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Effects of Pipeline Extension and Network Robustness Evaluation: the Case Study of Oil Distribution to the Northern Region of Thailand

Natthaporn Buaphut and Nanthi Suthikarnnarunai

***Abstract*—Oil distribution to the northern region of Thailand is large-scale infrastructure systems and never considers performance of network as emergency situations while government of Thailand has a policy to develop Thailand as energy center of Southeast Asia by investing pipeline expansion. This study defines a new measurement index for robustness evaluation of oil distribution. Base model and alternative model of distribution are formulated on linear programming. AMPL with CPLEX is used to solve these problems. In the process of model validation, distribution characteristics of base case are compared with previous study. After analysis, the results of study express the significance of future network impacts in this region.**

***Index Terms*—Network robustness, oil distribution, pipeline extension, linear programming**

I. Introduction

THE extension of pipeline would provide great potential for Thailand as Energy Center of South East Asia [1]. This would also reduce retail oil price differential gap, which is unfavorable for upcountry residents [2], [3], especially in the northern region, as shown in Fig. 1.

Previous strategic planning studies [5], [6], [7] shows that the extension of pipeline will provide direct benefit to save cost and energy, as well as other indirect benefit to stimulate regional economic development and improve wealth distribution. However, Risky situations due to terrorists, disasters, unrests, and other actions can affect continuity of oil distribution. Records of security incidents during 1980-2000, which concerning pipelines, oil and gas facilities, and personnel involved in the discovery, construction and exploitation of these resources, indicate that this incident occurred in Thailand [8].

Thus, It is essential to analyze network robustness of oil distribution existing today and will occur in the future to ensure oil distribution can meet the needs of oil continue to go under circumstances that are difficult to predict.

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N. Buaphut is Ph.D. Student in Logistics, School of Engineering, University of the Thai chamber of commerce, Bangkok, Thailand (e-mail: buaphut@gmail.com, buaphut@yahoo.com).

N. Suthikarnnarunai, Ph.D., is Director of Ph.D. program in Logistics, School of Engineering, University of the Thai Chamber of Commerce, Bangkok, Thailand (e-mail: nanthi_sut@utcc.ac.th, ssjnsj@yahoo.com).

II. Oil Distribution Networks and Effects of Pipeline Extension

A. Existing Distribution Networks

Currently, barge, pipeline, long-haul truck, and rail, respectively are major modes of primary transportation or shipment from refineries to depots and short-haul truck is only mode of secondary transportation or shipment from depots to end destinations. All existing distribution networks of Thailand are shown in Fig. 2.

For the northern region, pipeline is main mode to supply oil products to depots at Phra Nakhon Si Ayutthaya and Saraburi province and re-transported either to smaller depots via long-haul truck, rail, or to end destinations directly by short-haul truck [6].

B. Recommended Distribution Networks

The study [5] recommends two routes of pipeline extension from Saraburi province to Phitsanulok and Lampang province in the northern region and Nakhon Ratchasima and Khon Kaen province in the northeastern region, including the establishment of four new pipeline depots for the highest efficiency of oil distribution, as shown in Fig. 3.

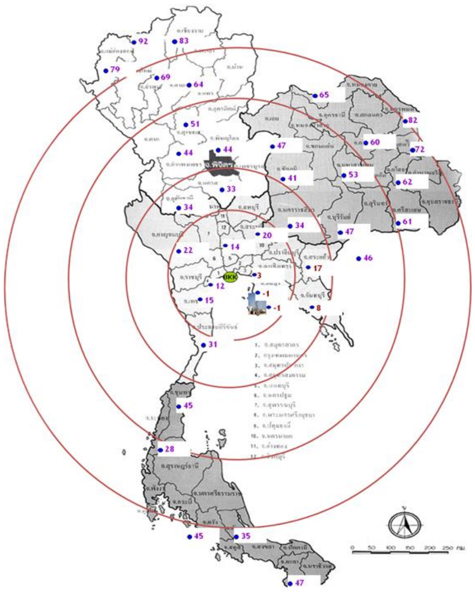

Fig. 1. Retail oil price difference between Bangkok and upcountry of Thailand [4]

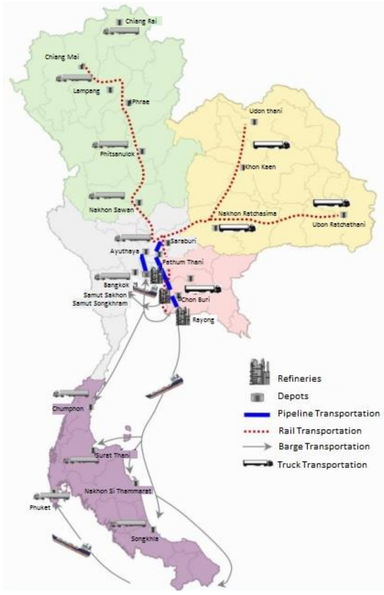

Fig. 2. Existing distribution networks of Thailand [6]

For the other regions, the existing transportation modes and facilities are already the most efficient. However, the study [5] also recommends utilizing infrastructures in oil distribution and collaborating activities among oil companies for enhancing the efficiency.

