

Cycle cost: $\sqrt{2K_j D_j h_j}$,where $D_j = \sum_{i \in I} \mu_i y_{ij}$

Safety stock cost: $h_j z_\alpha \sqrt{L_j \sum_{i \in I} \sigma_i^2 y_{ij}}$

Total Cost: $\sum_{j \in I} \left[f_j x_j + \sum_{i \in I} \mu_i (c_j + d_{ij}) y_{ij} + \sqrt{2K_j h_j \sum_{i \in I} \mu_i y_{ij}} + h_j z_\alpha \sqrt{L_j \sum_{i \in I} \sigma_i^2 y_{ij}} \right]$

With the following constraints:

$$\sum_{j \in I} y_{ij} = 1, \quad \text{for all } i \in I \tag{5.1}$$

$$y_{ij} \le x_j, \text{ for all } i \in I, j \in I \tag{5.2}$$

$$y_{ij}, x_j = 0 \text{ or } 1, \text{ for all } i \in I, j \in I \tag{5.3}$$

The first constraint is known as assignment constraints, which guarantees that all market will be served. The second constraint is to ensure market are assigned to an open distribution center only. The third constraint is non-negative constraint. The last constraint is binary constraint. The model is shown below:

$$\text{Minimize } \sum_{j \in I} \left[f_j x_j + \sum_{i \in I} \mu_i (c_j + d_{ij}) y_{ij} + \sqrt{2K_j h_j \sum_{i \in I} \mu_i y_{ij}} + h_j z_\alpha \sqrt{L_j \sum_{i \in I} \sigma_i^2 y_{ij}} \right] \tag{5.4}$$

$$\text{Subject to} \quad \sum_{j \in I} y_{ij} = 1 \quad \text{for all } i \in I \tag{5.5}$$

$$y_{ij} \le x_j, \quad \text{for all } i \in I, j \in I \tag{5.6}$$

$$y_{ij}, x_j = 0 \text{ or } 1, \text{ for all } i \in I, j \in I \tag{5.7}$$

5.1.4 Solution Technique

The Location Model with Risk Pooling (LMRP) is a non-linear integer program (NLIP) problem. Many solution techniques and algorithms were discussed in the literature, such as Set Covering algorithm and Lagrangian relaxation. Based on the problem structure, Shen et al. (2003) proposed a Set Covering algorithm to solve the NLIP problem. Set covering concept is used to enumerate all possible combinations and select the lowest cost.

5.1.4.1Notation

$\mathscr{R}$: The collection of all possible combinations (Subsets) of DC locations

R :Single subset of $\mathcal{R}$

<u>*Decision Variable:*</u>

$c_{R,j}$:Cost of serving all the market in R from DC located at j

z_R:equal 1 if set R is selected and zero otherwise

5.1.4.2Formulation

The first step is to develop the objective function using the above notations. Obviously, the objective function is to minimize the total cost.

We need to include the cost for each market, in a subset $R \in \mathscr{R}$ and for each market j ∈ $\mathscr{R}$. Let $c_{R,j}$ be the cost of establishing the DC and serving all the markets in the subset R is as following:

$$c_{R,j} = f_j + \sum_{i \in R} \mu_i (c_j + d_{ij}) + \sqrt{2K_j h_j \sum_{i \in R} \mu_i} + h_j z_\alpha \sqrt{L_j \sum_{i \in R} \sigma_i^2} \qquad (5.8)$$

After enumerating all subsets, the DC with lowest will be selected: $c_R = \min_{j \in R}\{c_{R,j}\}$

Total cost: $\sum_{\forall R} c_R z_R$

With the following constraints:

$$\sum_{\forall R\,:\, i \in R} z_R \geq 1 \;\; \textit{for all}\, i \in I \tag{5.9}$$

The constraint is known as assignment constraints, which guarantees that all market will be served. The model is shown below:

$$\text{Minimize} \qquad \sum_{\forall R} c_R z_R \tag{5.10}$$

$$\text{Subject to} \qquad \sum_{\forall R\,:\, i \in R} z_R \geq 1 \;\; \text{for all } i \in I \tag{5.11}$$

$$z_R \in \{0,1\}, \qquad \text{for all } R \in \mathcal{R} \tag{5.12}$$

All possible sets R ∈ $\mathscr{R}$ are enumerated, which are in market 1,2,3 and 4, namely Riyadh, Jeddah, Dammam and Yanbu. Other market in Buridah, Khamis and Tabuk are not allowed to open a DC as per the lubrication company management, due to the low demand in these markets. The result is 105 subsets. Enumeration technique is used to solve the model, due to the small size of possible sets. Otherwise, the column generation could be used for larger problems. The plant location had been previously determined to be in Yanbu in section 4.2.

