FUZZY MIXED INTEGER LINEAR PROGRAMMING MODEL FOR MONTHLY UNIT COMMITMENT IN THE NATIONAL LEVEL POWER SYSTEM

BY

MS. TRUONG QUYNH HOA

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE (ENGINEERING AND TECHNOLOGY)

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was approved as partial fulfillment of the requirements for
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ABSTRACT

In large-scale monthly unit commitment, the generation system is committed to schedule list of available generating units and available fuel provision for a whole month. Despite challenging numerous operational restrictions, especially in the national level power system, the fluctuating factors such as load demand, fuel price, affect to the decision making on generating electricity in the uncertain market. An effort to deal with price fluctuation by proposing a Fuzzy Mixed Integer Linear Programming Model focusing on fuel price in the uncertainty environment for the monthly unit commitment in the national level power system is introduced. Adding a fuzzy parameter which takes the fluctuation of fuel price, the crisp monthly unit commitment problem is transferred into a form of impreciseness. The price-based uncertainty in monthly unit commitment problem is handled with attempting to minimize fluctuation tolerance of fuel price. A real national planning level in Thailand power system which comprises multiple types of generators and supplied fuels is tested using the proposed technique. Particularly, the small test case including 24-unit system and the national level planning with 204-unit system are used for sensitivity analysis on fuel price and manifesting the efficiency of the proposed Fuzzy MILP model. Total cost and fuel cost are revealed by solving the modeling technique. Moreover, the fluctuation behaviors of fuel selection among such types providing to the same generating unit are also analyzed.

Keywords: Monthly unit commitment, Power system planning, Fuzzy Mixed Integer Linear Programming, Large-scale system, Uncertainty

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Ms. Truong Quynh Hoa

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LIST OF SYMBOLS/ABBREVIATIONS

Symbols/Abbreviations	Terms
MUC	Monthly unit commitment
MILP	Mixed Integer Linear Programming

CHAPTER 1
INTRODUCTION

1.1 Background of study

In the power system, monthly unit commitment (MUC) is one of an optimization problem which aims to operate the power generating units on each day of the month to satisfy the forecasted energy demand. The objective is to minimize the total cost including fuel cost and operational cost. The generating units are committed to be online state or turned on/turned off which are optimally decided throughout the operation process. With the development of the management level, the large-scale combinational optimization problem is challenging in term of the operation decisions and system planning of generators due to a large number of generating units, particularly in the national level power system. The MUC problems implement the optimal generation for a whole month system demand. An optimal monthly scheduling is considered to accommodate not only the forecasted demand and fuel preparation but also the daily consumption and short-term energy load as well. During a whole day, there are specific peak time periods that requires more electricity demand and accordingly leads to require more generating units to satisfy the total daily energy demand. Therefore, there might not be enough units for generating electricity at the peaks. In addition to the shortage of production, the supplied fuel to power system might not provide sufficiently in the daily operational generation planning. Besides, there is a diversification of power resources which recently exploited and multi-energy system including many types of power plants and their behaviors in large-scale system. Each operating unit in the power plant also has particular characteristics.

Optimizing MUC model is challenged by many operational restrictions and technical specifications in the power system. The overall generation consider the generating decisions in order to optimally produce electricity and avoid the overproduction as well as electricity shortage. It means that the actual demand is approximately balanced to the total power load. A decided generation scheduling needs to assure this operational balance and in case of admitting to the aforementioned risks, the cost-benefit tradeoff is determined. It is assigned that the power system would produce overload or incur a certain penalty for generating insufficiently. In a similar way, the fuel usage is also judged to increase cost when fuel is provided inadequately or overstock. At the specific stages, there is unexpected outage of generators and the power system may occur the loss power source such as transformation intermittent or overload. Therefore, the generation capacity should be installed to generate electricity more than the forecasted demand. Spinning reserve represents this total capacity and it committed that the generation capacity is online in addition to be unutilized at that time. However, it is quite hard to schedule the spinning reserve commitment since the overload must be eliminated in the entire system and the optimization of production planning is challenging within such multi-energy system.

In the multi-energy power system, on the other hand, there is a fuel selection for generating units during the operation time period. Among many fuel types with different technical aspects, the optimal decisions are capable to appropriately select which type of fuel should be used for each unit. The reason is that several units can have more than one type of fuel due to the compatibility of fuels and some fuel types can be used simultaneously for particular generators. One of the other challenges in MUC problem is the generating units cannot be suddenly turned on or turned off in the power system. Starting up and shutting down a power plant usually result in an increasing maintenance cost, and sometimes it may happen the interrupted system. The generating units are required to remain on at least some time periods which is termed as minimum uptime once it is turned on and before it can be turned off. It is defined for minimum downtime in the same meaning. There are several units, however, with the minimum uptime are less than one day. It must also be considered to schedule in the optimal decisions. Additionally, the ramp rate in power plants are discussed as an attempt to avoid damaging the turbine. In a multiple power system with multi-energy resource, the power output is limited by ramp up and ramp down of generating units. Normally, hydropower system has rapid ramping rate and its power output is used during the peak load period in order to quickly accommodate the electricity demand at time period.

