Journal of Engineering and Applied Sciences 12 (Special Issue 1): 5609-5616, 2017
ISSN: 1816-949X

Robust Optimization for Coal Transportation Planning

Marnwika Promban and Oran Kittithreerapronchai
Department of Industrial Engineering, Chulalongkorn University, 10330 Bangkok, Thailand

Abstract: To response for the increases of electricity demands in thailand, ministry of energy through power development plan 2015 mandates the commissioning of additional coal-fired power plants. According to the plan, the full-scale operation in 2035 requires additional 20 million tons per annum. This unprecedented quantity of sub-bituminous and bituminous coals reflects a strategic challenge as coals must be imported and transported to the plants at competitive logistics costs while minimizing disruption of public transportation and environmental impacts. In addition to this logistics challenge, the plan also faces with local community scrutiny and politics pressures that may delay or even cancel some coal-fired plants. To elaborate these uncertainties, a mixed-integer linear programming is formulated to analyze and assess their impacts by determining suitable modes of transportation and locations of transit facility. The model also highlights importance of key parameters, specifically coal demands at power plants and construction period of transit facilities.

Key words: Coal transportation, robust network optimization, mixed-integer, linear programming, highlights, facilities

INTRODUCTION

Despite diversification of fuels and advent of renew-able energy, a coal-fired power plant has remained pivotal pillars to global energy in terms of electricity availability and prices stability. Because of its abundant and inexpensive comparing to other fuels, coal has been supplied more than 30% globally electricity. According to the estimation of international energy agency, South East Asia plans to install additional coal-fired power plants and increases the electricity contribution from 15% in 2013-29% in 2040.

As a country that heavily relies on gas-fired electricity generation, Thailand faces a grim prospect of its domestic resource shortage and competing demands of imported Myanmar's natural gas. To response for the increases of electricity demands, ministry of energy through Power Development Plan 2015 or PDP 2015 has mandated the commissioning of additional coal-fired power plants. According to the plan in 2035, the full-scale operation requires additional 20 million tons per annum. Combining with current imported coal (USDE, 2015a-c) the plant doubles import quantities of high quality coal. This unprecedented quantity of sub-bituminous and bituminous coals reflects a strategic challenge as coal must be imported and transported to the plants at competitive logistics costs while minimizing disruption of public transportation and environmental impacts. In addition to this logistics challenge, the plan also faces with local community scrutiny and politics pressures that may delay or even cancel some coal-fired power plants. To elaborate these uncertainties, a mixed-integer linear programming is formulated to analyze and assess their impacts by determining suitable modes of transportation and locations of transit facility. Before providing the background on current coal transportation in Thailand, it is important to review a relevant literature.

Literature review: In general, this study is developed based on two streams of research, particularly coal transportation and robust optimization.

Coal transportation: As bulk commodity, transportation of coals typically requires a large vessel to achieve economy of scales with a possibility of loose coal dust during shipments. Therefore, this stream of research typically focuses on transportation planning from coal mines to power plants or factories and its environmental impact during transportation. Because of its relatively low value, the transportation costs of coal may account more than half of coal retail price (Ash *et al*., 1992). As a result, earlier researches focused on minimizing total

Corresponding Author: Marnwika Promban, Department of Industrial Engineering, Chulalongkorn University, 10330 Bangkok, Thailand

transportation costs using water or rail as preferred single mode of transportation while assuming that demands of coal were constant (Gang and Bin, 2005). Recently, the realistic transportation planning involves determining multiple modes of transportation and uncertainty of demands as demonstrated by Satar and Peoples (2010) (Remli and Rekik, 2013).

Because of low bulk density, loose coal dust may cause environmental issue during unloading at a terminal and transporting to a destination. Since, a large deposit of coal dust may harm plants and animals living, Johnson and Bustin (2006) surveyed a terminal and reported that coal pstudys with diameter of 2.36 mm or larger are likely to settle near the terminal whereas a smaller particle may disperse and float on water surface before settle further away from the terminal. Such environmental such ash from a power plant (Yucekaya, 2013a) and pollution a noise during transportation (Yucekaya, 2013b) concerns are recently incorporated in a mathematical model.