5.1.4.3 Results

Using set covering, the result is to open one distribution center at Yanbu out of the four potential DC's locations at Riyadh, Jeddah, Dammam and Yanbu. The optimal objective function is SAR 5080.4 daily and SAR 1,854,355 annually, with markets' single sourcing from Yanbu's DC. While the deterministic model to select the optimal

DC location was in Riyadh with a cost of SAR 1,092,800. The cost of considering the demand uncertainty is SAR 761,555. This shows that the demand uncertainty has a large impact on the optimal supply chain cost and location.

5.1.4.4 Sensitivity Analysis

The model is tested for several demand growth and decline levels for both of the mean and standard deviation of the demand to test the result's sensitivity. The analysis is conducted in Table 5.1 below. The DC location at Yanbu is optimal under any demand reduction and for any demand growth up to 1900%, where opening another DC at Jeddah would be optimal. Figure 5.1 shows several Demand scenario annual costs.

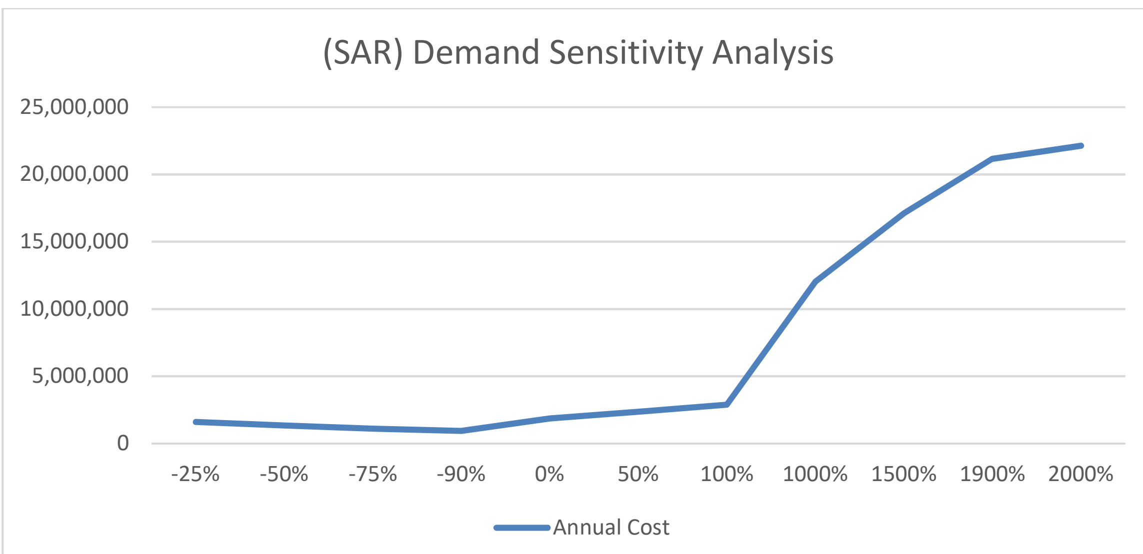

Figure 5.1: LMRP Sensitivity Analysis

Table 5.1: LMRP Sensitivity Analysis

Trend	Demand Scenarios	DC's Opened				Total Annual Cost
		Riyadh	Jeddah	Dammam	Yanbu	
Steady	Base Case Scenario				√	1,854,355
Growth	50%				√	2,363,612
	100%				√	2,872,797
	1000%				√	12,035,023
	1500%				√	17,124,381
	1900%		√		√	21,174,944
	2000%		√		√	22,145,771
Decline	25%				√	1,599,682
	50%				√	1,344,958
	75%				√	1,090,135
	90%				√	937,119

5.2 Multi–echelon stochastic Model

In this section, the problem is extended to consider optimal location for the production plant(s), distribution center(s) “DC”, optimal plant-DC assignment and DC-Markets assignment by extending (S. Park et al., 2010) model to include the supplier layer. The assumptions and notations used by the model will be listed and defined. Then, a mathematical model will describe the problem. The numerical results are conducted using MS Excel/open solver and the optimal results are shown in detail.

5.2.1 Assumptions

The model is constrained by the following assumptions:

- Supply is reliable, no stock outs
- Demand is stochastic with known distribution
- Four echelons with Supplier, Plant, DC’s and Market
- Demand and supply are considered on daily basis
- DC’s has continuous review (r,Q) inventory policy, where r is the reorder point and Q is the order quantity
- Single period
- Single Product
- The markets can be supplied by single DC’s
- The DC’s can be supplied by single plants
- The DC’s are un-capacitated
- DC’s hold safety stock levels
- Plants do not hold finished goods stock

5.2.2 Notations

Indices

{1,..,K} : the set of potential Plants' location

{1,..,J} : the set of potential DC's location

{1,..,I} : The set of markets

Parameters

f_j *: Fixed annual cost to have a DC in location j*

g_k *: Fixed annual cost to have a Plant in location k*

r_k *: Cost to transport one unit of raw material to plant k*

c_{ij} *: Cost to transport one unit of demand from DC in location j to market i*

d_{jk} : Cost to transport one unit of demand from plant in location k to DC at location j