Taking the challenge of this problem, many efforts have been devoted to optimally construct the UC problem. Meanwhile, it is inevitable to face with flexibility in the electricity markets. In fact, uncertain factors become the critical terms and significantly influence to the manufacturing process, especially the production cost and the fluctuation of energy resource. These elements need to be included into modeling by appropriate techniques. So far, fuzzy optimization has been introduced as a robust approach to handle uncertainties. Founded by Professor Lotfi Zadeh, fuzzy set theory is a conceptual framework dealing with situations in which the data are uncertain. In such problems, fuzzy formulation is associated with figuring out the relationship among the optimal objectives and their possibilities which called degree of satisfaction or the degree of optimal objective possibility. Technically, fuzzy optimization procedure transforms objectives or constraints or both of them at the same modeling into the satisfaction degree of fuzzy sets. The optimal solutions are also evaluated by the correlation based on the satisfaction degree and eventually decided by scheduler in term of their objective functions. Optimization of this compromise can be obtained using an optimization technique. In this research, Fuzzy MILP modeling is applying. The basic work is to convert the fuzzy form into an equivalent crisp problem. Subsequently, the optimal results are revealed by maximizing the intersections of sets of satisfaction functions and subjected to the crisp constraints of the problem.

In this research, a Fuzzy MILP optimization model for MUC problem concerning with flexibility environment is developed. Focusing on the fluctuation of fuel price, the critical objectives and operational requirements are established for determining the optimal total cost and optimizing fluctuation tolerance of fuel price. Moreover, producing electricity and providing the fuel supply problem is also examined to satisfy electrical consumption in addition to cover the peak periods for the whole month of multi-energy systems in the national level planning. The experimental execution is analyzed in term of the impacts of fuel price to the decision optimization and systematic operation in the power system.

1.2 Objective of study

The study aims to propose a Fuzzy Mixed Integer Linear Programming Model focusing on fluctuation for fuel price. Moreover, an operation of next month where the fuel price is uncertain and fluctuate is planned.

1.3 Structure of study

The remaining of this study is organized as follows. The previous researches on monthly UC and their contributions are reviewed in Chapter 2. Chapter 3 describes the deterministic MUC model with MILP optimization and an imprecise optimal modeling beyond the crisp problem is proposed with fuzzy optimization and solved by Fuzzy MILP solution method. Chapter 4 provides a sensitivity analysis and experimental setting of multi-energy case study. The experimental execution is analyzed on the impacts of fuel price variance to the decision of optimization and operation of multi-energy system in the national level planning. The results are discussed in Chapter 5.

CHAPTER 2
LITERATURE REVIEW

2.1 Long-term unit commitment

The appearance of unit commitment problem in electrical power system has been first introduced since 1940s (Abdou & Tkiouat, 2018). Afterward, many issues of UC problem have discussed and solved by developed technique. The authors proposed various approach with objective to find the optimal production schedule of a set of generation units whereas satisfy operational constraints and systematic features. Especially, long-term planning has become a significant area due to its applicable effects in the reality. Recently, a view of deterministic MUC got attracted to numerous researchers (Bai et al., 2014; Geng et al., 2013; Truong & Jeenanunta, 2019; Wang et al., 2012). The large-scale system with a hundred of generators, namely provincial and national system, is experimentally studied. Accordingly, the advantage of MIP model is approached as a modeling problem. Most of them discussed Brand and Cut method to find out the optimal solution (Bai et al., 2014; Geng et al., 2013; Wang et al., 2012). Specifically, a fast-bounding technique was proposed to improve the traditional branch-and-cut algorithm. This method helped to increase the lower bound and decrease the upper bound for the optimal solution and improve the performance speed of monthly SCUC (Wang et al., 2012). In order to improve the traditional branch-and-cut algorithm, two-stage model transforming technique (Geng et al., 2013) and Inducing-objective-function-based method (Bai et al., 2014) are also developed in term of improving the speed of computation. Considering the peak-load constraints, the MUC modeling is demonstrated to satisfy the monthly forecasted demand and peak load for a whole month (Truong & Jeenanunta, 2019).