Robust optimization: One of the main drawbacks in classical deterministic optimization is that value of parameters must be realized before solving. To address inherent natural of uncertainty and sequential decisions of a problem, many researches have applied concepts of stochastic programming and formulated a problem with uncertainty parameters as robust optimization model (Chung *et al.*, 2011). Many scholars have been applied robust optimization to transportation planning problem, especially the cases in which demands and/or fuel costs are uncertain (Yao *et al.*, 2009; Baron *et al.*, 2011; Dimitris and David, 2011). Nabila considered the uncertainty shipment volumes. Recently, the uncertain events in terms of occurrence periods and their impacts were modeled as a robust optimization for example, emergency response and logistic planning (Tao, 2012). Interesting readers may consult (Dimitri and David, 2011) for the explanation of theoretical structure and surveys of robust optimization models.

Background: Located in a heart of Bangkok, the Thailand's first thermal power plant was commissioned in 1898 using coal, oil, logs and husk as fuels. After undergoing several decades of expansion and discovery of lignite in 1970's, Thailand has relied on coal-fired power plants. Coupling with hydroelectric, lignite-fired plants had supplied electricity in the northern part of the country. However, the depletion of many coal mines and potential health hazards has led to the imports of sub-bituminous and bituminous coals as low emission fuels as stated in power development plan.

Power Development Plan (PDP): PDP has been jointly developed by the electricity generating authority of Thailand and ministry of energy to serve as a framework and to ensure future reliability of power supply, fuel diversification and demand forecast, since, 2007. The plan is usually undergone a revision every 1-2 years. According to the latest version or PDP 2015, six coal-fired power plants with total capacity of 5,800 MW-hr must be built across Thailand as shown in Fig. 1.

In Fig. 1, locations of power plants and other industrial users are depicted. Their sizes represent required annual quantities of coal in 2035 according PDP 2015. The plan also requires a coal terminal to unload imported coal and to distribute to power plants and industrial users. Majority of power plants are located in southern provinces where electricity is insufficient and requires long distant transmission. Other potential users of coals are industrial users that are located in central provinces such as cement food and study industries. These industries currently purchase imported coal. In fact, some users are actively engaging in coal trading and mining through its subsidiary companies.

Hence, it is difficult to penetrate and gains significant market share from current players. Furthermore, their annual demand is overshadowed by power generation demand. As a result, a coal terminal is assumed to be located near future coal-fired power plants to minimize transportation costs and materials handling between major nodes.

Modes of transportation: Because a coal terminal requires deep-water seaport, shipments from the terminal can be classified into three options by modes of transportation and transit facilities as shown in Fig. 2.

Figure 2 shows modes of transportation for which power plants or industrial users can receive coal shipments from a coal terminal. Because of spatial limitation, the final mode of transportation must be truck. Option 1 represents a situation where a coal terminal and power plant are located adjacent there by only trucks are required for transportation. The remaining two options involve barges as the most economic mean of trans-portation. Option 2 requires two transit facilities as coal is shipped from a coal terminal by barges to the first transit facility and then transshipped by railway to the second transit facility before delivery to destinations by

