Optimization of Supply and Demand Balance in a Palm Oil Supply Chain

Chutchai Suksa-ard and Morrakot Raweewan
School of Management Technology, Sirindhorn Institute of Technology, Thammasat University, Pathum Thani 12121

Correspondence:
Morrakot Raweewan
School of Management Technology,
Sirindhorn Institute of Technology,
Thammasat University,
Pathum Thani 12121
Email: morrakot@siit.tu.ac.th

Abstract
This research investigates the issues of determining supply and demand balance in a palm oil supply chain. A methodology is presented for selecting markets and finding an optimized supply chain when considering agricultural plantation, oil production, and logistics. A proposed tool assists policy makers, with given market demands, in deciding which market should be selected, how much demand in that market should be served, and how to manage the supply chain optimally to meet the target demand (how much land should be allocated to what zone in the country, and how the logistics network from plantations to markets should be designed). A methodology is developed based on an optimization model that will allow policy makers to answer these questions. Numerical experiments are conducted to illustrate the models.

Keywords: Palm oil supply chain management, Supply and demand balance, Market selection, Optimization

1. Introduction

Palm oil can be found in many products ranging from foods (industrial frying, chocolate, margarine, cereals, crisps, sweets, and baked goods, etc.) to non-foods (such as soaps, washing powders, cosmetics, plastics, steel, textile, and animal feedstuffs) [1, 2, 3]. Univanich Palm Oil PCL [4] presents four factors driving growth of supply and demand in Thailand : (1) domestic biodiesel policy creating demand, (2) energy policies, generating new investment opportunities, (3) irrigation research, increasing crop yields, and (4) oil palm breeding, improving drought tolerance. The same article also mentions that, in 2010, Thailand produced 1,288,000 tons of crude palm oil (CPO) which was used in several industries: soap industry 2%, animal feeds 2%, margarine shortening 5%, export 9%, food industry 17%, cooking oil 30%, and biodiesel 35%. The increasing demand of palm oil has drawn large-scale plantation development to leading palm oil producers in Southeast Asia, such as Indonesia, Malaysia, and Thailand [5]. In 2012, the United States Department of Agriculture put Thailand among the top five annual growth rates in production of palm oil in the world. The plantations are approximately 90% concentrated in the southern provinces of Thailand, Krabi, Surat Thani, and Chumphorn accounted for 72.1% of the total planted area in 2008 [4]. The plantations have also been expanded in the northeastern provinces. However, because of regulation and availability of non-forest area, Thailand has limited area to expand plantations [6]. Many plantations in Malaysia and Indonesia are dominated by large estates and have their own crushing mills [7]. Unlike those two countries, plantations in Thailand are managed by independent smallholder farmers owning less than 50 ha [8, 9]. Roughly 80% of the palm oil produced in Thailand comes from them [10]. These farmers act independently from crushing mills – with no contracts or formal arrangement in planting and selling fresh fruit brunches (FFB) [11]. At the same time, a report from the Palm Oil Crushing Mill Association reveals that palm oil mills, overall, are over capacity. This shows the challenge in coordinating plantations and crushing mills in crude palm oil production. Chavananand [6] discusses other challenges in Thai palm oil supply chain and states that the Thai Palm Oil Industry Board needs a tool to assist decision making in matching demand with supply.

Research related to supply and demand balance in smallholder farming in palm oil supply chain management is rare. Most research focuses on solving large-scale plantations and waste utilization [see, for example, 12, 13]. Leão et al. [14] focus on oilseed production and small farmers, and cover transport logistics of raw materials and biodiesel fuels and the location of crushing and production units in Brazil, but do not cover the supply and demand balance for market selection. Seegraf et al. [10] study smallholder plantation in Thailand and propose management of harvesting practices and cooperation with mills and middlemen to increase the oil content of the palm fruits.

The purpose of this article is to present an integrated analysis of the palm oil supply chain for management of supply and demand balance in market selection. The proposed mathematical optimization model is an analysis tool for strategic decision making. The solution includes (1) market selection – which market to invest in, and how much demand should be satisfied; (2) agricultural dimensioning – how much land should be reserved for plantation, and in what zone; and (3) distribution network – how much supply from plantations from what zone should be distributed to crushing mills and to refineries in what zone.

2. Palm Oil Production

A palm fruitlet consists of peel, shell, kernel, and mesocarp (pulp), see Fig. 1. When pressed, the mesocarp gives crude palm oil (CPO) and the kernel gives crude palm kernel oil (CPK), or palm kernel oil (PKO). In a leading palm oil producing country like Malaysia, CPO has an oil extraction rate (OER) about 20%, higher than the average OER in Thailand due to better quality handling from seed selection to production at the crushing mill. CPO are then refined to produce refined bleached deodorized palm oil (RBD PO or RPO), palm olein, and palm stearin. These oils are used in exporting and producing commodity goods and biodiesel. Based on a composition chart of the palm fruit production processes in Muttamara et al. [15], we present a supply chain of palm oil production in Fig. 2.

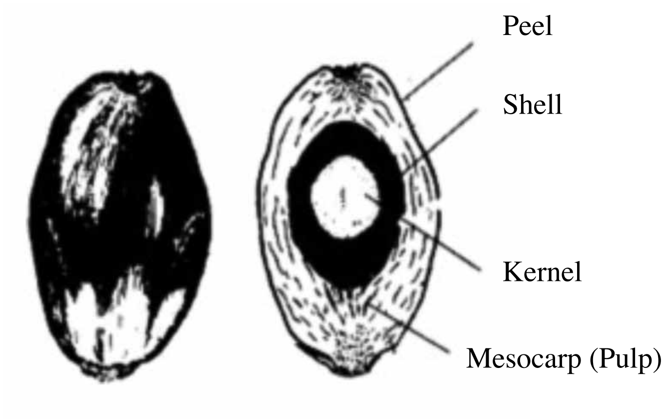

Fig. 1. Fresh oil palm fruit image with its longitudinal section [16].

Fig. 3 shows the supply-demand chain in our study. Plantations in the upstream in different zones produce FFBs that are then transported to crushing mills to produce CPO, CPK, and, as aby-product, fatty acid. CPO produced in different zones is transported to refineries in multiple zones to produce RPO; then, part of the RPO will be used in fractionation to produce olein and stearin. These oils (CPO, CPK, RPO, palm olein, and palm sterin) and by-products (fatty acid) will be sold to prospective industries to produce commodity products (cooking oil, animal feed, margarine, food, biodiesel, and soap) and to export. To produce one unit of each commodity product, these oils are mixed in different ratios as presented in Table 1 – based on information obtained from the Department of Agricultural Extension of Thailand [17].