A_j *: Fixed inventory ordering cost at DC j*

h_j *: per unit per year inventory holding cost at DC j*

B_j *: daily throughput capacity for DC j*

μ_i *:mean daily market demand at market i*

σ^2_i *:variance of daily market demand at market i*

l_{jk} *:order lead time in days from plant k to DC j*

X *:number of working days per year*

<u>*Decision Variables*</u>

x_j : equal to 1, if a DC is set in location j, and zero otherwise

z_k : equal to 1, if a plant is built at location k, and zero otherwise

y_{ij} : equal to 1, if a market at location i assigned to DC at location j, and zero otherwise

w_{jk} : equal to 1, if a DC at location j assigned to plant at location k, and zero otherwise

Q_j : order quantity from DC j

r_j reorder level at DC j

SS_j safety stock level at DC j

5.2.3 Formulation

The model is using (r, Q) policy. The optimal ordering quantity at each DC is approximately derived as

$$Q_j{}^* = \sqrt{2A_j \chi d \sum_i \mu_i y_{ij} / h_j} \tag{5.13}$$

Moreover, the optimal reorder level can be derived as

$$r_j = D_j L_j + Z_\alpha \sqrt{\Gamma_j L_j} \tag{5.14}$$

The optimal safety stock level at each DC can be derived as

$$SS_j = Z_\alpha \sqrt{\Gamma_j L_j} = Z_\alpha \sqrt{\sum_i \sigma^2{}_i y_{ij} . \sum_k l_{jk} y_{ij} w_{jk}} \tag{5.15}$$

The optimal inventory cost function at each DC is derived as

$$C_j^{INV*} = \sqrt{2A_j h_j \chi D_j} + h_j Z_\alpha \sqrt{\Gamma_j L_j} = \sqrt{2A_j h_j \chi \sum_i \mu_i y_{ij}} + Z_\alpha h_j \sqrt{\sum_i \sum_k \sigma^2{}_i l_{jk} y_{ij} w_{jk}} \tag{5.16}$$

The total annual cost in the whole supply chain network can be derived as

$$\begin{aligned} TC(x,y,z) = {} & \sum_k g_k z_k + \sum_k \sum_j r_k w_{jk} + \sum_j F_j x_j + \sum_i \sum_j \sum_k \chi \mu_i d_{jk} y_{ij} w_{jk} + \\ & \sum_i \sum_j \chi \mu_i c_{ij} y_{ij} + \sum_j \sqrt{2A_j h_j \chi \sum_i \mu_i y_{ij}} + Z_\alpha h_j \sqrt{\sum_i \sum_k \sigma^2{}_i l_{jk} y_{ij} w_{jk}} \end{aligned} \tag{5.17}$$

Where the first term is the fixed annual plant costs. The second term is the plant's raw material sourcing cost. The third is the DC setup costs. The fourth and fifth terms represent the inbound and outbound network transportation costs, respectively, and the last two terms indicate the average inventory holding and ordering cost at DC's, respectively.

The mathematical model:

Minimize

$$\begin{aligned} TC(x,y,z) = {} & \sum_k g_k z_k + \sum_k \sum_j r_k w_{jk} + \sum_j F_j x_j + \sum_i \sum_j \sum_k \chi \mu_i d_{jk} y_{ij} w_{jk} + \\ & \sum_i \sum_j \chi \mu_i c_{ij} y_{ij} + \sum_j \sqrt{2A_j h_j \chi \sum_i \mu_i y_{ij}} + Z_\alpha h_j \sqrt{\sum_i \sum_k \sigma^2{}_i l_{jk} y_{ij} w_{jk}} \end{aligned} \tag{5.18}$$

Subject to $\sum_j y_{ij} = 1, \forall i$ (5.19)

$$y_{ij} \le \sum_k w_{jk}, \forall i, j \tag{5.20}$$

$$\sum_{i} \mu_i y_{ij} \leq B_j x_{j,}, \forall j \tag{5.21}$$

$$\sum_{k} w_{jk} \leq 1, \forall j \tag{5.22}$$

$$w_{jk} \leq z_k, \forall j, k \tag{5.23}$$

$$x_{j,} y_{ij}, w_{jk}, z_k \in \{0,1\}, \forall i, j, k. \tag{5.24}$$

The first constraint represents the single sourcing for the DC. The second and fifth constraints ensures that opened DC's serve markets and DC's are served by open plants. The third constrained is due to the DC's capacity. The fourth constraint represents DC single sourcing.

5.2.4 Solution Technique & Results

The problem is solved using set covering algorithm and using open solver, the result is to open one plant at Yanbu out of the four potential plants' locations at Riyadh, Jeddah, Dammam and Yanbu and one distribution center at Yanbu out of the four potential DC's locations at Riyadh, Jeddah, Dammam and Yanbu. The optimal objective function is SAR 6,711,870 annually, with markets' single sourcing from Yanbu's DC. The model has the same supply chain for the multi-echelon deterministic model in section 4.2, which objective function optimal value is SAR 6,391,222. The cost of considering demand uncertainty is SAR 320,674.