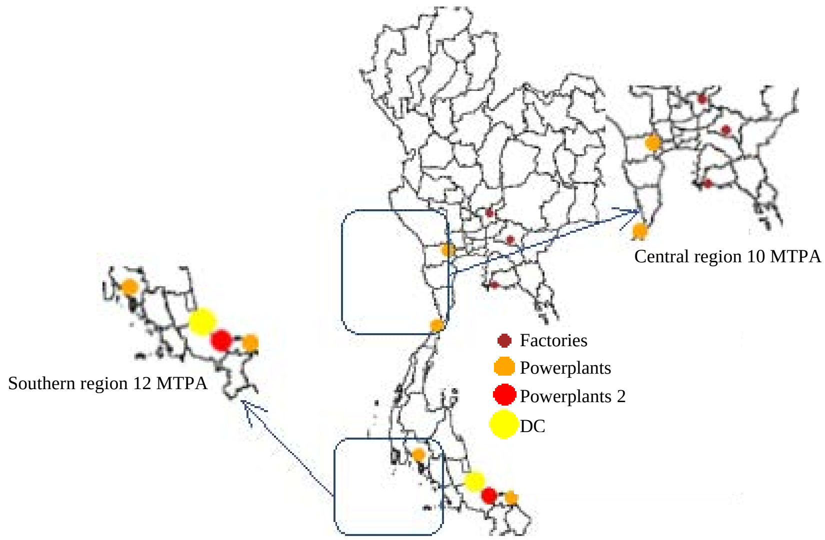

Fig. 1: Locations of power plants and industrial users

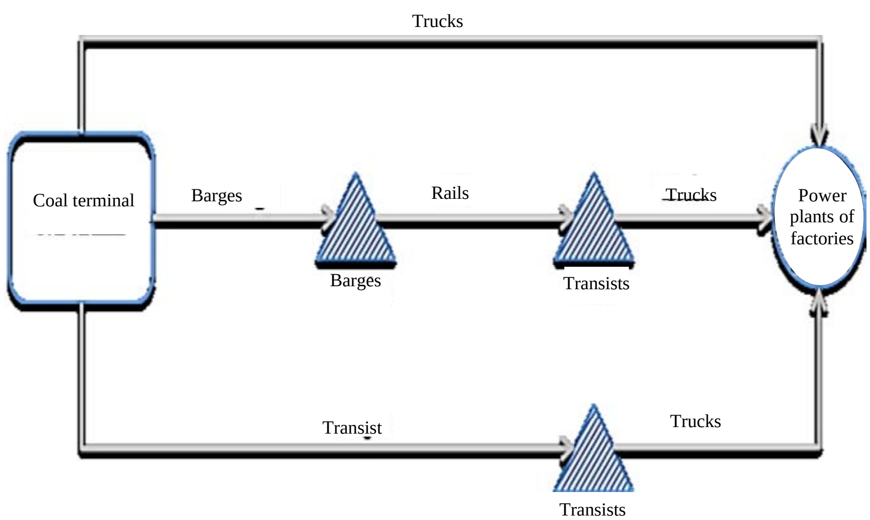

Fig. 2: Coal transportation from a coal terminal to power plants and industrial

trucks. The last option requires a single transit facility to switch from barges to trucks before reach destinations. Some modes of transportation such as barges and trucks may expose to operation risks such as traffic congestion and deterioration of public infrastructure. To account for such uncertainty, scenarios of coal transportation are developed.

Scenario development: Ever since the release of PDP 2015, the plan has faced with local community scrutiny and politics pressures that may delay or even cancel some coal-fired plants. To elaborate these uncertainties, the scenarios are developed based on two social topics.

Local community scrutiny: This is relatively mind topic. As construction of a coal terminal and coal-fired power plants are mega-infrastructure project, environmental impact assessment is required. Despite local setback and additional process, Thepha thermal power plants are expected to commission within 5 years.

Public perspective of power plants: This is a main topic that plagues electricity generating authority of Thailand electricity since the mae moh power plant incident. Excessive coal dust and air pollution from lignite-fired power plants undermined health of nearby population and led to the public relationship nightmare for large scale