2.2 Proposed technique

Nowadays, the accelerating growth in resource renewable energy in addition to fossil-fuel energy and initial features of electricity consumption lead to the uncertainty of MUC optimization. In the power system considering the flexibility, there are different approaches have been addressed. Based on mathematical programming techniques, stochastic programming and fuzzy programming are common methods to handle those problems. These technique can provide a concept that using different membership function for generation scheduler to make the optimal solution between the profit/cost and their degree of possibility in uncertain environment. Concerning the effect of wind power integration to optimal result, a view of stochastic is proposed. In particular, the chance-constrained stochastic formulation is transferred to a deterministic equivalent (Ge & Xia, 2015; Yin & Zhao, 2018). Due to the correlation and randomness of wind farms, the combined probability distribution of output is calculated by dependent sequence operation. The result of model considering wind power uncertainty and demand response uncertainty is optimized by using unit commitment model with conditional value-at-risk. Numerous researches have suggested fuzzy optimization to deal with uncertainty UC problem, even in the daily model (Assad, 2011; Kadam et al., 2009; Mantawy, 2004; Saneifard et al., 1997). The model could be formulated by multi-objective modeling which including profit maximization (Lotfi & Ghaderi, 2013), cost minimization (Saber et al., 2006), or satisfaction-based maximization. Regularly, fuzzy objective is expected according to the initial UC model. It could be the operational cost, fuel cost, electric sale profit, and so on. On the other hand, optimizing in the fuzzy model has been performed by maximizing the minimum of satisfaction parameters which setting the fuzzy set of objectives or constraints (Venkatesh et al., 2007; Venkatesh et al., 2000). The optimal solutions are obtained by intersection of membership functions which present the degree of optimal values and their effects to the objective.

In this research, we arise the perspective of previous studies to propose a fuzzy monthly unit commitment model focusing on fuel price in the flexibility market. The application of Fuzzy Mixed Integer Linear Programming is approached to handle this problem with large-scale system and combine extensive issues which the others have not simultaneously discussed. The fuzzy optimization provides an implementation to transfer multi-objective model into the crisp one dealing with uncertainty factors. The new proposed aspect brings out the behavior of fuel price fluctuation while the generators are available to have mixed fuel type. The reputable publications in monthly unit commitment problem are briefly given in Table 2.1.

Table 2.1 Summary of publications in unit commitment problem

No.	Author (Year)	Modeling technique									Objective function		Daily model	Monthly model	Types of fuel	Number of units
		MILP	MINLP	Stochastic	Fuzzy Possibilistic	Fuzzy SA	Fuzzy GA	Fuzzy If-Then Rule	Fuzzy LP	Fuzzy MILP	Single	Multiple				
1	Saneifard, et al. (1997)							✓			✓		✓		Thermal	4
2	Venkatesh, et al. (2000)								✓			✓	✓		-	-
3	Mantawy (2004)						✓				✓		✓		-	10
4	Saber, et al. (2006)					✓					✓			✓	Thermal	100
5	Venkatesh, et al. (2007)									✓		✓	✓		-	104
6	Kadam, et al. (2009)							✓			✓		✓		-	-
7	Assad (2011)							✓			✓		✓		Thermal	4
8	Wang, et al. (2012)	✓									✓			✓	Thermal	215

No.	Author (Year)	Modeling technique									Objective function		Daily model	Monthly model	Types of fuel	Number of units
		MILP	MINLP	Stochastic	Fuzzy Possibilistic	Fuzzy SA	Fuzzy GA	Fuzzy If-Then Rule	Fuzzy LP	Fuzzy MILP	Single	Multiple				
9	Lotfi & Ghaderi (2013)				✓							✓		✓	Multi-system	18
10	Geng, et al. (2013)	✓									✓			✓	-	117
11	Bai, et al. (2014)	✓									✓			✓	Coal	114
12	Xiaolin & Shu (2015)			✓							✓			✓	Wind power	-
13	Yin & Zhao, (2018)			✓								✓	✓		Wind power	10
14	Zhu, et al. (2019)		✓										✓		Wind power	100
15	Truong & Jeenanunta (2019)	✓									✓			✓	Multi-system	204
16	This research									✓		✓		✓	Multi-system	204

CHAPTER 3
MODEL FORMULATION

3.1 Definition of parameters and variables

3.1.1 Set

T	time horizon in monthly planning, based on the number of days in studied month
U	number of generators except steam units
S	number of steam units
F	number of fuel types
J	total selected fuel types using for unit (subset of fuel types, $J \subset F$)

3.1.2 Indices

t	time period, for all $t = 1,2,\ldots,T$
u	generator index, except steam units, for all $u = 1,2,\ldots,U$
s	steam unit index, for all $s = 1,2,\ldots,S$
f	fuel type index, for all $f = 1,2,\ldots,F$
j	the selected fuel from fuel type, for all $j = 1,2,\ldots,J$

3.1.3 Parameters

d_t	forecasted demand at time period t (GWh)
$peak_t$	peak load demand at time period t (MW)
$c_{t,u}$	start-up cost of unit u at time period t (Baht)
$pc_{t,f}$	fuel price (unit cost) of fuel type f at time period t (baht)
$dcost_{t,f}$	delivery cost of fuel type f at time period t (baht)
p_u^{min}	minimum generation capacity of unit u (MW)
p_u^{max}	maximum generation capacity of unit u (MW)
$ope_{t,u}$	generating capacity of unit u (MW)
$lag_{t,u}$	time for setting up the engine before generation (hour)
ic_u	the initial state of unit u which has been operated before the first day of studied period (day)