5.3 Multi-echelon demand stochastic model with price uncertainty

In this section, the multi-echelon demand stochastic model in section 5.2 is extended to include land price, energy price uncertainty, leading to uncertain set-up fixed cost and transportation cost. The assumptions and notations used in the model will be listed and defined. Then, a mathematical model will describe the problem. The numerical results are conducted using MS Excel/open solver and the optimal results are shown in detail.

5.3.1 Assumptions

The model is constrained by the following assumptions:

- Supply is reliable, no stock outs
- Demand is stochastic with known distribution
- Fixed costs are uncertain, based on section 3.6 scenarios
- Transportation costs are uncertain, based on section 3.6 scenarios
- Four echelons with Supplier, Plant, DC's and Market
- Demand and supply are considered on daily basis
- (r,Q) Inventory Policy
- Single period
- Single Product
- The markets can be supplied by single DC's
- The DC's can be supplied by single plants
- The DC's are un-capacitated
- DC's hold safety stock levels

- Plants do not hold finished goods stock

5.3.2 Notations

Indices

{1,.., K}: the set of potential Plants' location

{1,.., J}: the set of potential DC's location

{1,.., I}: The set of markets

{1,..,S}: The set of scenarios

Parameters

q_s : *Probability of scenario q happens.*

f_{js} : *Fixed annual cost to have a DC in location j in scenario s*

g_{ks} : *Fixed annual cost to have a Plant in location k in scenario s*

r_{ks} : *Cost to transport one unit of raw material to plant k in scenario s*

c_{ijs} : *Cost to transport one unit of demand from DC in location j to market I in scenario s*

d_{jks} : *Cost to transport one unit of demand from plant in location k to DC at location j in scenario s*

A_{js} : *Fixed inventory ordering cost at DC j*

h_{js} : *per unit per year inventory holding cost at DC j*

B_j : *daily throughput capacity for DC j*

μ_i *:mean daily market demand at market i*

σ^2_i *:variance of daily market demand at market i*

l_{jks} *:order lead time in days from plant k to DC j*

X *:number of working days per year*

<u>*Decision Variables*</u>

x_j : equal to 1, if a DC is set in location j, and zero otherwise

z_k : equal to 1, if a plant is built at location k, and zero otherwise

y_{ij} : equal to 1, if a market at location i assigned to DC at location j, and zero otherwise

w_{jk} : equal to 1, if a DC at location j assigned to plant at location k, and zero otherwise

Q_j : order quantity from DC j

r_j reorder level at DC j

SS_j safety stock level at DC j

5.3.3 Formulation

The total annual cost in the whole supply chain network for each scenario (s) can be derived as

$$TC_s(x,y,z) = \sum_k g_{ks} z_k + \sum_k \sum_j r_{ks} w_{jk} + \sum_j F_{js} x_j + \sum_i \sum_j \sum_k \chi \mu_i d_{jks} y_{ij} w_{jk} + \sum_i \sum_j \chi \mu_i c_{ijs} y_{ij} + \sum_j \sqrt{2 A_{js} h_{js} \chi \sum_i \mu_i y_{ij}} + Z_\alpha h_{js} \sqrt{\sum_i \sum_k \sigma^2{}_i l_{jks} y_{ij} w_{jk}} \tag{5.25}$$

The total cost is extended from the model developed in section 5.2, to include price uncertainty, by considering the three scenarios suggested by the experts as described in section 3.6. Each scenario has its own prices. The model objective to find the most robust supply chain design against all the scenarios.

The mathematical model:

Minimize
$$\sum_s q_s [\sum_k g_{ks} z_k + \sum_k \sum_j r_{ks} w_{jk} + \sum_j F_{js} x_j + \sum_i \sum_j \sum_k \chi \mu_i d_{jks} y_{ij} w_{jk} + \sum_i \sum_j \chi \mu_i c_{ijs} y_{ij} + \sum_j \sqrt{2 A_{js} h_{js} \chi \sum_i \mu_i y_{ij}} + Z_\alpha h_{js} \sqrt{\sum_i \sum_k \sigma^2{}_i l_{jks} y_{ij} w_{jk}}] \tag{5.26}$$

Subject to $\sum_j y_{ij} = 1, \forall i$ (5.27)

$$y_{ij} \le \sum_k w_{jk}, \forall i, j \tag{5.28}$$

$$\sum_i \mu_i y_{ij} \le B_j x_{j,}, \forall j \tag{5.29}$$

$$\sum_k w_{jk} \le 1, \forall j \tag{5.30}$$

$$w_{jk} \le z_k, \forall j, k \tag{5.31}$$

$$x_{j,} y_{ij}, w_{jk}, z_k \in \{0,1\}, \forall i, j, k. \tag{5.32}$$

The first constraint represents the single sourcing for the DC. The second and fifth constraints ensures that opened DC's serve markets and open plants serve DC's. The third constrained is for the DC's capacity. The fourth constraint represents markets' single sourcing.