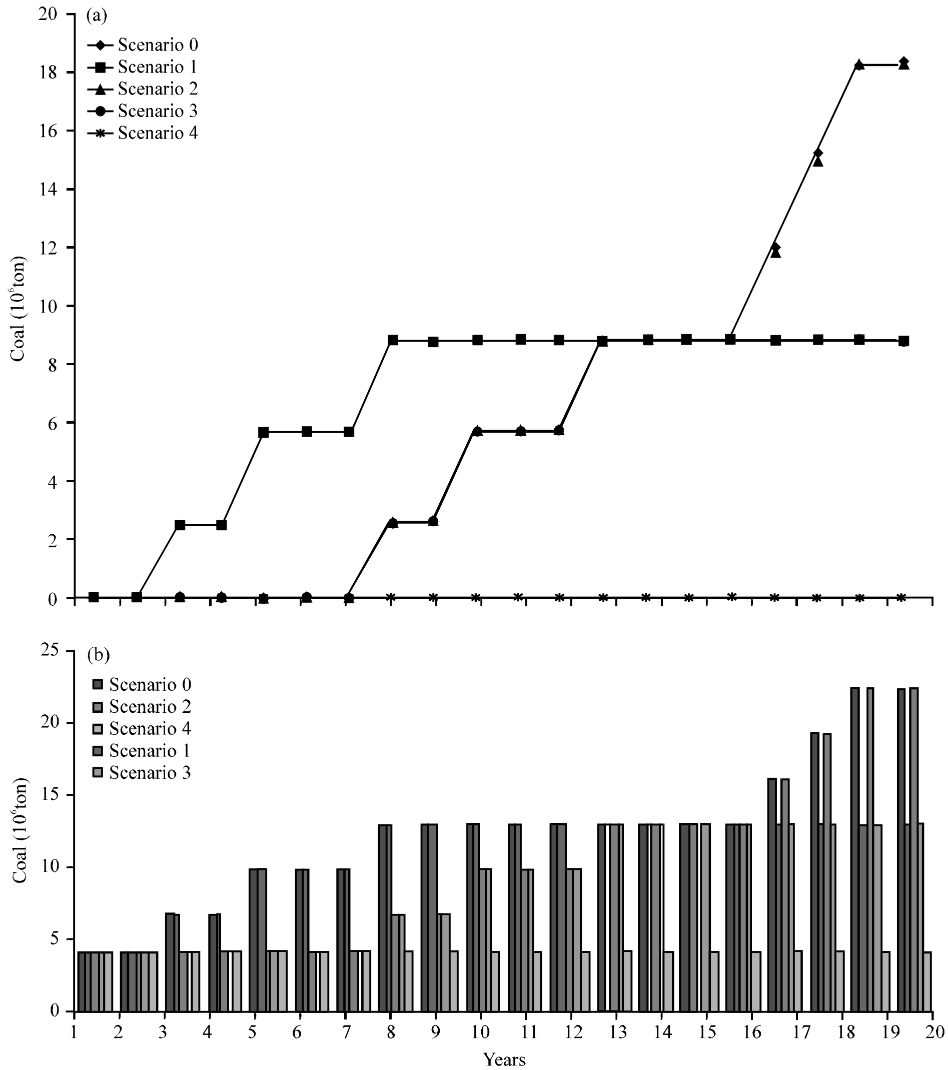

Fig. 3: Coal demands and projected electricity demands

power plants. Consequence of this topic may result to 10 years delay or even cancel of all coal-fired projects. The analysis of these uncertain topics leads to inter-dependent development of two time periods in PDP 2015, particularly.

First 10 years of PDP 2015: This is referred to years 2016-2025. In general, this time period can be foreseen and it consists of three possibilities, particularly (A0) follow PDP 2015 projection, (A1) delay commission of initial power plant for 5 years and (A2) cancel all power plants.

Last 10 years of PDP 2015: This is referred to years 2026-2035. This time period exhibits highly uncertainty and depends on the first 10 years. Two possibilities are (N1) follow PDP2015 projection (N2) cancel all power plants because of inter-dependent nature of two time periods, the analysis focuses on five distinct scenarios and their corresponding coal demands of power plants and industry user as well as projected electricity demands as shown in Table 1 and Fig. 3, respectively.

Table 1: Scenario development in two time periods

Scenarios	First 10 years	Last 10 years
0	A0: follow PDP2015	N0: follow PDP 2015
1	A0: follow PDP2015	N1: cancel power plant
2	A1: delay 5 years	N0: follow PDP 2015
3	A1: delay 5 years	N1: cancel power plant
4	A2: cancel power plant	N1: cancel power plant

MATERIALS AND METHODS

Mathmatical model: After explaining uncertainties as well as operational risks, a mixed-integer linear programming to determine suitable modes of transportation and locations of transit facility is formulated to analyze and access impacts. The model can be considered as a generalization of transshipment problem that allows coal inventory and optional construction at transit facilities and consists of following components.