C. *Effects of Pipeline Extension and Risks*

Fig. 3 clearly shows oil distribution networks of Thailand in the future. While extended pipeline and new pipeline depots in the northern and northeastern regions start operation to distribute oil products in the expected year of operation A.D. 2018, some transportation modes and facilities in both areas will be not used for oil shipment and finally closed.

Especially in the northern region, all existing depots at Nakhon Sawan, Phitsanulok, Phrae, Lampang, Chiang Mai, and Chiang Rai province will be closed. Furthermore, long-haul truck and rail will be go out of oil transportation business. All effects of pipeline extension on infrastructures in the northern region of Thailand are shown in Table I.

TABLE I
EFFECTS OF PIPELINE EXTENSION ON INFRASTRUCTURES IN THE NORTHERN REGION OF THAILAND

Transportation modes and facilities	Without extended pipeline	With extended pipeline [5]
Primary transportations		
Extended Pipeline	None	Used
Rail	Used	Not used
Barge	None	None
Long-haul Truck	Used	Not used
Secondary transportation		
Short-haul Truck	Used	Used
Regional depots		
Chiang Rai	Opened	Closed
Chiang Mai	Opened	Closed
Lampang	Opened	Closed
Phrae	Opened	Closed
Phitsanulok	Opened	Closed
Nakhon Sawan	Opened	Closed
Extended pipeline depots		
Lampang	None	Opened
Phitsanulok	None	Opened

Thus, cases of future distribution networks are disrupted, the high impacts will occur to customers in this area. The potential threats to oil facilities and transportation systems due to terrorists and other actions are presented by the study [9], such as major damage to the infrastructure facility, serious disruption in oil supply, and fire and explosion in refineries, storage, distribution terminal, and transportation systems. Other than that, distribution networks are also threats by earthquake as seismic hazard map of Thailand shows risk areas in Fig. 4. This study discovers that extended pipeline depot at Phitsanulok province will be located in zone 1, which has intensity III-V Mercalli scale that will be felt quite noticeably indoor especially on upper floor of buildings. The other, extended pipeline depot at Lampang province will be located in zone 2A, which has intensity V-VII Mercalli scale that will be felt by nearly everyone, unstable objects overturned.

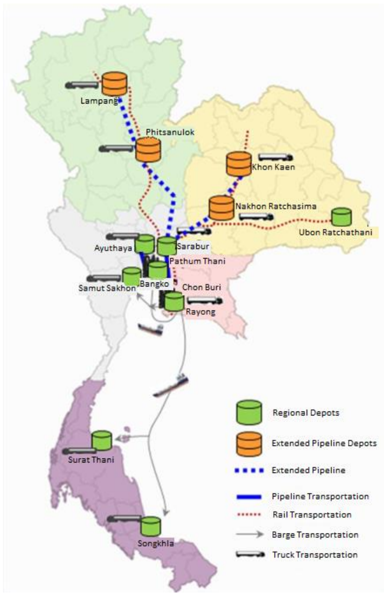

Fig. 3. Recommended distribution networks of Thailand [5]

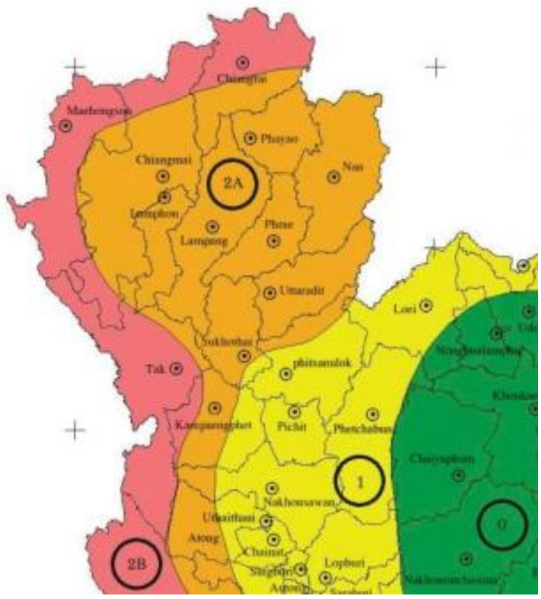

Fig. 4. Seismic hazard of Thailand [10]

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III. Application of Robustness Indices

A. Network Robustness Index (NRI)

Emergency management organizations and firms may also want to prepare link-specific plans in the event of a network disruption due to natural (e.g., mudslides, earthquakes) or human-induced (e.g., vehicle collisions, terrorism) occurrences and NRI is a valuable measure [11].