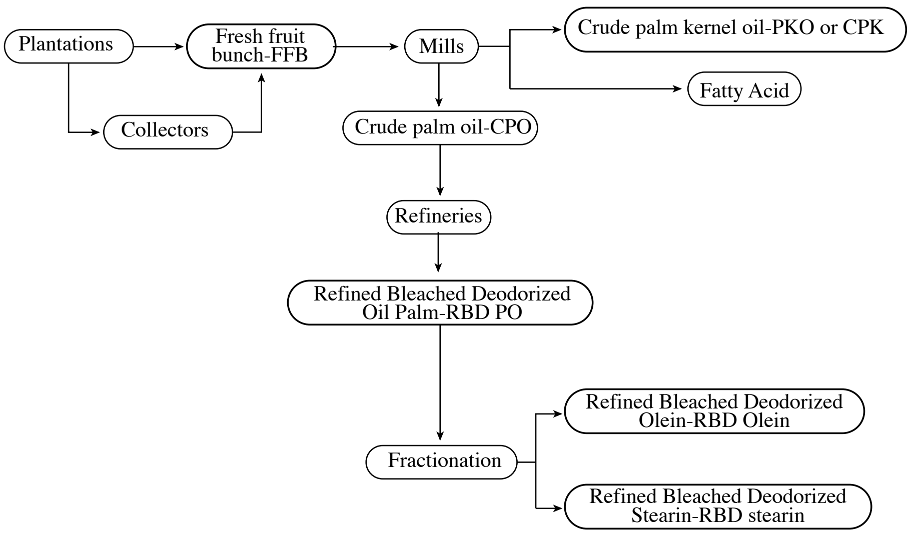

Fig. 2. Palm oil production process from upstream to downstream supply chain.

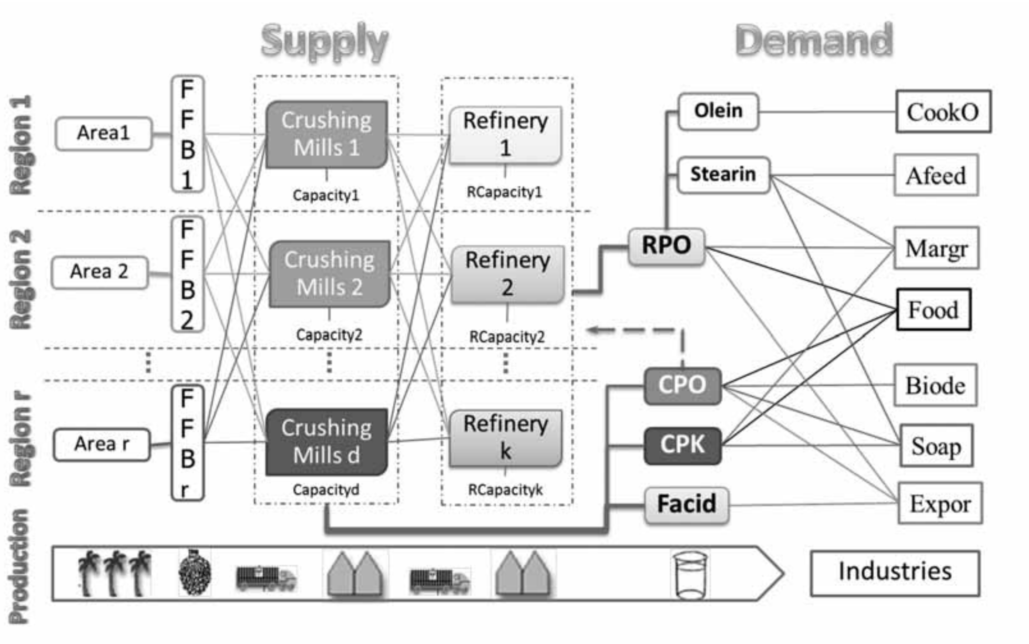

Fig. 3. Distribution network from plantation to commodity product and export market.

3. Methods

The goal of this section is to present and detail mathematical optimization models that have been designed. As determined by the Office of Agricultural Economics of Thailand, there are two types of demand in the palm oil market: (1) demand of crude palm oils CPO and CPK and (2) demand of commodity products, value-added products produced from palm oils. Given resources (limited land size, capacity of crushing mills and refineries in different zones in the country) and two types of demand, our objective is not to try to satisfy all given demands, but rather to select markets and to determine the size of demand to be satisfied to maximize profit of the entire supply chain. Thus two models are proposed to investigate the effect of demand of different types on supply chain management and logistics network. The differences of the models are illustrated in Fig. 4.

Model 1: Demand is given in a type of crude palm oil CPO and CPK. The supply chain includes activities from plantations to crude palm oil producers (e.g. crushing mills). Given the maximum and minimum demands of CPO and CPK, to maximize profit in the supply chain, this model explores the following issues; how much demand should be satisfied, how much land should be allocated for plantations, in what zones to produce supply, and how should the distribution network from plantations to crushing mills be designed?

Model 2: Demand is given in a profile of oils used in making commodity products listed in Table 1. Thus the second model examines the chain from plantation to crushing mills to refineries, to optimally meet the demand profile of commodity products. Model 2 answers the following questions: which market should be selected, how much demand in the selected markets should be satisfied, how much land for plantations should be allocated, in what zones to produce supply for selected demands, and how should the distribution network from plantations to crushing mills to refineries be designed?

To clarify, the elements that compose the mathematical models are stated as follows ;

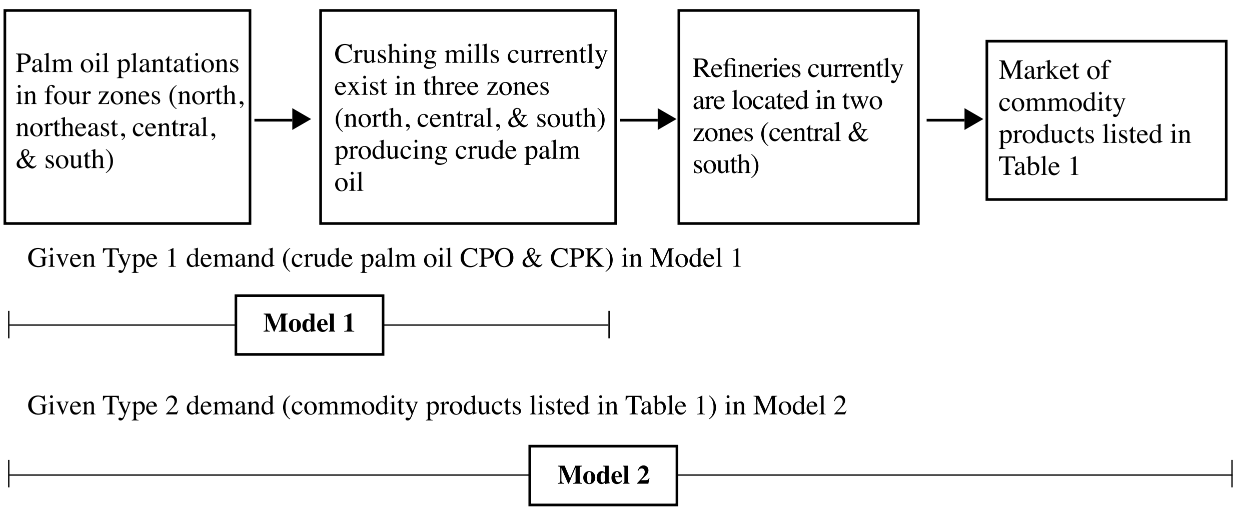

Fig. 4. The differences between Model 1 and Model 2.

Table 1. Proportion of palm oils to produce one unit of commodity product [17].