Indices:

- O = Set of coal centers
- P = Set of coal-fired generation plants
- F = Set of factories
- L = Set of transit nodes
- A = Set of arcs A = {O×L L×P L×F L×L}
- V = Set of types of vessels
- T = Set of periods
- T' = Set of appended periods, T' = T {|T+1|}
- Ω = Set of scenario

Parameters and decision variables:

- $w^{trans}_{ijvt\omega}$ = Weight of coal shipped through arc (i, j) using vessel type v at period t and scenario ω
- $w^{end}_{lt\omega}$ = Weight of coal inventory at node l at the end of period t and scenario ω
- $w^{avg}_{lt\omega}$ = Weight of average coal inventory at node l at period t and scenario ω
- $w^{end}_{pt\omega}$ = Weight of coal inventory at power plant p at the end of period t and scenario ω
- $w^{avg}_{pt\omega}$ = Weight of average coal inventory at power plant p at period t and scenario ω
- $w^{end}_{ft\omega}$ = Weight of coal inventory at factory f at the end of period t and scenario ω
- w^{avg}_{ftw} = Weight of average coal inventory at factory f at period t and scenario ω
- $w^{trans}_{ijvt\omega}$ = Binary variable representing

$$x^{trans}_{ijvt\omega} = \begin{cases} 1, & \text{if coal is shipped through arc } (i,j) \text{ using vessel type v at period t and scenerio } \omega \\ 0, & \text{otherwise} \end{cases}$$

- $z^{const}_{lt\omega}$ = Binary variable representing:

$$z^{const}_{lt} = \begin{cases} 1, & \text{if node is constructed at period t and scenerio } \omega \\ 0, & \text{otherwise} \end{cases}$$

- $z^{const}_{lt\omega}$ = Binary variable representing:

$$z^{avail}_{lt\omega} = \begin{cases} 1, & \text{if node l is available to transit coal at period t and scenerio } \omega \\ 0, & \text{otherwise} \end{cases}$$

- $z^{const}_{lt\omega}$ = Binary variable representing

$$z^{avail}_{pt\omega} = \begin{cases} 1, & \text{if power plant p is available to service at period t and scenerio } \omega \\ 0, & \text{otherwise} \end{cases}$$

- d_{ijv} = Distance of arc (i, j) using vessel type v
- c^{trans}_{v} = Unit transportation cost of vessel type v
- c^{inv}_{j} = Unit holding cost of transit node l
- c^{maint}_{j} = Annual maintenance cost of transit node l
- c^{const}_{lt} = Construction cost of transit node l at period t
- c^{oper}_{j} = Operation cost of transit node l
- $c^{purch}_{pt\omega}$ = Purchase electricity cost to fulfill power plant p at period t and scenario ω
- $c^{lost}_{pt\omega}$ = Lost electricity of power plant p at period t and scenario ω
- $c_{pt\omega}$ = Tonnage demands of coal in at power plant p at period t and scenario ω
- $D_{ft\omega}$ = Tonnage demands of coal in at factory f at period t and scenario ω
- γ_{ijv} = Average numbers of round a vessel type v can make arc (i, j)
- $\underline{c}_l$ = Minimum coal storage capacity of transit node l
- $\bar{c}_l$ = Maximum coal storage capacity of transit node l

Objective function:

$$TC \geq TC^{trans}_{\omega} + TC^{inv}_{\omega} + TC^{faci}_{\omega} + TC^{admin}_{\omega} + TC^{purch}_{\omega}, \forall\omega \in \Omega \quad (1)$$

Constraints:

$$TC^{trans}_{\omega} = \sum_{t}\sum_{v}\sum_{(i,j)} c^{trans}_{v} d_{ijv} w^{trans}_{ijvt\omega},\ \forall\omega \in \Omega \quad (2)$$

$$TC^{inv}_{\omega} = \sum_{t}\sum_{l} c^{inv}_{l} \omega^{avg}_{lt\omega}, \forall\omega \in \Omega \quad (3)$$

$$TC^{faci}_{\omega} = \sum_{l}\sum_{t}\left(c^{maint}_{l} z^{avail}_{lt\omega} + \sum_{t} c^{const}_{lt} z^{const}_{lt\omega}\right), \forall\omega \in \Omega \quad (4)$$

$$TC^{admin}_{\omega} = \sum_{t}\sum_{l} c^{oper}_{l} z^{avail}_{lt\omega},\ \forall\omega \in \Omega \quad (5)$$

$$TC_{\omega}^{purch} = \sum_{p}\sum_{t} c_{pt\omega}^{purch} e_{pt\omega}^{lost}, \forall\omega \in \Omega \quad (6)$$