5.3.4 Solution Technique & Result

The problem is solved using set covering algorithm and using open solver, the result is to open one plant at Yanbu out of the four potential plants' locations at Riyadh, Jeddah, Dammam and Yanbu and one distribution center at Yanbu out of the four potential DC's locations at Riyadh, Jeddah, Dammam and Yanbu. The optimal objective function is SAR 6,783,220.72 annually, with markets' single sourcing from Yanbu's DC. The model has the same supply chain design of the multi-echelon deterministic model in section 4.2, and the multi-echelon demand stochastic model in section 5.2. The cost of considering price uncertainty is only SAR 71,350.

5.3.5 Sensitivity Analysis

The model is tested for the expected scenario when Saudi Arabia achieve the 2030 vision goal of diversifying the economy and attracting foreign industrial companies, where the land prices in the industrial cities would increase dramatically. In this case, Jeddah would be the optimal solution for the scenario with a total cost of SAR 7,045,322.28.

CHAPTER 6

MULTI-CRITERIA WAREHOUSING STRATEGY SELECTION

As company X is trying to capture higher Saudi lubricant's market share by redesigning its supply chain network, the company is evaluating the regional retail/warehouse' branches strategy, which is company-managed branches. The company has main six regional retail/warehouse' branches: Riyadh, Jeddah, Dammam, Buridah, Khamis Mushait and Tabuk. However, the company would like to select a retail/warehouse's strategy to fit each city's profile. The company has identified the following retail/warehouse' strategies:

- Company-managed (CM) retail/warehouse branch: Company X operates the branch.
- Premium outsourced retail/warehouse branch: High-end experienced outsourcing company operates the branch
- Standard outsourced retail/warehouse branch: standard outsourcing company operates the branch
- 3rd Party Logistic (3PL): allocated space at 3PL is rented by company X as a regional distributer
- Satellite warehouse: Company X supplies Regional demand by hauling the products from Company X's distribution center (DC).

Each warehousing strategy if selected would have its own financial, operational, and risk implications that might be too complex to determine. Rosaria et al. (2015) reviewed the literature of criteria in AHP and discussed that the experts in the field are one of the common sources of AHP's criteria. Therefore, the supply chain head was interviewed. Five main criteria were endorsed, and those will be used to decide on which warehousing strategy to select in each city. The company identified the five criteria as follow:

- Initial Investment: the money invested to set up the warehousing strategy (depending on the type, the investment may include infrastructure, and other fixed costs).
- Operating Cost: the expenses incurred to run and operate the selected setup such as labor, material, utility cost, and other.
- Health, Safety, Security and Environment (HSSE): there is no exact value for a given type however this is more related to the company's assessment of the warehousing strategy in a given.
- Responsiveness: this is also a subjective indication of the level of market requests fulfillment as assessed by the company.
- Brand Image: the degree by which each warehousing strategy will support Company X Brand to maximize the overall company's returns.

To decide on the selected type for a given city, it might be quite cumbersome to find the trade-off between one criterion and the other. For example, what Responsiveness level could be achieved under one setup and what is associated operating cost to increase from one level to the other? Such conflicting subjective criteria might be better assessed using a multi-criteria decision-making approach such as the Analytic Hierarchy Process (AHP). AHP approach is commonly used to determine the best alternative in complex problems with conflicting criteria.

6.1 AHP Methodology

The procedure that will be followed for each city is divided into 4 steps, which are as follow:

1) Structure the decision-making problem by identifying all criteria and alternatives. This established in Figure 6.1.
2) Determine the criteria and alternative ranking using pairwise comparison using the scale proposed by Saaty (1980), shown in Table 6.1:
3) Determine the normalized priorities by normalization for each criteria and sub-criteria.
4) Calculate the overall priority of each alternative. This accomplished by multiplying the weight of each criterion by the score of each alternative under that criterion. Then, adding the results for each alternative to determine the total priority. The alternative with the highest priorities will be selected.
5) Ensure the consistency ratio is under 0.1. Otherwise, the decision maker judgment should be reconsidered.

For the problem considered here, we have five retail/warehousing strategies and five criteria. Therefore, there 6 pairwise comparison matrices for each city in total: one for the criteria with the respect to each other, and 5 pair-wise matrices comparing all 5 alternatives with respect to each criterion. For every pair-wise matrix, the consistency ratio was calculated to ensure the respective matrix is consistent (i.e., the consistency ratio does not exceed 0.1).