SR_t^{min} minimum spinning reserve at time period t (MW)

SR_t^{max} maximum spinning reserve at time period t (MW)

$gdap_t$ generation capacity of hydro power at peaks of day t (MW)

$re_{t,u}$ reliability level of power output

is_f the initial amount of fuel stock of fuel type f

$h_{t,f}$ fuel heat value of fuel type f at time period t

$FU_{t,f}^{max}$ maximum amount of fuel type f using per day

$FU_{t,f}^{min}$ minimum amount of fuel type f using per day

FS_f^{max} maximum fuel stock of fuel type f

FS_f^{min} minimum fuel stock of fuel type f

ϕ_f^{max} maximum fuel ratio, $\phi_f^{max} \in [0,1]$

ϕ_f^{min} minimum fuel ratio, $\phi_f^{max} \in [0,1]$

MF_f maximum total amount of fuel type f using for the time horizon

MD_f maximum total amount of fuel type f delivering for the time horizon

TU_u minimum uptime of unit u (day)

TD_u minimum downtime of unit u (day)

M a very large number

3.1.4 Decision variables

$u_{t,u}$ unit operating status (1 = on, 0 = off)

$x_{t,u}$ turn-on decision (1 = turned on, 0 = maintain current status)

$y_{t,u}$ turn-off decision (1 = turned off, 0 = maintain current status)

$d_{t,f}$ delivery decision (1 = delivered, 0 = non-delivered)

$p_{t,u}$ amount of electricity generated by unit u at time period t (GWh)

$a_{t,f,u}$ amount of fuel type f used for unit u at time period t

$dev_{t,f}$ amount of fuel type f delivered at time period t

$sk_{t,f}$ amount of fuel stock of fuel type f at time period t

$OFl_{t,f}$ amount of fuel type f supplied exceedingly at time period t

$SFl_{t,f}$ shortage of fuel type f used at time period t

OPr_t amount of power generated exceedingly at time period t (MW)

SPr_t shortage of generation at time period t (MW)

OPk_t amount of power generated exceedingly at peak at time period t (MW)

SPk_t shortage of generation at peak at time period t (MW)

3.2 Deterministic MUC model

3.2.1 Objective function

An initial MILP model is proposed in term of mathematical formulation which objective is to minimize the total cost. In Eq. (3.1), the formulated total cost consists of fuel cost, start-up cost, fuel delivery cost, and penalty costs. The first term is fuel cost including constant fuel price pc_f^t and it is a critical aspect affecting to the decisions of fuel usage by each fuel type. Start-up cost is an investment cost required to set up the engine when it starts to operate while delivery cost is considered as the fuel transportation for specific type of fuel. When an operator is turned on ($x_u^t = 1$) or a type of fuel is delivered to the power plant ($d_f^t = 1$), the performance of operation system is correspondingly assessed. Involving with violation of production shortage or overproduction, it is subjected to produce electricity and supply the fuel sufficiently. It is noteworthy that the system is forced to reasonably operate to meet the demand as well as operational restrictions, in contrary it may incur a large of cost called penalty cost.

$$Min\ Z = \sum_{f \in F} \sum_{u \in U} \sum_{t \in T} pc_{t,f} a_{t,f,u} + \sum_{u \in U} \sum_{t \in T} c_{t,u} x_{t,u} + \sum_{f \in F} \sum_{t \in T} dcost_{t,f} d_{t,f}$$

$$+M \left[\sum_{t \in T} (SPr_t + SPk_t) + \sum_{t \in T} \sum_{f \in F} SFl_{t,f} \right] \tag{3.1}$$

3.2.2 Constraints

The minimizing objective function is subject to demand constraints, unit operational constraints and fuel constraints and these constraints are summarized as below:

- ❖ **Demand constraints**

Energy load demand: The power system may face the risk of power shortage if the optimization planning satisfies only total energy without consideration of peak load demand. The electricity production involving with overproduction and shortage must satisfy the load demand.

$$\sum_{u \in U} p_{t,u} + \left(\sum_{s \in S} p_{t,s} \right) - OPr_t + SPr_t = d_t \qquad ,\forall\, t \in T \tag{3.2}$$

Spinning reserve limits: The spinning reserve represents total capacity and it committed that the generation capacity is online in addition to be unutilized at that time. The maximum and minimum spinning reserve allows units to keep optimally generating at a certain level of generation capacity and reserve the unused capacity for uncertainty and peak periods. The constraints below schedule the spinning reserve commitment considering the overload and storage at peaks. They also include the power generated from hydropower units at peak periods. Hydropower system has rapid ramping rate and its power output is used during the peak load period in order to quickly accommodate the electricity demand at time period.

$$peak_t - spp_t + SR_t^{min} - gdap_t \leq \sum_{\substack{u \in U, \\ u \neq hydropower}} u_{t,u} p_u^{max} re_{t,u} + \sum_{s \in S} u_{t,s} p_s^{max} + SPk_t \tag{3.3}$$

$$peak_t - spp_t + SR_t^{max} - gdap_t \geq \sum_{\substack{u \in U, \\ u \neq hydropower}} u_{t,u} p_u^{max} re_{t,u} + \sum_{s \in S} u_{t,s} p_s^{max} - OPk_t \tag{3.4}$$

$$,\forall\, t \in T$$

where spp_t is the capacity of small power producer at time period t, which allows the private power companies partially cooperate in supplying electricity with the national power grid.