In each scenario, Eq. 2-6 define trans portation costs, inventory costs, facility construction and maintenance costs, administrative costs and difference in electricity with altenative sources, respectively:

$$\underline{C}_l z_{lt\omega}^{avail} \le \omega_{lt\omega}^{end} \le \overline{C}_l z_{lt\omega}^{avail}, \forall l \in L, \forall t \in T, \forall\omega \in \Omega \quad (7)$$

$$\underline{C}_l z_{lt\omega}^{avail} \le \omega_{lt\omega}^{avg} \le \overline{C}_l z_{lt\omega}^{avail}, \forall l \in L, \forall t \in T, \forall\omega \in \Omega \quad (8)$$

$$\underline{C}_p z_{pt\omega}^{avail} \le \omega_{pt\omega}^{end} \le \overline{C}_p z_{pt\omega}^{avail}, \forall p \in P, \forall t \in T, \forall\omega \in \Omega \quad (9)$$

$$\underline{C}_p z_{pt\omega}^{avail} \le \omega_{pt\omega}^{avg} \le \overline{C}_p z_{pt\omega}^{avail}, \forall p \in P, \forall t \in T, \forall\omega \in \Omega \quad (10)$$

$$\underline{C}_f \le \omega_{ft\omega}^{end} \le \overline{C}_f, \forall f \in F, \forall t \in T, \forall\omega \in \Omega \quad (11)$$

$$\underline{C}_f \le \omega_{ft\omega}^{avg} \le \overline{C}_f, \forall f \in F, \forall t \in T, \forall\omega \in \Omega \quad (12)$$

Eqauation 7-12 assure that average quantities of coal at any locations and any periods never exceed their storage capacities:

$$\omega_{lt\omega}^{avg} = \frac{1}{inv_{l\omega}}\left(\sum_{i}\sum_{v} \omega_{ilvt\omega}^{trans} - \omega_{lt\omega}^{end} + \omega_{l(t+1)\omega}^{end}\right), \quad \forall l \in L, \forall t \in T, \forall\omega \in \Omega \quad (13)$$

$$\omega_{pt\omega}^{avg} = \frac{1}{inv_{p\omega}}\left(D_{pt\omega} - \omega_{pt\omega}^{end} + \omega_{p(t+1)\omega}^{end}\right), \quad \forall p \in P, \forall t \in T, \forall\omega \in \Omega \quad (14)$$

$$\omega_{ft\omega}^{avg} = \frac{1}{inv_{f\omega}}\left(D_{ft\omega} - \omega_{ft\omega}^{end} + \omega_{f(t+1)\omega}^{end}\right), \quad \forall f \in F, \forall t \in T, \forall\omega \in \Omega \quad (15)$$

Equation 13 and 15 determine the average quantities of coal at different facilities that reflect both operations such as available inventory and quantities of transported coal as well as policy such as inventory turnover:

$$\sum_{v} x_{ijvt\omega}^{trans} \le 1, \forall(i,j) \in A, \forall t \in T, \forall\omega \in \Omega \quad (16)$$

$$\omega_{ijvt\omega}^{trans} \le M x_{ijvt\omega}^{trans}, \forall(i,j) \in A, \forall v \in V, \forall t \in T, \forall\omega \in \Omega \quad (17)$$

Equation 16-17 specify a usage of single mode of transportation at any pair and given period:

$$\omega_{lt\omega}^{end} + \sum_{i}\sum_{v} \omega_{ilvt\omega}^{trans} = \omega_{l(t+1)\omega}^{end} + \sum_{j}\sum_{v} \omega_{ljvt\omega}^{trans}, \quad \forall l \in L, \forall t \in T, \forall\omega \in \Omega \quad (18)$$

$$\omega_{pt\omega}^{end} + \sum_{i}\sum_{v} \omega_{ipvt\omega}^{trans} = \omega_{p(t+1)\omega}^{end} + D_{pt\omega}, \quad \forall p \in P, \forall t \in T, \forall\omega \in \Omega \quad (19)$$

$$\omega_{ft\omega}^{end} + \sum_{i}\sum_{v} \omega_{ifvt\omega}^{trans} = \omega_{f(t+1)\omega}^{end} + D_{ft\omega}, \quad \forall f \in F, \forall t \in T, \forall\omega \in \Omega \quad (20)$$