Commodity Product	Proportion to produce one unit of commodity product					Description
	Olein	Stearin	RPO	CPO	CPK	
Cooking Oil	0.50	-	-	-	-	1.00 part cooking oil contains 0.50 parts of palm olein
Margarine		0.10	0.60	-	0.30	1.00 part margarine consists of 0.10, 0.60, and 0.30 part of stearin, RPO, and CPK respectively
Food Industry	-	-	1.00	1.00	1.00	Purely or mixed use RPO, CPO, or CPK
Soap Industry	-	0.40	0.40	0.10	1.00	part soap composes of 0.40, 0.40, and 0.10 part of stearin, CPO, and CPK, respectively
Animal Feed	-	0.10	-	-	-	One unit of animal feed uses 0.10 part of stearin
Biodiesel	-	-	-	1.14	-	1.14 parts CPO is used to produce 1.0 part of biodiesel
Export	-	-	-	1.00	1.00	Either CPO or CPK

Sets	Index
Plantation zone	r
Crushing mill zone	d
Refinery zone	k
Crude palm oil product = {CPO, CPK}	i
Palm oil product = {CPO, CPK, RPO, olein, stearin}	z
Refined palm oil from CPO = {olein, stearin}	g
Commodity product and export market = {cooking oil, margarine, food industry, soap, animal feed, biodiesel, export}	j

Decision variables	Description	Unit
q_r	Land size for plantation in zone r	Rai
w_{rd}	Amount of FFB transported from plantation in zone r to mill in zone d	Tons/year
X_{dx}	Amount of CPO transported from mill in zone d to refinery in zone k	Tons/year
cpo_d	Supply of CPO in zone d	Tons/year
rpo_k	Supply of RPO in zone k	Tons/year
$crpo_k$	Amount of CPO to produce olein and stearin in zone k	Tons/year
p_{zj}	Amount of palm oil product z to supply the demand of commodity product j	Tons/year
c_j	Amount of commodity product j to supply the market demand	Tons/year

Parameters	Description	Unit
L_r	Total size of available plantation area in zone r	Rai
y_r	Yield of FFB per area in plantation zone r	Tons/rai
f_r	Purchasing cost of FFB in zone r	Baht/ton
t_{rd}	Transportation cost to transport FFB from plantation in zone r to mill in zone d	Bath/ton
h_{dk}	Transportation cost to transport CPO from mill in zone d to refinery in zone k	Baht/ton
D_d	Capacity of crushing mill in zone d	Tons FFB/year
A_k	Capacity of refinery in zone k	Tons CPO/year
m_d	Production cost in producing CPO and CPK from one ton of FFB at mill in zone d	Baht/ton
e_{id}	Oil extraction rate of palm oil product i from FFB in zone d	Percentage
c_k	Refined rate of RPO from CPO in zone k	Percentage
o_{gk}	Refined rate of refined palm oil product g from CPO in zone k	Percentage
n_{zj}	Proportion of palm oil product z in commodity product j (Table 1)	Unitless
min_i	Minimum demand of palm oil product i	Tons/year
max_i	Maximum demand of palm oil product i	Tons/year
min_j	Minimum demand of commodity product j	Tons/year
max_j	Maximum demand of commodity product j	Tons/year
s_i	Selling price of crude palm oil product i	Baht/ton
s_z	Selling price of palm oil product z	Baht/ton
a_k	Cost in producing RPO from one ton of CPO at refinery in zone k	Baht/ton
b_g	Cost per ton of refined palm oil product g producing from CPO at refinery in zone k	Baht/ton

3.2 Model 1: mathematical model

$$maximize \sum_i \sum_d \sum_r s_i e_{id} w_{rd} - \sum_r f_r y_r q_r - \sum_r \sum_d t_{rd} w_{rd} - \sum_d \sum_r m_d w_{rd} \quad (1)$$

subject to

$$q_r \leq L_r \quad (2)$$

$$\sum_d w_{rd} \leq y_r q_r \quad (3)$$

$$\sum_r w_{rd} \leq D_d \quad (4)$$

$$min_i \leq \sum_d \sum_r e_{id} w_{rd} \leq max_i \quad (5)$$

$$q_r \geq 0, w_{rd} \geq 0 \quad (6)$$

The objective of Equation (1) is to maximize profit of selling palm oil products comprising total revenue from selling palm oil products subtracted by total costs, including cost of purchasing FFB, transportation cost and cost of operating crushing mill. Constraint (2) states that the required land size for a plantation should not exceed the total land available for a plantation in each zone. Constraint (3) and (4) define that the total FFB transported from zone *r* to crushing mills in zone *d* is equal to or less than FFB production in zone *r* and total capacity of crushing mills in zone *d*, respectively. Constraint (5) states that the total palm oil serving product *i* should satisfy minimum demand, but not more than maximum demand. Constraint (6) is a non-negativity condition.

3.3 Model 2: mathematical model

$$maximize \sum_{z}\sum_{j} s_z\, p_{zj} - \sum_{r} f_r\, y_r\, q_r \tag{7}$$

$$- \sum_{r}\sum_{d} t_{rd}\, w_{rd} \quad - \sum_{d}\sum_{r} m_d\, w_{rd}$$

$$- \sum_{d}\sum_{k} h_{dk}\, x_{dk} \quad - \sum_{k}\sum_{d} b_g\, 0_{gk}\, crpo_k$$

$$- \sum_{k}\sum_{d} a_k\, (x_{dk} - crpo_k)$$

subject to

$$q_r \leq L_r \tag{8}$$

$$y_r q_r \geq \sum_{d} w_{rd} \tag{9}$$

$$D_d \geq \sum_{r} w_{rd} \tag{10}$$

$$cpo_d + \sum_{k} x_{dk} \leq \sum_{r} w_{rd} e_{id},\ i \text{ is } cpo \tag{11}$$

$$\sum_{d} x_{dk} \leq A_k \tag{12}$$

$$rpo_k = \sum_{d} (x_{dk} - crpo_k)\, c_k \tag{13}$$

$$\sum_{j} p_{zj} \leq \sum_{d} cpo_d,\ z \text{ is } cpo \tag{14}$$

$$\sum_{j} p_{zj} \leq \sum_{r} w_{rd}\, e_{id},\ z \,\&\, i \in \{\text{CPK}\} \tag{15}$$

$$\sum_{j} p_{zj} \leq \sum_{k} rpo_k,\ z \text{ is } RPO \tag{16}$$

$$\sum_{j} p_{zj} \leq \sum_{k} crpo_k\, o_{gk}, \tag{17}$$

$$z = g,\ z \,\&\, g \in \{olein,\ stearin\}$$

$$c_j = \sum_z p_{zj}, \ j \text{ is export } \& \ z \in \{CPO, CPK\} \quad (18)$$

$$c = \sum_z p_{zj}, \ j \text{ is food } \& \ z \in \{CPO, CPK, RPO\} \quad (19)$$

$$P_{zj} = n_{zj} \ C_j, \ j \in \{\text{cooking oil, soap, margarine, animal feed, biodiesel}\} \quad (20)$$

$$min_j \leq C_j \leq max_j \quad (21)$$

$$q_r \geq 0, w_{rd} \geq 0, x_{dk} \geq 0, cpo_d \geq 0, \quad (22)$$
$$rpo_k \geq 0, \ crpo_k \geq 0, p_{zj} \geq 0, c_j \geq 0$$