❖ **Unit operational constraints**

Generation limit: The electricity production is enabled within the generation capacities of specific unit at time period.

$$0.024 u_{t,u} p_u^{min} \leq p_{t,u} \leq 0.024 u_{t,u} p_u^{max} \qquad ,\forall u \in U, t \in T \tag{3.5}$$

Operational time: The actual production is not exceeded the operating capacity, excluding warm-up time of the engines.

$$p_{t,u} \leq 0.024 u_{t,u} op_u^t - \frac{x_{t,u} ope_{t,u} lag_{t,u}}{1000} \qquad ,\forall u \in U, t \in T \tag{3.6}$$

Minimum uptime/downtime: Generating units are forced to be on/off at least minimum uptime/downtime before shutting down/starting up. In fact, the operators need a specific time to remain their current status avoiding the engine from unexpected breaking down.

$$\sum_{i=t-TU_u+1} x_{i,u} \leq u_{t,u} \qquad ,\forall u \in U, t > TU_u \tag{3.7}$$

$$\sum_{i=t-TD_u+1} y_{i,u} \leq 1 - u_{t,u} \qquad ,\forall u \in U, t > TD_u \tag{3.8}$$

Initial uptime/downtime: Similar to minimum uptime/downtime constraints, initial uptime/downtime restriction associates with the initial condition of units when the scheduling horizon has begun. These constraints also assure that the installed minimum uptime/downtime of units are conducted.

- if $0 < ic_u < TU_u$, then

$$\sum_{k=1}^{k=TU_u-ic_u} u_{k,u} = TU_u - ic_u \qquad ,\forall u \in U \tag{3.9}$$

- if $ic_u < 0$ and $-ic_u < TD_u$, then

$$\sum_{k=1}^{k=TD_u+ic_u} u_{k,u} = 0 \qquad ,\forall u \in U \tag{3.10}$$

❖ **Fuel constraints**

Monthly fuel capacity: The amount of fuel for generating is limited by maximum total amount of fuel per month.

$$a_{t,f,u} \leq u_{t,u} MF_f \qquad ,\forall u \in U, f \in F, t \in T \tag{3.11}$$

Daily fuel capacity: The amount of fuel for generating is limited by maximum/minimum capacity per day, considering the fuel shortage and over-supply amount of fuel.

$$FU_{t,f}^{max} \geq \sum_{f \in F} \sum_{u \in U} a_{t,f,u} - OFl_{t,f} \qquad ,\forall f \in F, t \in T \tag{3.12}$$

$$FU_{t,f}^{min} \leq \sum_{f \in F} \sum_{u \in U} a_{t,f,u} + SFl_{t,f} \qquad ,\forall f \in F, t \in T \tag{3.13}$$

Fuel mixed ratio: As aforementioned, a few units can have more than one type of fuel due to the compatibility of fuels and some fuel types can be used simultaneously for certain generators. These constraints below range between the amount of fuel used for generating and its mixed ratio.

$$a_{t,f,u}h_{t,f} \leq \phi_f^{max} \sum_{j\in J}\sum_{u\in U}\sum_{t\in T} a_{t,j,u}h_{t,j} \quad ,\forall u \in U, f \in F, t \in T \tag{3.14}$$

$$a_{t,f,u}h_{t,f} \geq \phi_f^{min} \sum_{j\in J}\sum_{u\in U}\sum_{t\in T} a_{t,j,u}h_{t,j} \quad ,\forall u \in U, f \in F, t \in T \tag{3.15}$$

Initial fuel stock: Determining the amount of fuel stock at the beginning of period.

$$is_f + dev_{1,f} - \sum_{f\in F}\sum_{u\in U} a_{1,f,u} = sk_{1,f} \quad ,\forall f \in F \tag{3.16}$$

Fuel usage: Determining the amount of fuel stock in two successive time periods.

$$sk_{t-1,f} + dev_{t,f} - \sum_{f\in F}\sum_{u\in U} a_{t,f,u} = sk_{t,f} \quad ,\forall f \in F, t \in T, t > 1 \tag{3.17}$$

Fuel stock capacity: The amount of fuel in stock is controlled by maximum/minimum fuel storage capacity.

$$FS_f^{min} \leq sk_{t,f} \leq FS_f^{max} \quad ,\forall f \in F, t \in T \tag{3.18}$$

Fuel monthly delivery capacity: The amount of fuel for delivery is limited by maximum total amount of fuel per month.

$$dev_{t,f} \leq d_{t,f}MD_f \quad ,\forall f \in F, t \in T \tag{3.19}$$

3.3 Fuzzy MILP model and solution method

In this section, a developed MUC model relying on fuzzy modeling is presented. In particular, the fuel price is reformulated as imprecise objective coefficient with considering the fluctuation of fuel price. Fuzzy set and membership function are also defined in the following subsection. Optimization of MUC problem in imprecise nature is conducted by applying fuzzy formulation and solved by MILP technique with subjecting to other crisp constraints of the problem.