Equation 18-20 ensure the balance of coals at each facility. At any time period, the quantities of incoming coals plus its initial inventory must equate to their outgoing ones and final inventory. For a power plant and a factory, the remaining inventory must reflect the quantities of consumption and transportation:

$$\sum_{t=1}^{\hat{t}} z_{lt\omega}^{avail} \le \hat{t} \sum_{t=1}^{\hat{t}} z_{lt\omega}^{const} \; \forall l \in L, \forall\hat{t} \in T, \forall\omega \in \Omega \quad (21)$$

$$z_{lt\omega}^{avail} \le z_{l(t+1)\omega}^{avail} \; \forall l \in L, \forall t \in T, \forall\omega \in \Omega \quad (22)$$

$$\sum_{i}\sum_{v} \omega_{ilvt\omega}^{trans} \le M\, z_{lt\omega}^{avail}, \forall l \in L, \forall t \in T, \forall\omega \in \Omega \quad (23)$$

Equation 21-23 governs shipped coals through a transit facility and its construction, particularly a facility is available to transport coal after construction and available through the end of time horizon:

$$C_v^{wt} r_{ijv} \ge \omega_{ijvt\omega}^{trans}, \forall(i,j) \in A, \forall v \in V, \forall t \in T, \forall\omega \in \Omega \quad (24)$$

Equation 24 ensures that the relationship between shipped coals and vehicle capacity:

$$\omega_{lt\omega}^{end}, \omega_{lt\omega}^{avg} \ge 0, \forall l \in L, \forall t \in T', \forall\omega \in \Omega \quad (25)$$

$$\omega_{pt\omega}^{end}, \omega_{pt\omega}^{avg} \ge 0, \forall p \in P, \forall t \in T', \forall\omega \in \Omega \quad (26)$$

$$\omega_{ft\omega}^{end}, \omega_{ft\omega}^{avg} \geq 0, \forall f \in F, \forall t \in T', \forall \omega \in \Omega \quad (27)$$

$$\omega_{ijvt\omega}^{trans} \geq 0, \forall (i,j) \in A, \forall v \in V, \forall t \in T, \forall \omega \in \Omega \quad (28)$$

$$z_{lt\omega}^{avail}, z_{lt\omega}^{const} \in \{0,1\}, \forall l \in L, \forall t \in T, \forall \omega \in \Omega \quad (29)$$

$$x_{ijvt\omega}^{trans} \in \{0,1\}, \forall (i,j) \in A, \forall v \in V, \forall t \in T, \forall \omega \in \Omega \quad (30)$$

Equation 25-30 account for non-negativity and binary of decision variables.

RESULTS AND DISCUSSOIN

The five scenarios are embedded into the model and solved with IBM ILOG CPLEX 12.4 interfaced with IBM OPL 6.3 on an Intel (R) Core™ i7-4210U machine with physical memory 8 GB. The robust solution is derived from total cost in scenarios 4 or no coal-fired power plant is commissioned. The components of solution are listed in Table 2.

The solution emphasizes the important roles of coal fired power plants in Thailand. The difference in electricity in Table 2 shapes the solution as electricity generating authority of Thailand needs to pursue natural gas to meet the PDP 2015 energy projection.

The results also shade insights to strategic logistics planning. Particularly, truck is a dominated mode of transportation in highly uncertain scenarios whereas rail and river provide more economic benefits as shown in Fig. 4.

Table 2: Components of solution (in 10^9 THB)

Variables	Scenario 0	1	2	3	4
Transportation	43.18	42.04	38.15	37.88	32.43
Inventory	28.16	29.29	33.12	33.40	26.48
Facility	0.08	0.08	0.12	0.11	0.12
Administrative	0.05	0.06	0.08	0.08	0.08
Diff. in elec.	0.00	579.00	901.00	1480.00	3373.00
Total	71.47	650.47	972.47	1551.47	3432.41

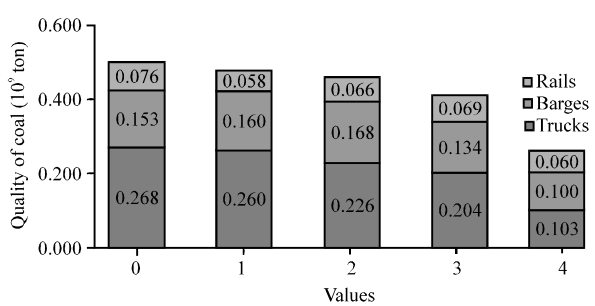

Fig. 4: Transported coals by mode of transportation

Despite, higher unit cost and limited capacities, trucks require neither construction nor maintenance of transit facilities. Furthermore, suggested transit facilities should be constructed at the beginning of project to ensure high utilization and to reap economic benefits of railway and barges.