The objective of Equation (7) is to maximize profit of selling palm oil products, which is the difference between total revenue from selling palm oil products and total costs (FFB purchasing cost, FFB and CPO transportation costs, crushing mill cost, refinery cost, and cost of producing value added products (olein and stearin)). Constraint (8) states that the required land size for plantations should not exceed the total land available for plantations in each zone. Constraint (9) defines that the amount of total FFB transported from zone r to crushing mills in zone d cannot be more than the amount of FFB produced in zone *r*. Constraint (10) states that the total amount of FFB transported from zone r should not exceed the capacity of crushing mills in zone *d*. Constraint (11) explains that CPO produced at crushing mills in zone d is separated into two amounts – one is kept as CPO and the other is sent to a refinery in zone *k* (see Fig. 3). Constraint (12) states that the total amount of CPO transported from zone *d* to a refinery in zone *k* is equal to or less than total capacity of the refinery in zone *k*. Constraint (13) restricts the amount of CPO to produce olein and stearin from the total amount of CPO that is sent to a refinery. The rest is for producing RPO in zone *k*. Constraints (14) – (17) state that palm oil product *z,* supplying the production of commodity *j,* cannot exceed the amount of total palm oil product *z* produced in all zones. Constraint (18) states that the amount of palm oil to export is the amount of CPO and CPK that is available for the export market. Constraint (19) defines the available amount of palm oil for the food market that is gathered from CPO, CPK, and RPO. To produce one unit of commodity products, the amount of crude oils and refined oils are mixed in different ratios, presented in Table 1. Therefore, constraint (20) states that the amount of palm oil *z* to supply the demand of commodity *j* (cooking oil, soap, margarine, animal feed, and biodiesel) is the amount of that commodity product *j* to supply the market demand, multiplied by the associated proportion of crude oils and refined oils from Table 1. Constraint (21) defines that the total amount of commodity product *j* to supply the market demand should satisfy minimum demand but cannot be more than maximum demand of that oil product. Constraint (22) is a non-negativity condition.

4. Numerical Examples

This section illustrates examples employing Models 1 and 2. The section includes values of parameters used in the models, and results and discussion of the models.

4.1 Input Parameters

The values of parameters in this study are collected from the industry. Information is from direct interviews of stakeholders in the palm oil supply chain in Surat Thani and from secondary data from various sources. In the following examples, the plantation areas are located in the northern, northeastern, central, and southern zones of Thailand; crushing mills exist in only three zones (northeastern, central, and southern zones); and refineries are in two zones (central and southern zones). Input parameters of plantations, crushing mills, and refineries in four zones are shown in Table 2. Next, we present the input of market demands of two types (1) crude palm oils CPO and CPK and (2) demand of commodity products produced from palm oils), transportation cost, and selling price of palm oil products. The Office of Agricultural Economics of Thailand [19] reports that the demand in 2012 for domestic use was 1.559 million tons (consumption 0.933 and biodiesel 0.626) and export was 411,926 tons. Therefore, we set minimum demand and maximum demand of CPO to 1.559 and 1.97 million tons, respectively. We also assign 0.16 million tons to minimum demand of CPK, or 10 % of the minimum CPO. The amount of maximum demand of CPK is unlimited. The market demand for commodity products and exports (or Type 2 demand) is shown in Table 3. Table 4 shows the transportation cost which is estimated on average for 21-ton trucks based on distance between four zones, using a cost rate from DX Innovation Co., Ltd. (apsthailand.com) and Table 5 shows the selling price of palm oil products.

4.2 Result and discussion

Model 1 and Model 2 use CPO's OER at 17%, meaning one ton of FFB yields 0.17 tons of CPO. This is the average of crushing mills' OER in all zones of Thailand. However, crushing mills are worse (15%) than the average. This variation is studied in OER sensitivity test where OERs are 15%, 17%, and 20%. The optimization models were written in IBM® ILOG® CPLEX®. Results of models and sensitivity test are now presented.

4.2.1 Result of Model 1

Numerical results are illustrated in Fig. 5. Maximum profit is 8,932.905 million baht per year. The result shows that the CPO demand is satisfied with 1,925.549 kilotons, in between minimum and maximum market demands.

Table 2. Input parameters of plantation, crushing mills, and refineries in four zones.

Factors	Unit	North	Northeast	Central	South
Available plantation area [18]	Rai	18,326	75,598	735,127	3,446,530
Yield [18]	Tons/rai	0.576	1.334	1.557	2.922
FFB cost [19]	Baht/ton	4,100	4,100	4,100	4,100
Crushing mills' capacity [6]	Tons/year	N/A	144,000	1,418,400	18,676,800
OER to produce CPO at mill*	% of FFB	N/A	17%	17%	17%
OER to produce CPK at mill*	% of FFB	N/A	3%	3%	3%
Mills' operating cost*	Baht/ton	N/A	500	500	500
Refineries' capacity [6]	Tons CPO/year	N/A	N/A	1,975,500	90,000
Refined rate of RPO [20]	% of CPO	N/A	N/A	93%	93%
Refined rate of olein [20]	% of CPO	N/A	N/A	66%	66%
Refined rate of stearin [20]	% of CPO	N/A	N/A	29%	29%
Refineries' operating cost [20]	Baht/ton CPO	N/A	N/A	1,500	1,500
Olein production cost [20]	Baht/ton of olein	N/A	N/A	2,500	2,500
Stearin production cost [20]	Baht/ton of stearin	N/A	N/A	2,500	2,500

N/A = no mills or refineries in the zone, *Direct interview of crushing mill managers

Table 3. Demand of commodity products and export (tons/year).

Demand	Cooking Oil	Margarine	Food	Soap	Animal Feed	Biodiesel	Export
Minimum	400,000	100,000	100,000	400,000	50,000	500,000	0
Maximum	500,000	300,000	200,000	800,000	100,000	1,650,000	820,000

Table 4. Transportation cost (baht/ton).

To \ From	North	Northeast	Central	South
North	N/A	372	384	652
Northeast	N/A	182	391	712
Central	N/A	391	174	425
South	N/A	712	425	175

N/A = no mills in the northern zone

Table 5. Selling price of palm oil products (baht/ton) [19].

CPO	CPK	RPO	Olein	Stearin
27,810	27,870	28,530	28,950	26,580

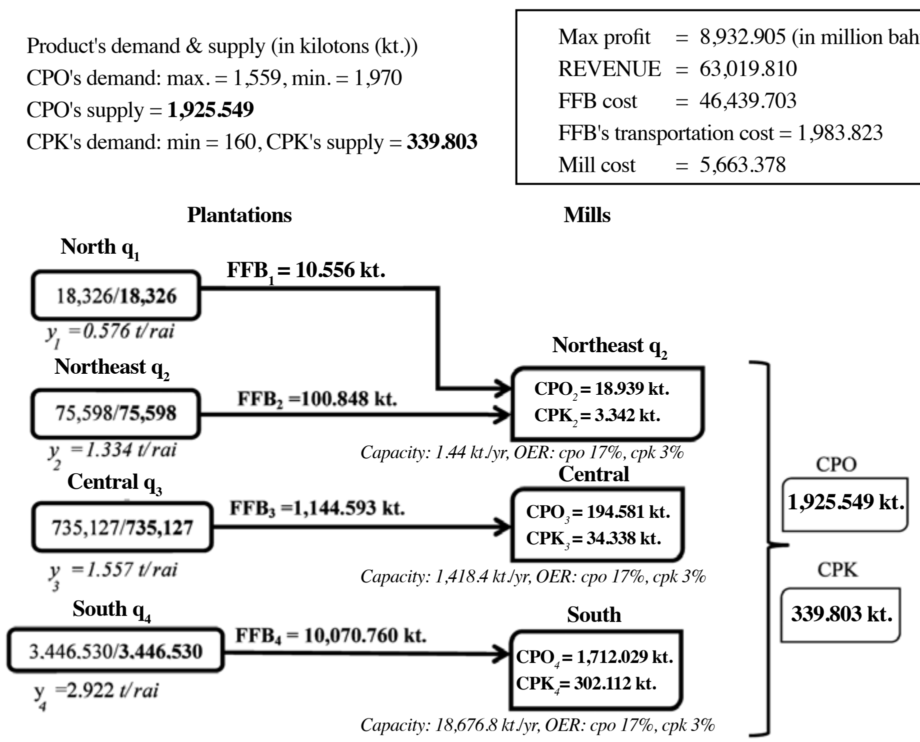

Fig. 5. An optimal supply chain from plantations in zone *r* to crushing mills in zone *d*, in Model 1.