The function of NRI for evaluating the critical link of system is expressed on two steps. First step, computation of total cost when network contains all links (c) and total cost after removing link a and rerouting all flows in network (c_a). These equations are written as (1), (2).

$$c = \sum_a t_a \cdot x_a \tag{1}$$

$$c_a = \sum_a t_a \cdot x_a \cdot \delta_a \tag{2}$$

Where;

$$\delta_a = \begin{cases} 1, & \text{if link } a \text{ is not the link removed} \\ 0, & \text{otherwise} \end{cases}$$

Obviously, cost presented above is defined as travel time cost associated with travel time (t) and flow (x) of each link. Cost of link a is shown as (3).

$$t_a \cdot x_a \tag{3}$$

Second step, the c in base case and c_a in alternative case are compared in term of change in cost of removing link a (q_a). This equation is shown as (4).

$$q_a = c_a - c \tag{4}$$

This q_a is value of NRI for link a and usually shown in term of percentage change from base case. Thus, these indices are used to evaluate network robustness.

Furthermore, the concepts of impact analysis using the estimation of increased impact due to network's disruption or links belonging to network are applied to the studies [12]-[18].

B. Extended Network Robustness Index as Network Trip Robustness (NTR)

Extension of NRI is presented by the study [19] as NTR. NTR's equation is shown as (5).

$$NTR_n = \frac{\sum_a NRI_a}{D_n} \tag{5}$$

This NTR_n is calculated as the sum of NRI across all links divided by all flows (D_n) in network n. Thus, NTR is an index that can be used to compare networks with different in size scale, connectivity level, and varying demand. In addition to, NTR can be used to forecast effects of future network expansion [20].

C. Modified Robustness Indices as Oil Network Robustness (ONR)

This study applies robustness indices from previous studies to define a new measure for robustness evaluation as Oil Network Robustness (ONR). The new index integrates positive aspects of previous indices which comparing networks in different size and forecasting effects of future network expansion.

ONR_n is value in term of change in unit cost of disrupting the evaluated infrastructure n in oil distribution associated with re-optimizing all flows in network. ONR's equation is shown as (6).

$$ONR_n = uc_n - uc \tag{6}$$

Unit cost will be expressed in the appropriate unit of total cost of oil distribution per all flows of demand volume (V) in network. The uc in base case and uc_n in alternative case will be calculated by (7), (8):

$$uc = \frac{TC}{V} \tag{7}$$

$$uc_n = \frac{TC_n}{V} \tag{8}$$

Where;

TC is optimal total cost of oil distribution when network contains all infrastructures.

TC_n is optimal total cost of oil distribution after disrupting infrastructure n.

This ONR will be used to evaluate impacts of future pipeline expansion in the northern region of Thailand. Moreover, its evaluation will express in term of percentage change from base case.

IV. Distribution Models and Validation

A. Model Formulation

Two distribution models will calculate total cost of oil distribution to the northern region of Thailand in each situation. In the process of model formulation, linear programming (LP) is applied to construct equations of base model and Oil Network Robustness (ONR) is modified to create equations of alternative model. These equations are shown as (9)-(15).

Base Model

Decision variables:

x_{ij} : Volumes of 2 oil products (gasohol and biodiesel) transported from 25 regional depots, 5 pipeline depots (100 supply systems) to 20 companies' customers in 1,000 districts of the northern region of Thailand (20,000 destinations) (liters per year)

Objective function:

Minimize total cost of oil distribution (baht per year)

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$$\min \sum_{i=1}^{100}\sum_{j=1}^{20000} x_{ij}\cdot cs_{ij} + x_{ij}\cdot R\cdot cb_i + x_{ij}\cdot(1-R)\cdot cp_i \qquad (9)$$

Subject to:

Customers' constraints;

$$\sum_{i=1}^{100} x_{ij} = D_j,\ j=1,\ldots,20000 \qquad (10)$$

Northern depots' constraints;

$$\sum_{i=1}^{100}\sum_{j=1}^{20000} x_{ijn} \le S_n, n=1,\ldots,8 \qquad (11)$$

Other depots' constraints;

$$\sum_{i=1}^{100}\sum_{j=1}^{20000} x_{ijd} \le S_d, d=1,\ldots,6 \qquad (12)$$

Refineries' constraints;

$$\sum_{i=1}^{100}\sum_{j=1}^{20000} x_{ijr} \le S_r, r=1,\ldots,3 \qquad (13)$$

Decision variables;

$$x_{ij} \ge 0, \forall_i, \forall_j \qquad (14)$$

Parameters:

cp : Unit cost of primary transportation (refinery's gantry fee, barge transportation's cost, pipeline transportation's cost, rail transportation's cost, truck transportation's cost, distribution depot's throughput fee, and oil loss) (baht per liter)

cb : Unit cost of biofuel transportation (truck transportation's cost and biofuel loss) (baht per liter)

cs : Unit cost of secondary transportation (regional depot's throughput fee, truck transportation's cost, and oil loss) (baht per liter)

R : Blend ratio of biofuel (E100 and B100)

D_j : Customers' demands (liters per year)

S_n : Northern depots' capacities (liters per year)

- $n=1$: Regional depots at Nakhon Sawan
- $n=2$: Regional depots at Phitsanulok
- $n=3$: Regional depot at Phrae
- $n=4$: Regional depots at Lampang
- $n=5$: Regional depots at Chiang Mai
- $n=6$: Regional depot at Chiang Rai
- $n=7$: Extended pipeline depot at Phitsanulok
- $n=8$: Extended pipeline depot at Lampang

S_d : Other depots' capacities (liters per year)

- $d=1$: Regional depot at Pathum Thani
- $d=2$: Regional depots at Phra Nakhon Si Ayutthaya
- $d=3$: Regional depots at Saraburi
- $d=4$: Pipeline depot at Pathum Thani
- $d=5$: Pipeline depot at Phra Nakhon Si Ayutthaya
- $d=6$: Pipeline depot at Saraburi

TABLE II
MODEL VALIDATION

Distribution characteristics	Comparisons with previous study	
	This study	Study [6]
Total oil volume distributed through networks in the northern region of Thailand in year 2018 (million liters)	3,407	3,412
(% Diff)	- 0.15	-
Oil volume transported through extended pipeline in year 2018 (million liters)	2,624	2,618
(% Diff)	+ 0.23	-
Total cost of oil distribution to the northern region of Thailand in year 2018 (baht per liter)	4,219	4,152
(% Diff)	+ 1.61	-

S_r : Refineries' capacities (liters per year)

- $r=1$: Refinery at Bangkok
- $r=2$: Refineries at Chon Buri
- $r=3$: Refineries at Rayong

Alternative Model

Alternative model consists of most equations as base model, except equation of northern depots' constraints. The equation is used for critical situations of extended pipeline depots at Phitsanulok and Lampang province. This equation is shown as (15).

Northern depots' constraints;

$$\sum_{i=1}^{100}\sum_{j=1}^{20000} x_{ijn} \le S_n \cdot \delta_n, n=1,\ldots,8 \qquad (15)$$

Where;

$$\delta_n = \begin{cases} 1, & \text{if depot } p \text{ is not threatened} \\ 0, & \text{otherwise} \end{cases}$$

B. *Programming Solver*

AMPL with CPLEX is powerful program to solve large-scale systems. Thus, this study uses AMPL with CPLEX to optimize base case and alternative case that their models are formulated on linear programming problems.

C. *Base Model Validation*

Model validation is important process of study. Total oil volume distributed through networks in the northern region of Thailand (million liters), oil volume transported through extended pipeline (million liters), and total cost of oil distribution to this region (baht per liter) of base case are compared with the results of previous study, as shown in Table II.

The comparisons of these distribution characteristics in year 2018 of this study and previous study indicate that all % Diff are both positive and negative values, but not much different and not more than 2 percent. Therefore, this model is reliable.