CONCLUSION

This study studied the transportation effects of commissioning additional coal-fired plants according to PDP 2015. Because of unprecedented coals and as uncertainty factors, the commissioning plan may be delayed or even canceled. As a result, the strategic transportation planning of coal was modeled as a robust optimization model. The optimal solution revealed the economic impacts of coal-fired power plants and the domination of trucks as land transportation.

Because of significant economic impacts, it is important to investigate other alternative fuels and to verify the energy projection in PDP2015. Another possible extension is solution method as a robust optimization model has inherited L-shaped structure. Therefore, the model can be decomposed into one single master problem and a sub-problem representing each scenario to improve computational time.

ACKNOWLEDGEMENT

The researchers would like to thank contributors and companies for interviews and site visits as well as other various supports from Industrial Management and Technology center.

REFERENCES

Ash, G.R., J.S. Chen, A.E. Frey and B.D. Huang, 1992. Realtime network routing in a dynamic class-of-service network. Proc. ITC., 13: 187-194.

Baron, O., J. Milner and H. Naseraldin, 2011. Facility location: A robust optimization approach. Prod. Oper. Manage., 20: 772-785.

Chung, D.B., T. Yao, C. Xie and A. Thorsen, 2011. Robust optimization model for a dynamic network design problem under demand uncertainty. Networks Spatial Econ., 11: 371-389.

Dimitris, B.B.B. and C. David, 2011. Constantine theory and appli-cations of robust optimization. Soc. Ind. Appl. Math., 53: 464-501.

Gang, Z. and Q. Bin, 2005. Pan on shanghai power coal transportation system on Yangtze River. Syst. Eng. Theory Pract., 1: 140-142.

Johnson, R. and R.M. Bustin, 2006. Coal dust dispersal around a marine coal terminal 1977-1999 British columbia: The fate of coal dust in the marine environment. Int. J. Coal Geol., 68: 57-69.

Remli, N. and M. Rekik, 2013. A robust winner determination problem for combinatorial transportation auctions under uncertain shipment volumes. Transp. Res. C. Emerging Technol., 35: 204-217.

Satar, N.M. and J. Peoples, 2010. An empirical test of modal choice and allocative efficiency: Evidence from US coal transportation. Transp. Res. E. Logistics Transp. Rev., 46: 1043-1056.

Tao, Y., 2012. Large Scale Evacuation Transportation Systems: Robust Models and Real Time Operations. Mid-Atlantic Christian University, Elizabeth, North Carolina,.

USDE., 2015a. U.S. energy information administration: Annual energy outlook. Department of Energy, Washington, DC, USA., http://www.eia.gov/forecasts/ aeo /pdf/0383 (2015).pdf.

USDE., 2015b. US Energy information administration: Coal prices and outlook. US Department of Energy, Washington, D.C., USA., http://www.eia. gov/Energy explained/index.cfm?page=coal_prices.

USDE., 2015c. US energy information administration: Analysis of the impact of the clean power plan. Department of Energy, Washington, DC, USA., http://www.eia.gov/analysis/requests/powerplants/cleanplan/pdf/powerplant.pdf.

Yao, T., S.R. Mandala and D.B. Chung, 2009. Evacuation transportation planning under uncertainty: A robust optimization approach. Networks Spatial Econ., 9: 171-189.

Yucekaya, A., 2013b. Cost minimizing coal logistics for power plants considering transportation constraints. J. Traffic Logistics Eng., 1: 122-127.

Yucekaya, A., 2013a. Managing fuel coal supply chains with multiple objectives and multimode transportation. Eng. Manage. J., 25: 58-70.