3.3.1 Fuzzification - Objective coefficient transformation

Based on the crisp objective function of initial model, the objective function as shown below is fuzzified focusing to the fluctuation of fuel price.

$$Min\ \tilde{Z} = \sum_{f\in F}\sum_{u\in U}\sum_{t\in T}\widetilde{pc_{t,f}}a_{t,f,u} + \sum_{u\in U}\sum_{t\in T}c_{t,u}x_{t,u} + \sum_{f\in F}\sum_{t\in T}dcost_{t,f}d_{t,f}$$
$$+M\left[\sum_{t\in T}(SPr_t + SPk_t\ ) + \sum_{t\in T}\sum_{f\in F}SFl_{t,f}\right] \tag{3.20}$$

subject to constraints (2) - (19)

where $\widetilde{pc_{t,f}}$ is imprecise fuel price (or imprecise fuel unit cost) and the fuel cost $\sum_{f\in F}\sum_{u\in U}\sum_{t\in T}\widetilde{pc_{t,f}}a_{t,f,u}$ becomes an imprecise value with total amount of fuel usage. Moreover, the imprecise fuel price is approximately assumed to have optimistic price and pessimistic price (cheap and expensive price) which fluctuate according to the historical fuel price during a specific time interval. Thus, we have $\widetilde{pc_{t,f}} = [(pc^o_{t,f}), (pc^p_{t,f})]$, where $pc^o_{t,f}$ is the optimistic price and $pc^p_{t,f}$ is the pessimistic price for all t and f.

3.3.2 Fuzzy set and membership function

In the imprecise nature, the fuzzy set in which contains imprecise elements is defined by vague boundaries. The elements also called the variables or objectives have their own membership degree in this set and functioned by attempting to describe vagueness. The fuzzy set could be defined by the objective value and the boundaries of this set could be assumed (Venkatesh et al., 2007). However, it is more facilitated to predetermine the boundaries instead of describing the impreciseness.

Let consider the objective cost moves from the lower-bound objective $\underline{Z}$ and the upper-bound objective $\bar{Z}$. Accordingly, the fuzzy set of the objective is defined in Eq.(3.21).

$$\tilde{Z} = \{(Z^*, \mu_{Z^*})|\underline{Z} \le Z^* \le \bar{Z}\} \tag{3.21}$$

where $\tilde{Z}$ is the fuzzy set of Z which was defined in Eq.(3.1). μ_{Z^*} is the membership function of objective value Z^* or the degree the closeness of the objective Z^* to positive-solution value. The membership function is formulated in the Eq.(3.22) as below:

$$\mu_{Z^*} = \begin{cases} 1 & \text{If } Z^* < \underline{Z} \\ \dfrac{\bar{Z} - Z^*}{\bar{Z} - \underline{Z}} & \text{If } \underline{Z} < Z^* < \bar{Z} \\ 0 & \text{If } Z^* > \bar{Z} \end{cases} \tag{3.22}$$

According to Eq.(3.22), the measures of membership are defined in the continuous interval [0,1], such that $0 < \mu_{Z^*} < 1$. The low total cost is revealed, the high optimization is expected. Therefore, the LB objective is getting satisfaction degree of 1 and it is gradually decreased to 0 for the UB objective. Figure 3.1 illustrates the membership function of objective value Z^*.

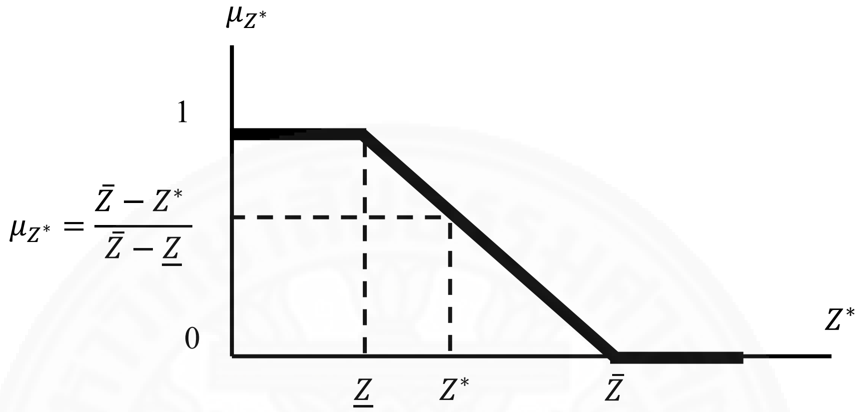

Figure 3.1 Membership function of Z^*

Regarding the formulation of fuzzy objective presented in Eq.(3.20), the fuzzy MILP is then solved by three auxiliary crisp MILP models. We first determine the lower bound (LB) and upper bound (UB) boundaries of fuzzy objective value. Eq.(3.23) and Eq.(3.24) indicate two objective functions of two models, respectively. This method is a fundamental step to derive the membership function based on fuzzy logic and it will be presented hereunder.