The CPK's demand is served by 339.803 kilotons, satisfying the minimum demand. The optimized supply chain is designed in the following way. Land size that is available for plantations in every zone (north, northeast, central, and south) is completely used. FFB from the northern and northeastern zones is transported to crushing mills in the northeastern zone in the amount of 10,556 and 100,848 kilotons, respectively. Mills in the northeastern zone can produce 18.939 kilotons of CPO and 3.342 kilotons of CPK. The amount of 1,144.593 kilotons of FFB from the central zone is transported to crushing mills in the same zone to produce 194.581 kilotons of CPO and 34.338 kilotons of CPK. FFB produced in the southern zone (10,070.760 kilotons) is transported to crushing mills in the same zone to produce 1,712.029 kilotons of CPO and 302.112 kilotons of CPK.

4.2.2 Result of Model 2

The optimal supply chain is illustrated in Fig. 6(a) and (b). Fig. 6(a) shows the supply chain network of palm oil production from plantations to crushing mills to refineries and to stock. These stocks are then used in manufacturing to satisfy the demands of commodity products and of export, displayed in Fig. 6(b). The result shows that the maximum profit is 5,603.426 million baht per year where demand of cooking oil, biodiesel, soap, export, and food is satisfied, in between minimum demand and maximum demand; and demands of margarine and animal feed are only met at the minimum level. To calculate a serving unit of commodity product on the right node of Fig. 6(b), the number on the path flowing from the stock on the left node, is first multiplied by the proportion n_{zj}, stated in Table 1. For example, material - flow for cooking oil from stocked olein is 398.278 tons; and one unit of cooking oil is made from a half unit of olein. Therefore, 398.278 tons of olein yields 796.552 tons of cooking oil. Likewise, material in - flow for biodiesel from stocked CPO is 1,097.584 tons. From Table 1, 1.14 parts CPO is used to produce 1.0 part of biodiesel; hence, 1,097.584 tons of CPO yield 962.793 tons of biodiesel. A similar calculation is done at all nodes. As a result, the supply to optimize profit from selling to each industry of cooking oil, biodiesel, soap, export, food, margarine, and animal feed is 796.552, 962.793, 400, 69.803, 200, 100, and 50 kilotons per year, respectively. The optimal network design for this result is described next.

FFB from plantations in northern and central zones are transported to crushing mills in the central zone to produce 196.375 and 34.654 kilotons of CPO and CPK, respectively. FFB harvested in the northeastern zone is sent to crushing mills in the same zone to produce CPO and CPK, 17.144 and 3.025 kilotons, respectively. FFB in the southern zone is transported to produce CPO and CPK in the same zone, 1,712.029 and 302,122 kilotons, respectively. CPOs from three zones are sent to be refined in the next process. The amount of 90 kilotons of CPO from the central zone is refined at refineries in the same zone. The rest of the CPO from the south together with CPO from the northeastern and central zones are transported to be refined in the central zone. Note that refineries are located in two zones only, and the total capacity of refineries in the central zone is larger than in the south. These refined oils (RPO, olein, and stearin) are used to meet commodity product and export demand as described previously.

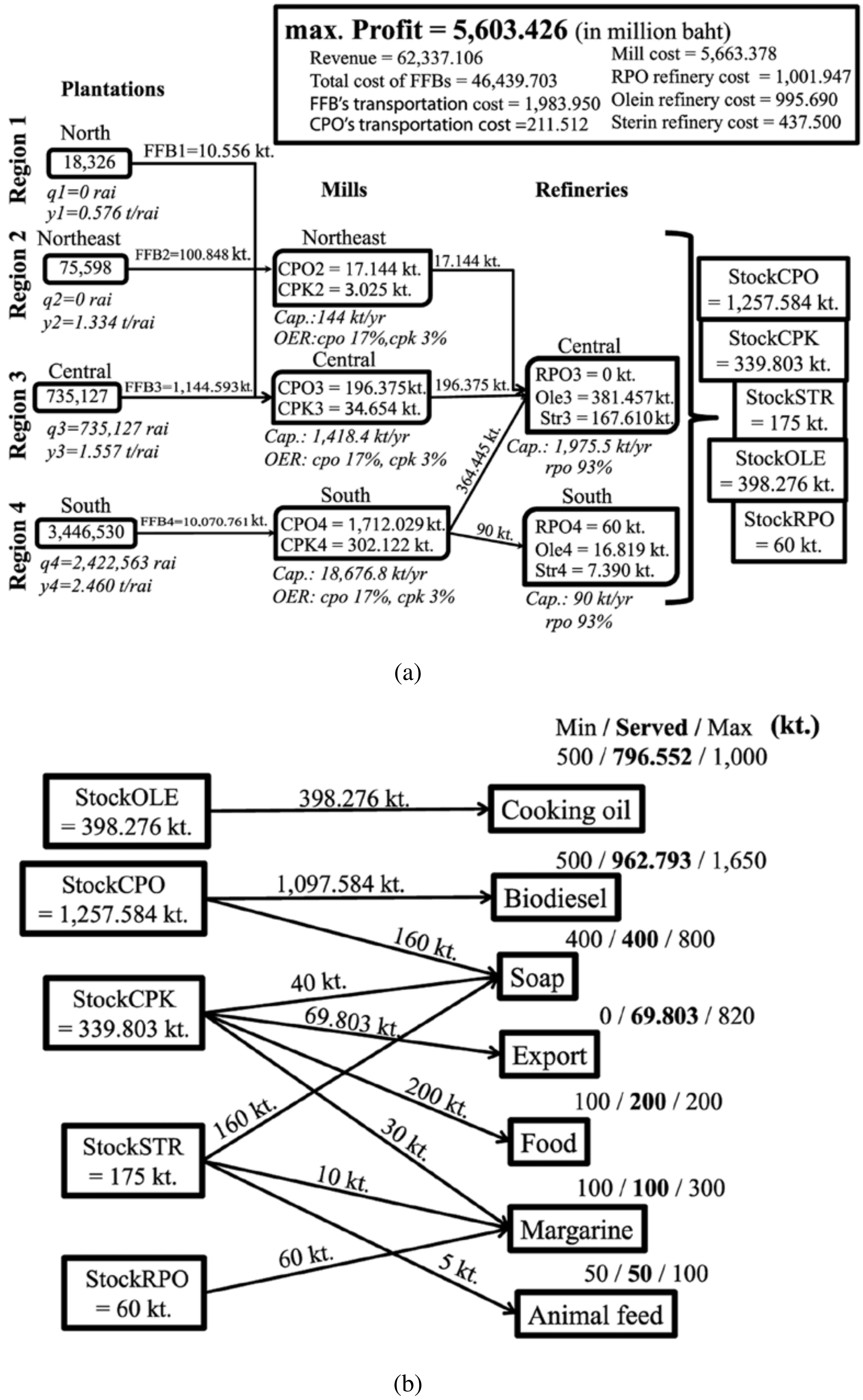

Fig. 6. Result of Model 2 (a) An optimal supply chain from plantations in zone *r* to crushing mills in zone *d*, to a refinery in zone *k*. (b) The connecting chain from stock satisfying the demands of commodity products and export.