Table 6.1: Saaty Scale

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	Experience and judgement slightly favor one activity over another
3	Moderate importance	
4	Moderate plus	Experience and judgement strongly favor one activity over another
5	Strong importance	
6	Strong plus	An activity is favored very strongly over another; its dominance demonstrated in practice
7	Very strong or demonstrated importance	
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

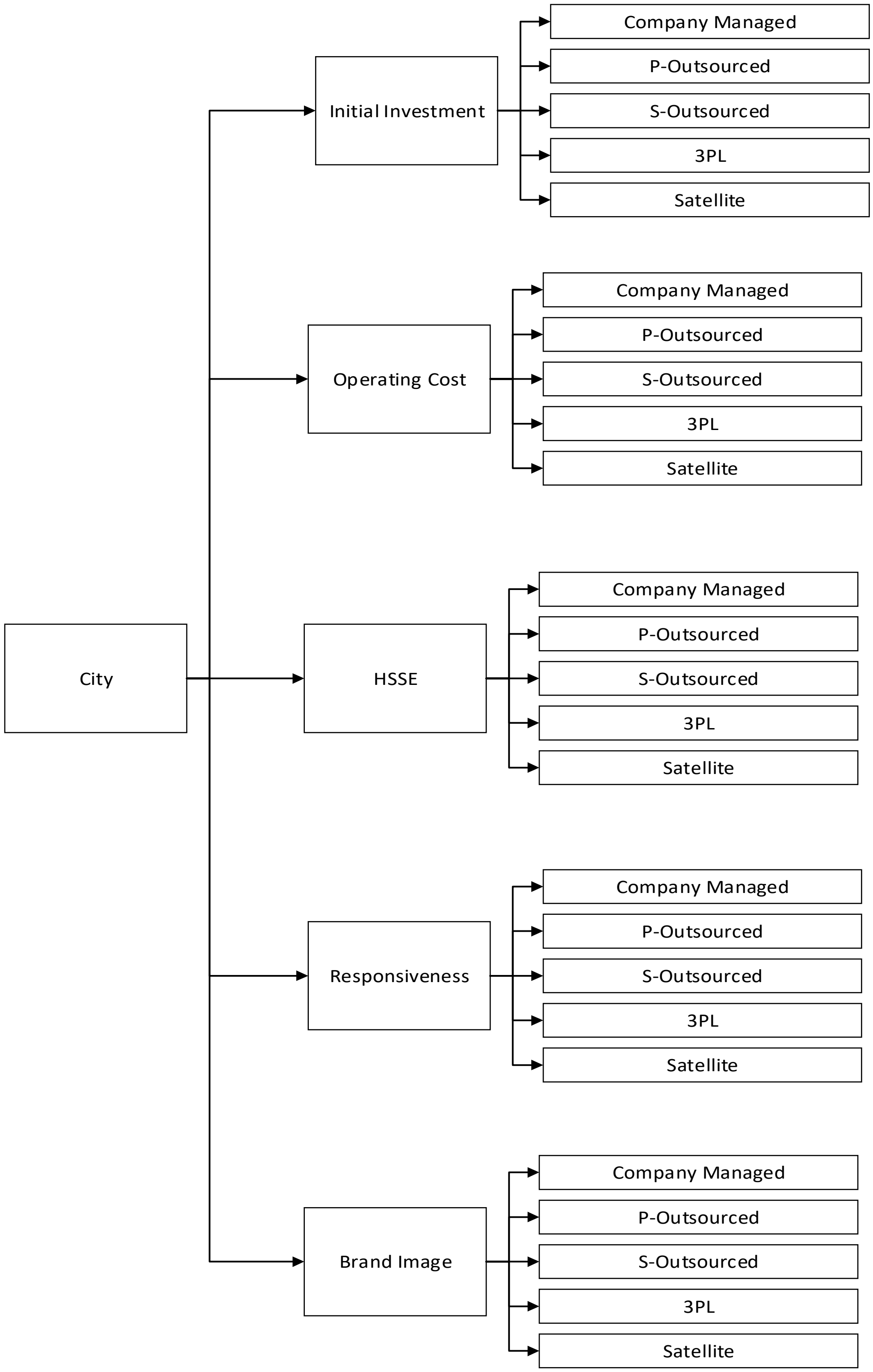

Figure 6.1: Warehousing Strategy Selection Criteria and Alternatives

6.2 AHP Results

After multiple workshop with the Supply Chain Director at the company, the criteria weights were determine as shown in Table 6.2. These weights will be used for each city, which leaves only five pair-wise comparisons to be done for each warehousing strategy in each city. Table 6.3-6.8 summarize the results of AHP for each city.