- Model 1 (LB model): The lower bound of fuzzy objective cost

$$Min\ \underline{Z} = \sum_{f \in F} \sum_{u \in U} \sum_{t \in T} pc^{o}_{t,f} a_{t,f,u} + \sum_{u \in U} \sum_{t \in T} c_{t,u} x_{t,u} + \sum_{f \in F} \sum_{t \in T} dcost_{t,f} d_{t,f}$$
$$+M \left[\sum_{t \in T} (SPr_t + SPk_t) + \sum_{t \in T} \sum_{f \in F} SFl_{t,f} \right] \quad (3.23)$$

subject to constraints (2) - (19)

where the optimistic price $pc^{o}_{t,f}$ (or cheap price) is converted from the imprecise fuel price $\widetilde{pc_{t,f}}$.

- Model 2 (UB model): The upper bound of fuzzy objective cost

$$Min\ \bar{Z} = \sum_{f\in F}\sum_{u\in U}\sum_{t\in T} pc^{p}_{t,f} a_{t,f,u} + \sum_{u\in U}\sum_{t\in T} c_{t,u} x_{t,u} + \sum_{f\in F}\sum_{t\in T} dcost_{t,f} d_{t,f}$$

$$+M\left[\sum_{t\in T}(SPr_t + SPk_t\ ) + \sum_{t\in T}\sum_{f\in F} SFl_{t,f}\right] \quad (3.24)$$

subject to constraints (2) - (19)

where the pessimistic price $pc^{p}_{t,f}$ (or expensive price) is converted from the imprecise fuel price $\widetilde{pc_{t,f}}$.

3.3.3 Fuzzy MILP model (α model)

The last model is a single-objective Linear Programming model where the solution for the degree of optimal objective possibility. An additional decision variables α are defined from function (3.22) as auxiliary possibility value or satisfactory condition. The fuzzy MILP model with objective (3.20) and crisp constraints given in Eq.(3.2) to Eq.(3.19) are reformulated as Model 1 and Model 2 and the solution is derived by formulating an optimization model to maximize α. By maximizing satisfaction degree (α), the degree of optimal cost μ_{Z^*} will be close to 1. Then Z^* will be closed to lower bound $\underline{Z}$ and the level of fluctuation are accordingly optimized. The total cost Z^* becomes to a decision variable and it is defined by Eq.(3.26). Total cost Z^* includes four element costs in which the penalty cost plays a role as forcing the system to produce electricity for satisfying the demand as shown in constraint (3.2)-(3.4). The shortage on production and fuel supply might happen when total cost is not explicitly included as one of the constraints. α model is presented as below:

Objective function $\quad Max\ \alpha$

subject to

Fuzzy objective $\quad \mu_{Z^*} = \dfrac{\bar{Z} - Z^*}{\bar{Z} - \underline{Z}} \geq \alpha \quad (3.25)$

Satisfactory condition $\quad 0 \leq \alpha \leq 1$

Total cost

$$Z^* = \sum_{f \in F} \sum_{u \in U} \sum_{t \in T} pc_{t,f} a_{t,f,u} + \sum_{u \in U} \sum_{t \in T} c_{t,u} x_{t,u} + \sum_{f \in F} \sum_{t \in T} dcost_{t,f} d_{t,f} + M \left[\sum_{t \in T} (SPr_t + SPk_t) + \sum_{t \in T} \sum_{f \in F} SFl_{t,f} \right] \quad (3.26)$$

$$Z^* \geq 0$$

Demand constraints in Eq.(3.2)-(3.4)

Unit operational constraints in Eq.(3.5)-(3.10)

Fuel constraints in Eq.(3.11)-(3.19)

CHAPTER 4
EXPERIMENTATION AND ANALYSIS

4.1 Sensitivity analysis and experimental setting

This section presents a sensitivity analysis of the proposed Fuzzy MILP by using the small cases with 24-unit system. The detail of operational generating unit data used in this case is given in Appendix. A monthly forecasted demand and daily peak load are taken within a month of 31 days and presented in Figure 4.1