4.2.3 OER sensitivity test

Oil extraction rate or OER at a crushing mill is an important factor in palm oil production. The impact of OER changes on the optimal supply chain is studied and presented here. The average of a crushing mill's OER in Thailand is 17%, meaning one ton of FFB yields 0.17 tons of CPO. However, OER at some areas can either be better (20%) or worse (15%) than the average. In Thailand, there are crushing mills in three zones – northeastern, central, and southern zones. Let OER in these zones be 15%, 17%, and 20%. The OERs of northeastern, central, and southern zones are written in order and presented in 27 cases located in the first column of Tables 6, 7(a), and (b). For example, 151720 means the OERs of northeastern, central, and southern are 15%, 17%, and 20%, respectively.

The OER sensitivity test of Model 1 is presented next. Given CPO minimum and maximum demand of 1.559 and 1.970 million tons, respectively, the output of these 27 cases from Model 1 is sorted by profit in descending order and presented in Table 6. The result of the sensitivity test yields four observations. First, if the OER of each zone is 17%, the optimal solution shows that the maximum profit is positive and total land available in all zones is fully used for plantations; and the demand is satisfied, in between minimum and maximum demands. Second, the southern zone is the most important area to supply FFB because it is the biggest for plantations and has the maximum yield of FFB, compared to other zones. If the OER of crushing mills in this southern zone is improved from 17 to 20%, the maximum demand of CPO can be met when using 98% of available plantations in the zone; There is no need to use land from the other three zones. Third, if the OER of crushing mills is 20% in both central and southern zones, the output can meet CPO maximum demand when using 100% and only 86% of plantations in the central zone and southern zone, respectively. Lastly, if the OER in the south is still 17%, CPO maximum demand still can be met only if the OER in the central and northeastern zones is improved to 20%, but all plantation land available in all zones needs to be used.

Now, the impact of OER variation in Model 2 is presented in Table 7(a) and (b). The market demand in this model is the demand of commodity products and of export. If the OER in every zone can be improved from 17 to 20%, the maximum demand of all products can be satisfied. The profit of the supply chain relies on crushing mills' OER in the southern, central, and northeastern zones, in order from strong to weak. If the OER in the southern and central zones drop to 15%, the profit of the entire supply chain becomes negative. The change of OER' in a crushing mill in the northeastern zone rarely affects the optimal chain because it receives FFB from the same zone plus from the northern zone, which has smaller plantation size and lower FFB yield compared to the southern and central zones. Finally, transportation cost significantly affects total profit in Model 2. The transportation cost in Model 2 consists of the cost of transporting FFB from plantations to mills , and the cost of transporting crude palm oil from mills to refineries.

Table 6. Results of OER sensitivity test in Model 1 where OER in northern, central, & southern zone is 15%, 17%, and 20%, written in order in the first column.

OER Cases	Max Profit	CPO	Plantation size in zone r (q_r)				t_{rd}= transportation cost to send one ton of FFB from plantationsin zone *r* to a crushing mill in zone *d*											
			q_1	q_2	q_3	q_4	t_{12}	t_{13}	t_{14}	t_{22}	t_{23}	t_{24}	t_{32}	t_{33}	t_{34}	t_{42}	t_{43}	t_{44}
152020	15,988.680	1,970.000	0	0	735,127	2,979,263.265	0	0	0	0	0	0	0	1,144.593	0	0	0	8,705.407
172020	15,988.680	1,970.000	0	0	735,127	2,979,263.265	0	0	0	0	0	0	0	1,144.593	0	0	0	8,705.407
202020	15,988.680	1,970.000	0	0	735,127	2,979,263.265	0	0	0	0	0	0	0	1,144.593	0	0	0	8,705.407
151720	15,987.535	1,970.000	0	0	0	3,370,979.000	0	0	0	0	0	0	0	0	0	0	0	9,850.000
151520	15,987.535	1,970.000	0	0	0	3,370,979.000	0	0	0	0	0	0	0	0	0	0	0	9,850.000
171520	15,987.535	1,970.000	0	0	0	3,370,979.000	0	0	0	0	0	0	0	0	0	0	0	9,850.000
171720	15,987.535	1,970.000	0	0	0	3,370,979.000	0	0	0	0	0	0	0	0	0	0	0	9,850.000
201520	15,987.535	1,970.000	0	0	0	3,370,979.000	0	0	0	0	0	0	0	0	0	0	0	9,850.000
201720	15,987.535	1,970.000	0	0	0	3,370,979.000	0	0	0	0	0	0	0	0	0	0	0	9,850.000
202017	10,141.509	1,970.000	18,326	75,598	735,127	3,441,657.000	10.556	0	0	100.848	0	0	32.596	1,111.996	0	0	306.404	9,750.118
152017	10,054.471	1,968.100	18,326	75,598	735,127	3,446,530.000	0	10.556	0	0	100.848	0	0	1,144.593	0	0	162.404	9,908.357
172017	10,054.471	1,968.100	18,326	75,598	735,127	3,446,530.000	0	10.556	0	0	100.848	0	0	1,144.593	0	0	162.404	9,908.357
201717	9,045.971	1,929.869	18,326	75,598	735,127	3,446,530.000	10.556	0	0	100.848	0	0	32.596	1,111.996	0	0	0	10,070.761
171717	8,932.905	1,925.549	18,326	75,598	735,127	3,446,530.000	10.556	0	0	100.848	0	0	0	1,144.593	0	0	0	10,070.761
151717	8,911.701	1,925.549	18,326	75,598	735,127	3,446,530.000	0	10.556	0	0	100.848	0	0	1,144.593	0	0	0	10,070.761
201517	8,766.860	1,929.869	18,326	75,598	735,127	3,446,530.000	10.556	0	0	100.848	0	0	32.596	0	1,111.996	0	0	10,070.761
171517	8,646.721	1,925.549	18,326	75,598	735,127	3,446,530.000	10.556	0	0	100.848	0	0	32.596	0	1,111.996	0	0	10,070.761
151517	8,589.207	1,925.549	18,326	75,598	735,127	3,446,530.000	0	0	10.556	0	0	100.848	0	0	1,144.593	0	0	10,070.761
202015	4,721.806	1,777.134	18,326	75,598	735,127	3,446,530.000	10.556	0	0	100.848	0	0	32.596	1,111.996	0	0	306.404	9,764.357
172015	4,601.666	1,772.813	18,326	75,598	735,127	3,446,530.000	10.556	0	0	100.848	0	0	32.596	1,111.996	0	0	306.404	9,764.357
152015	4,543.443	1,769.933	18,326	75,598	735,127	3,446,530.000	0	10.556	0	0	100.848	0	0	1,144.593	0	0	162.404	9,908.357
201715	3,538.435	1,734.581	18,326	75,598	735,127	3,446,530.000	10.556	0	0	100.848	0	0	32.596	1,111.996	0	0	306.404	9,764.357
171715	3,418.295	1,730.262	18,326	75,598	735,127	3,446,530.000	10.556	0	0	100.848	0	0	32.596	1,111.996	0	0	306.404	9,764.357
151715	3,360.072	1,727.381	18,326	75,598	735,127	3,446,530.000	0	10.556	0	0	100.848	0	0	1,144.593	0	0	162.404	9,908.357
201515	2,826.121	1,706.213	18,326	75,598	735,127	3,446,530.000	10.556	0	0	100.848	0	0	32.596	1,111.996	0	0	0	10,070.761
171515	2,705.982	1,701.893	18,326	75,598	735,127	3,446,530.000	10.556	0	0	100.848	0	0	32.596	1,111.996	0	0	0	10,070.761
151515	2,632.963	1,699.013	18,326	75,598	735,127	3,446,530.000	10.556	0	0	100.848	0	0	0	1,144.593	0	0	0	10,070.761

Table 7. Results of OER sensitivity test in Model 2 where OER in northern, central, & southern zone is 15%, 17%, and 20%, written in order in the first column.