Table 6.2: Criteria Pair-wise comparison matrix Scale

Criteria	Initial Investment	Operating Cost	HSSE	Responsiveness	Brand Image	Normalized Weight
Initial Investment	1	2	7	1	1/2	0.235
Operating Cost	1/2	1	5	1/2	1/3	0.150
HSSE	1/7	1/5	1	1/7	1/9	0.033
Responsiveness	1	2	7	1	1/2	0.235
Brand Image	2	3	9	2	1	0.347
Consistency Ratio						0.018

Table 6.3: Riyadh AHP Results

Riyadh AHP						
Criteria	Weights	Alternatives Ranking				
		Company Branch	P-Outsourced Branch	S-Outsourced Branch	3PL	Satellite Branch
Initial Investment	0.235	0.093	0.048	0.180	0.265	0.414
Operating Cost	0.150	0.136	0.069	0.267	0.393	0.136
HSSE	0.033	0.278	0.453	0.159	0.055	0.055
Responsiveness	0.235	0.283	0.438	0.177	0.036	0.067
Brand Image	0.347	0.357	0.357	0.161	0.048	0.077
Overall priority for each warehouse type		0.242	0.263	0.185	0.148	0.162

Table 6.4: Jeddah AHP Results

Jeddah AHP						
Criteria	Weights	Alternatives Ranking				
		Company Branch	P-Outsourced Branch	S-Outsourced Branch	3PL	Satellite Branch
Initial Investment	0.235	0.093	0.048	0.180	0.265	0.414
Operating Cost	0.150	0.136	0.069	0.267	0.393	0.136
HSSE	0.033	0.278	0.453	0.159	0.055	0.055
Responsiveness	0.235	0.283	0.438	0.177	0.036	0.067
Brand Image	0.347	0.357	0.357	0.161	0.048	0.077
Overall priority for each warehouse type		0.242	0.263	0.185	0.148	0.162

Table 6.5: Dammam AHP Results

Dammam AHP						
Criteria	Weights	Alternatives Ranking				
		Company Branch	P-Outsourced Branch	S-Outsourced Branch	3PL	Satellite Branch
Initial Investment	0.235	0.093	0.048	0.180	0.265	0.414
Operating Cost	0.150	0.136	0.069	0.267	0.393	0.136
HSSE	0.033	0.278	0.453	0.159	0.055	0.055
Responsiveness	0.235	0.283	0.438	0.177	0.036	0.067
Brand Image	0.347	0.357	0.357	0.161	0.048	0.077
Overall priority for each warehouse type		0.242	0.263	0.185	0.148	0.162

Table 6.6: Buridah AHP Results

Buridah AHP						
Criteria	Weights	Alternatives Ranking				
		Company Branch	P-Outsourced Branch	S-Outsourced Branch	3PL	Satellite Branch
Initial Investment	0.306	0.132	0.034	0.158	0.272	0.403
Operating Cost	0.182	0.136	0.069	0.267	0.393	0.136
HSSE	0.036	0.278	0.453	0.159	0.055	0.055
Responsiveness	0.068	0.296	0.431	0.171	0.035	0.066
Brand Image	0.408	0.357	0.357	0.161	0.048	0.077
Overall priority for each warehouse type	0.241		0.214	0.180	0.179	0.186

Table 6.7: Khamis AHP Results

Khamis AHP						
Criteria	Weights	Alternatives Ranking				
		Company Branch	P-Outsourced Branch	S-Outsourced Branch	3PL	Satellite Branch
Initial Investment	0.306	0.140	0.037	0.071	0.306	0.445
Operating Cost	0.182	0.136	0.069	0.267	0.393	0.136
HSSE	0.036	0.278	0.453	0.159	0.055	0.055
Responsiveness	0.068	0.296	0.431	0.171	0.035	0.066
Brand Image	0.408	0.357	0.357	0.161	0.048	0.077
Overall priority for each warehouse type		0.243	0.215	0.153	0.189	0.199

Table 6.4: Tabuk AHP Results

Tabuk AHP						
Criteria	Weights	Alternatives Ranking				
		Company Branch	P-Outsourced Branch	S-Outsourced Branch	3PL	Satellite Branch
Initial Investment	0.306	0.171	0.036	0.066	0.296	0.431
Operating Cost	0.182	0.136	0.069	0.267	0.393	0.136
HSSE	0.036	0.278	0.453	0.159	0.055	0.055
Responsiveness	0.068	0.296	0.431	0.171	0.035	0.066
Brand Image	0.408	0.357	0.357	0.161	0.048	0.077
Overall priority for each warehouse type		0.253	0.215	0.152	0.186	0.194

From the above tables, the best warehousing strategy for Riyadh, Jeddah and Dammam is the premium-outsourced branch, while the best for Buridah, Khamis Mushait and Tabuk is Company managed branch. The overall priority for each warehousing strategy is shown in Figure 6.2.