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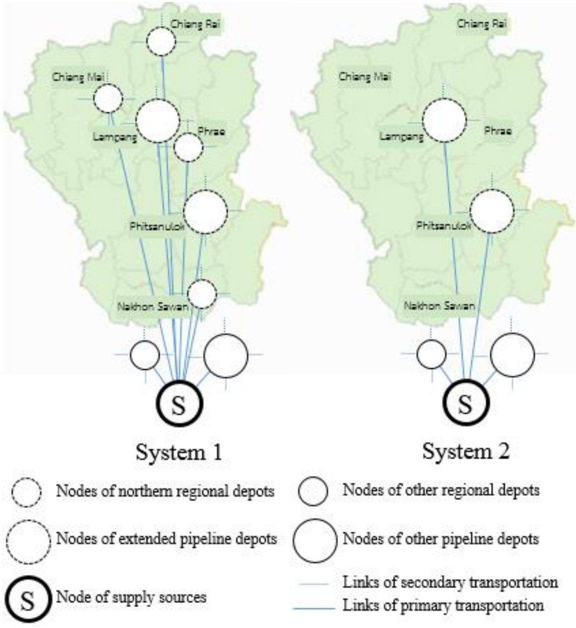

Fig. 5. Alternative systems for robustness evaluation

V. Robustness Evaluation

A. Base System

Base system in this study consists of all existing networks, including extended pipeline and new pipeline depots at Phitsanulok and Lampang province in the northern region of Thailand. The distribution characteristics are forecasted by base model. Thus, unit cost of oil distribution to the northern region of Thailand in year 2018 of base system or this base case is 1.238 baht per liter, as shown in Table III.

TABLE III
Robustness Evaluation of Extended Pipeline in the Northern Region of Thailand

Network systems	Oil distribution to the northern region of Thailand in year 2018		
	Unit cost (baht per liter)	ONR	% change
Base System (Regional depots and extended pipeline depots are opened and not disrupted)	1.238	-	-
System 1 (Regional depots are opened and not disrupted)			
1.1 Extended pipeline depots (Phitsanulok and Lampang) are threatened.	1.449	0.211	+ 17.04
1.2 Extended pipeline depot (Phitsanulok) is threatened.	1.310	0.072	+ 5.82
1.3 Extended pipeline depot (Lampang) is threatened.	1.296	0.058	+ 4.68
System 2 (Regional depots are closed. [5])			
2.1 Extended pipeline depots (Phitsanulok and Lampang) are threatened.	1.557	0.319	+ 25.77
2.2 Extended pipeline depot (Phitsanulok) is threatened.	1.324	0.086	+ 6.95
2.3 Extended pipeline depot (Lampang) is threatened.	1.320	0.082	+ 6.62

B. Alternative Systems

Alternative system 1 consists of most networks as base system, unless regional depots at Phitsanulok and Lampang province are not considered, because there will be extended pipeline depots in these province

Recommended networks of oil distribution to the northern region of Thailand by the study [5] are defined as alternative system 2. Thus, there are only two extended pipeline depots at Phitsanulok and Lampang province in the northern area.

The distribution characteristics of alternative systems or these alternative cases are forecasted by alternative model.

C. Results of Robustness Evaluation

System 1 and 2 are evaluated by Oil Network Robustness (ONR) and percentage change from base case (% change).

System 1

Robustness evaluation of system 1 is found that ONR evaluations of alternative scenario 1.1, 1.2, and 1.3 are 0.211, 0.072, and 0.058, and % change comparisons are +17.04, +5.82, and +4.68 respectively. The ONR and % change of situation 1.1, both extended pipeline depots at Phitsanulok and Lampang province threatened, is the highest impacts while the ONR and % change of situation 1.3, extended pipeline depot at Lampang threatened, is the lowest impacts.

System 2

Robustness evaluation of system 2 is found that ONR evaluations of alternative scenario 2.1, 2.2, and 2.3 are 0.319, 0.086, and 0.082, and % change comparisons are +25.77, +6.95, and +6.62 respectively. As same as system 1, the ONR and % change of situation 2.1, both extended pipeline depots at Phitsanulok and Lampang province threatened, is the highest impacts while the ONR and % change of situation 2.3, extended pipeline depot at Lampang threatened, is the lowest impacts.

Obviously, in emergency situations, system 1 expresses the significance of less impacts in all alternative scenarios of oil distribution to the northern region of Thailand than system 2, as shown in Table III.

VI. Conclusion

After analysis of above results, this study concludes that future network of oil distribution to the northern region of Thailand should consist of existing regional depots. These depots should continual go on their business while new pipeline depots in Phitsanulok and Lampang province start operation to distribute oil products in the expected year 2018 to ensure oil distribution can meet the needs of oil continue to go under emergency situations.

Future work on network robustness evaluation should be considered on other important infrastructures in energy supply chain such as gas facilities. Furthermore, the network robustness evaluation of oil distribution through flood areas is obviously interesting point in Thailand.

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