(a) Result from upstream to midstream supply chain

OER Cases	Max Profit	Plantation size in zone *r* (q_r)				t_{rd} = transportation cost to send one ton of FFB from plantations in zone *r* to a crushing mill in zone *d*											
		q_1	q_2	q_3	q_4	t_{12}	t_{13}	t_{14}	t_{22}	t_{23}	t_{24}	t_{32}	t_{33}	t_{34}	t_{42}	t_{43}	t_{44}
202020	15,062.141	18,326	75,598	735,127	3,446,530	0	10.556	0	100.848	0	0	0	1,144.593	0	0	0	10,070.761
152020	15,045.440	18,326	75,598	735,127	3,446,530	0	10.556	0	0	100.848	0	0	1,144.593	0	0	0	10,070.761
172020	15,045.440	18,326	75,598	735,127	3,446,530	0	10.556	0	0	100.848	0	0	1,144.593	0	0	0	10,070.761
201520	14,718.388	18,326	75,598	735,127	3,446,530	10.556	0	0	100.848	0	0	32.596	0	1,111.996	0	0	10,070.761
201720	14,718.388	18,326	75,598	735,127	3,446,530	10.556	0	0	100.848	0	0	32.596	0	1,111.996	0	0	10,070.761
151720	14,659.896	18,326	75,598	735,127	3,446,530	0	0	10.556	0	0	100.848	0	0	1,144.593	0	0	10,070.761
151520	14,659.896	18,326	75,598	735,127	3,446,530	0	0	10.556	0	0	100.848	0	0	1,144.593	0	0	10,070.761
171520	14,659.896	18,326	75,598	735,127	3,446,530	0	0	10.556	0	0	100.848	0	0	1,144.593	0	0	10,070.761
171720	14,659.896	18,326	75,598	735,127	3,446,530	0	0	10.556	0	0	100.848	0	0	1,144.593	0	0	10,070.761
202017	6,845.699	18,326	75,598	735,127	3,446,530	10.556	0	0	100.848	0	0	32.596	1,111.996	0	0	306.404	9,764.357
152017	6,746.450	18,326	75,598	735,127	3,446,530	0	10.556	0	0	100.848	0	0	1,144.593	0	0	162.404	9,908.357
172017	6,746.450	18,326	75,598	735,127	3,446,530	0	10.556	0	0	100.848	0	0	1,144.593	0	0	162.404	9,908.357
201717	5,715.174	18,326	75,598	735,127	3,446,530	10.556	0	0	100.848	0	0	32.596	1,111.996	0	0	0	10,070.761
171717	5,603.426	18,326	75,598	735,127	3,446,530	0	10.556	0	100.848	0	0	0	1,144.593	0	0	0	10,070.761
151717	5,586.070	18,326	75,598	735,127	3,446,530	0	10.556	0	0	100.848	0	0	1,144.593	0	0	0	10,070.761
201517	5,388.614	18,326	75,598	735,127	3,446,530	10.556	0	0	100.848	0	0	32.596	0	1,111.996	0	0	10,070.761
171517	5,268.328	18,326	75,598	735,127	3,446,530	10.556	0	0	100.848	0	0	32.596	0	1,111.996	0	0	10,070.761
151517	5,209.982	18,326	75,598	735,127	3,446,530	0	0	10.556	0	0	100.848	0	0	1,144.593	0	0	10,070.761
202015	1,414.764	18,326	75,598	735,127	3,446,530	10.556	0	0	100.848	0	0	32.596	1,111.996	0	0	306.404	9,764.357
172015	1,294.477	18,326	75,598	735,127	3,446,530	10.556	0	0	100.848	0	0	32.596	1,111.996	0	0	306.404	9,764.357
152015	1,235.422	18,326	75,598	735,127	3,446,530	0	10.556	0	0	100.848	0	0	1,144.593	0	0	162.404	9,908.357
201715	220.712	18,326	75,598	735,127	3,446,530	10.556	0	0	100.848	0	0	32.596	1,111.996	0	0	306.404	9,764.357
171715	100.426	18,326	75,598	735,127	3,446,530	10.556	0	0	100.848	0	0	32.596	1,111.996	0	0	306.404	9,764.357
151715	41.370	18,326	75,598	735,127	3,446,530	0	10.556	0	0	100.848	0	0	1,144.593	0	0	162.404	9,908.357
201515	-510.258	18,326	75,598	735,127	3,446,530	10.556	0	0	100.848	0	0	32.596	1,111.996	0	0	0	10,070.761
171515	-630.544	18,326	75,598	735,127	3,446,530	10.556	0	0	100.848	0	0	32.596	1,111.996	0	0	0	10,070.761
151515	-702.383	18,326	75,598	735,127	3,446,530	0	10.556	0	100.848	0	0	0	1,144.593	0	0	0	10,070.761