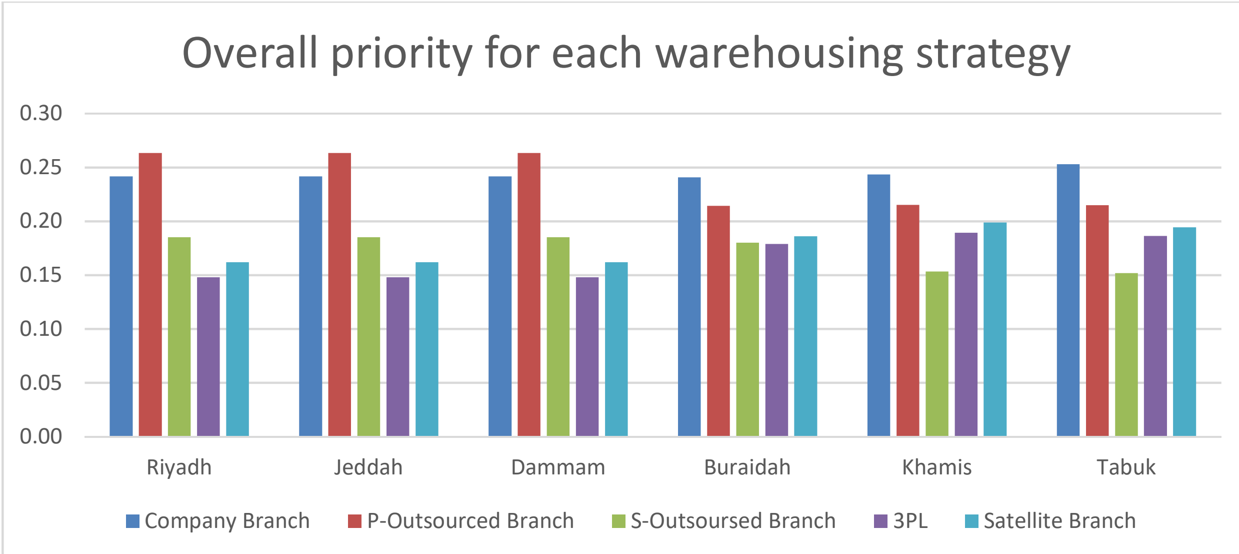

Figure 6.2: Warehousing strategy comparison for each city

The premium-outsourced branches at the three main cities would provide better market service (Responsiveness criteria) than the current company branches. However, the study suggests continuing having the company-managed branch at Buridah, Khamis Mushait and Tabuk, as the switching cost for better market service (Responsiveness criteria) is higher than the payoff.

CHAPTER 7

CONCLUSION

This thesis considers a case study for a major lubrication company in Saudi Arabia. The case study addresses a single-sourcing network redesign problem for a four-level supply chain consisting of suppliers, plants, distribution centers (DC's) and markets. The demand, land prices, and energy prices are uncertain parameters with DC-to-market dependent lead times. The objective is to determine the optimal number and locations of plants and DC's, the assignment of each plant-DC and DC-market, which minimizes the system-wide location, transportation, and inventory costs for each scenario. Models details are listed in section 7.1. Finally, a multi criteria decision-making approach is developed to decide the best warehouse type for the six different local markets.

7.1 Models Summary

In this thesis, five mathematical models are developed to address the problem, namely: Un–capacitated fixed–charge location Model, Multi–echelon deterministic Model, Location Model with Risk Pooling (LMRP), Multi–echelon stochastic Model, and Multi-echelon demand stochastic model with price uncertainty. The models are summarized and compared to the current supply chain set up in Table 7.1.

Table 7.1: Mathematical Models Comparison

Models	Model 1	Model 2	Model 3	Model 4	Model 5	Current SC
# of Echelons	2	4	2	4	4	2
Uncertain Parameters	-	-	Demand	Demand	• Demand • Energy Prices • Land Prices	-
Uncertainty Type	-	-	Known Continuous Probability	Known Continuous Probability	• Known Demand Continuous Probability • Unknown Energy and Land Prices	-
Solution Method	MILP Open Solver	MILP Open Solver	Set Covering	Set Covering	Set Covering	-
Optimal DC Location	Riyadh	Yanbu	Yanbu	Yanbu	Yanbu	-
Optimal plant Location	-	Yanbu	-	Yanbu	Yanbu	Outsourced
SC Annual Cost (SAR)	1,092,800	6,391,222	1,854,355	6,711,870	6,783,220	9,600,723.40

7.2 Result

The company is advised to open a plant and a DC in Yanbu, which is robust against demand, land and energy prices uncertainties. The future supply chain annual cost is SAR 6,783,220 with an additional investment of SAR 3,100,000. While the current supply chain annual cost is SAR 9,600,723. The payback period is 13 months with annual savings of SAR 2,817,503, which is outstanding in the business world.

7.3 Thesis Contribution

The thesis contribution is summarized in the following points:

- Four-echelon demand stochastic model with price uncertainty, where land prices is considered for the first time.
- New detailed case study in the lubrication industry.
- Multi criteria Decision making process for local warehouse strategy selection.

7.4 Future Work

The thesis work can be extended as following:

- Find more sophisticated approach to address the land prices uncertainty
- Extend the multi-echelon demand stochastic model with price uncertainty with other financial uncertainty, such as tax and exchange rate
- Investigate other stochastic optimization methods, for unknown probability distributions
- Consider safety stock and inventory at market level
- Extend the model to be dynamic for multi periods
- Consider the problem as profit maximization model, subject to a service level
- Consider tactical and operational decisions such as Vehicle Routing for regional networks

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