(b) Result from midstream to downstream supply chain

	t_{dk} = transportation cost to send one ton of CPO from a crushing mill in zone *d* to a refinery in zone *k*						Commodity products and export market						
OER Cases	t_{23}	t_{24}	t_{33}	t_{34}	t_{43}	t_{44}	Cooking Oil Supply	Margarine Supply	Soap Supply	Animal Feed Supply	Biodiesel Supply	Food Supply	Export Supply
202020	20.170	0	231.030	0	326.765	90	796,551.724	100,000	400,000	50,000	602,797.968	200,000	820,000.000
152020	0	0	251.199	0	326.765	90	796,551.724	100,000	400,000	50,000	602,797.968	200,000	820,000.000
172020	0	0	251.199	0	326.765	90	796,551.724	100,000	400,000	50,000	602,797.968	200,000	820,000.000
201520	28.800	0	0	0	549.164	90	796,551.724	100,000	400,000	50,000	602,797.968	200,000	820,000.000
201720	28.800	0	0	0	549.164	90	796,551.724	100,000	400,000	50,000	602,797.968	200,000	820,000.000
151720	0	0	0	0	577.964	90	796,551.724	100,000	400,000	50,000	602,797.968	200,000	820,000.000
151520	0	0	0	0	577.964	90	796,551.724	100,000	400,000	50,000	602,797.968	200,000	820,000.000
171520	0	0	0	0	577.964	90	796,551.724	100,000	400,000	50,000	602,797.968	200,000	820,000.000
171720	0	0	0	0	577.964	90	796,551.724	100,000	400,000	50,000	602,797.968	200,000	820,000.000
202017	28.800	0	283.680	0	265.484	90	796,551.724	100,000	400,000	50,000	500,000.000	200,000	644,258.977
152017	0	0	283.680	0	294.284	90	796,551.724	100,000	400,000	50,000	500,000.000	200,000	639,938.977
172017	0	0	283.680	0	294.284	90	796,551.724	100,000	400,000	50,000	500,000.000	200,000	639,938.977
201717	28.800	0	189.039	0	360.125	90	796,551.724	100,000	400,000	50,000	500,000.000	200,000	601,706.977
171717	17.144	0	196.375	0	364.445	90	796,551.724	100,000	400,000	50,000	962,793.219	200,000	69,802.707
151717	0	0	213.519	0	364.445	90	796,551.724	100,000	400,000	50,000	962,793.219	200,000	69,802.707
201517	28.800	0	0	0	549.164	90	796,551.724	100,000	400,000	50,000	500,000.000	200,000	601,706.977
171517	24.480	0	0	0	553.484	90	796,551.724	100,000	400,000	50,000	962,793.219	200,000	69,802.707
151517	0	0	0	0	577.964	90	796,551.724	100,000	400,000	50,000	962,793.219	200,000	69,802.707
202015	28.800	0	283.680	0	265.484	90	796,551.724	100,000	400,000	50,000	500,000.000	200,000	448,971.838
172015	24.480	0	283.680	0	269.804	90	796,551.724	100,000	400,000	50,000	500,000.000	200,000	444,651.838
152015	0	0	283.680	0	294.284	90	796,551.724	100,000	400,000	50,000	500,000.000	200,000	441,771.838
201715	28.800	0	241.128	0	308.036	90	796,551.724	100,000	400,000	50,000	500,000.000	200,000	406,419.838
171715	24.480	0	241.128	0	312.356	90	796,551.724	100,000	400,000	50,000	791,488.712	200,000	69,802.707
151715	0	0	241.128	0	336.836	90	796,551.724	100,000	400,000	50,000	500,000.000	200,000	399,219.838
201515	28.800	0	166.799	0	382.365	90	796,551.724	100,000	400,000	50,000	500,000.000	200,000	378,051.838
171515	24.480	0	166.799	0	386.685	90	796,551.724	100,000	400,000	50,000	766,604.501	200,000	69,802.707
151515	15.127	0	173.272	0	389.565	90	796,551.724	100,000	400,000	50,000	764,078.185	200,000	69,802.707

5. Conclusion

A methodology has been proposed to provide policy makers with quantitative tools to assist in making decisions regarding plantation allocation, market allocation, and distribution network planning. This research explores determining how much demand in each market should be satisfied, how much land should be allocated to which zones in the country to serve those demands, and what distribution network should be assigned from plantations to mills to refineries in order to profitably manage the entire supply chain. For future work, time will be integrated into the planning to manage FFB plantation and stocks of crude oil and refined oil.

6. Acknowledgement

This work was supported by the National Research University Project of Thailand Office of Higher Education Commission.

7. References

[1] Foo, K. Y. and Hameed, B. H., Utilization of biodiesel waste as a renewable resource for activated carbon: Application to environmental problems, Renewable and Sustainable Energy Reviews, Vol. 13, pp. 2495-2504, 2009.

[2] Sheil, D., Casson, A., Meijaard, E., van Noordwjik, M., Gaskell, J., Sunderland-Groves, J., Wertz, K. and Kanninen, M., The impacts and opportunities of oil palm in Southeast Asia: What do we know and what do we need to know?, Center for International Forestry Research (CIFOR), Bogor, Indonesia, 2009.

[3] Koh, L. P. and Wilcove, D. S., Is oil biodiversity? Conservation Letters, Vol. 1, pp. 60-64, 2008.

[4] Univanich Palm Oil PCL, Palm Oil Practices in Thailand, Paper Presented at: Thai Philippines Congress, 24-25 August 2011.

[5] Sundaram, J. K., Chang, Y. T. and Khoo, K. J., Deforesting Malaysia: the political economy and social ecology of agricultural expansion and commercial logging, Zed Books in association with United Nations Research Institute for Social Development, 2004.

[6] Chavananand, K., Future of the Thai Palm Oil Industry. Paper Presented at: Palmex Thailand 2011 Conference, IMPACT, Bangkok, 2011.

[7] AOCS Lipid Library, Oils and Fats in the market place: Commodity oils and fats-Palm oil. http://lipidlibrary.aocs.org/market/palm oil.htm, 2013. [Accessed 14 April 2013].

[8] Dallinger, J., Oil palm development in Thailand: economic, social and environmental considerations. In M. Colchester and Sophie Chao (ed), with Jonas Dallinger, H. E. P. S. V. T. D. J. V., Oil Palm Expansion in South East Asia: Trends and implications for local communities and indigenous peoples (Perkumpulan Sawit Watch), Chapter 1, 2011.

[9] Vermeulen, S. and Goad, N., Towards Better Practice in Smallholder Palm Oil Production, International Institute for Environment and Development, 2006.

[10] Seegräf, M., May, D., Breuer, T. and Schukat, P., Palm Oil – sustainability is possible! Promotion and certification of smallholders helps sustainable palm oil production, publication on behalf of GTZ and Federal Ministry for the Environment, Nature Conservation and Nuclear Safety of the Federal Republic of Germany, 2010.

[11] Preechajarn. S., Thailand, Oil Palm Situation Field Trip. GAIN Report Number TH0114. USDA Foreign Agricultural Service, Global Agricultural Information Network. http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Oil%20Palm%20Situation%20Field%20Trip_Bangkok_Thailand_8-9-2010.pdf, 2010. [Accessed 16 October 2012].

[12] Chiew, Y. L., Iwata, T. and Shimada, S., System analysis for effective use of palm oil waste as energy resources, Biomass and Bioenergy, Vol. 35, pp. 2925-2935, 2011.

[13] Haslenda, H. and Jamaludin, M. Z., Industry to Industry By-products Exchange Network towards zero waste in palm oil refining processes, Resources, Conservation and Recycling, Vol. 55, pp. 713-718, 2011.

[14] Leão, R. R. d. C. C., Hamacher, S. and Oliveira, F., Optimization of biodiesel supply chains based on small farmers: A case study in Brazil, Bioresource Technology, Vol. 102, pp. 8958 - 8963, 2011.

[15] Muttamara, S., Vigneswaran, S. and Shin, H.S., Palm Oil Mill Effluent Management in Thailand: A Preliminary Study, Final report submitted to UNDP/FAO, Asian Institute of Technology, Bangkok, 1987.

[16] Guo, J. and Lua, A. C., Kinetic study on pyrolytic process of oil-palm solid waste using two-step consecutive reaction model. Biomass and Bioenergy, Vol. 20, pp. 223-233, 2001.

[17] Department of Agricultural Extension Palm oil downstream industries product. http://k-center.doae.go.th/getKnowledge.jsp?id=234, 2013.

[18] Office of Agricultural Economics (2012) Agricultural Statistics of Thailand 2012, The Agricultural Cooperative Federation of Thailand, Thailand.

[19] Office of agricultural Economic (2012) Weekly production and marketing situation: Oct. 29, 2012-Nov. 4, 2012. http://www.oae.go.th/ewt_news.php?nid=13697. [Accessed 12 December 2012].

[20] Research institute, Suratthani Rajabhat University (2012) Oil palm supply chain, Suratthani. Publication report in Thailand Research Expo 2012, Bangkok.