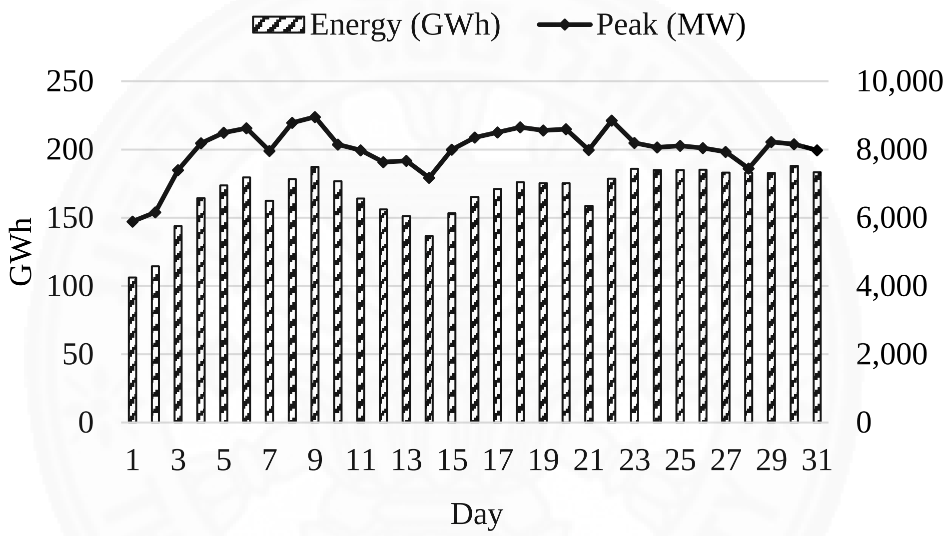

Figure 4.1 Load demand and peak load in 24-unit system

Furthermore, a national level power system which consists of various generating unit types and supplied fuel types is given to verify the reliability and the efficiency of model in term of the proposed method. Input data are referred from the national operation consisting of 204-unit system (Truong & Jeenanunta, 2019). There are 4 cases which consist 6 types of generators such as thermal unit, single-shaft gas turbine (SSGT), combine-cycle gas turbine (CCGT), combine-cycle steam turbine (CCST), hydro power (HP), and imported power from purchasing abroad. Table 4.1, Table 4.2 and Table 4.3 provides specifically the experimental setting of these cases. Fluctuation level of fuel price are calculated from historical data. Based on the constant price and historical data, a unit having multiple selection of fuel type is modified in term of fuzzy fuel price and its fluctuation level. Due to the characteristic of generator, a unit can have more than one type of fuel and the model helps to select which type of fuel should be used in order to minimize the total cost. The problem is behavior of fuzzy optimization dealing with fuel price fluctuation while being restricted by many constraints.

Table 4.1 Number of unit in each case study

Case study	Number of unit					
	Thermal	SSGT	CCGT	CCST	HP	Import
Case 1.1	6	3	6	3	4	2
Case 1.2	6	3	6	3	4	2
Case 1.3	6	3	6	3	4	2
Case 2	26	19	66	32	49	12

Table 4.2 Summary case setting of case 1

Case study	Selective unit	Fuel type	Unit of measurement	Fuel price		
				Optimistic price	Constant price	Pessimistic price
Case 1.1	BLCP-T1	Coal 1	Baht/kg	2.40	3	3.60
		Coal 2	Baht/kg	2.85	3	3.15
	NPO-GT11	N-Gas	Baht/MMBTU	120	150	180
		W-Gas	Baht/MMBTU	142.5	150	157.5
	KA-T1	KA Oil	Baht/liter	20	25	30
		KN Oil	Baht/liter	23.75	25	26.25
Case 1.2	BLCP-T1	Coal 1	Baht/kg	2.10	3	3.90
		Coal 2	Baht/kg	2.50	3	3.45
		Coal 3	Baht/kg	2.80	3	3.15
Case 1.3	NPO-GT11	N-Gas	Baht/MMBTU	120	150	180
		W-Gas	Baht/MMBTU	152	160	168
	KA-T1	KA Oil	Baht/liter	20	25	30
		KN Oil	Baht/liter	26.6	28	29.4

Table 4.3 Summary case setting of case 2 (including Thermal, SCGT, CCGT)

Unit group	Number of unit	Fuel type	Unit of measurement	Fuel price		
				Optimistic price	Constant price	Pessimistic price
1	3	Coal 1	Baht/kg	2.40	3	3.60
		Coal 2	Baht/kg	2.85	3	3.15
2	13	Lignite	Baht/kg	0.8	1	1.2
		Coal 2	Baht/kg	2.85	3	3.15
3	19	E-Gas	Baht/MMBTU	200	250	300
		J-Gas	Baht/MMBTU	237.5	250	262.5
4	2	K-Gas	Baht/MMBTU	120	150	180
		N-Gas	Baht/MMBTU	142.5	150	157.5
5	10	LNG-Gas	Baht/MMBTU	320	400	480
		W-Gas	Baht/MMBTU	380	400	420
6	10	L-Gas	Baht/MMBTU	40	50	60
		N-Gas	Baht/MMBTU	142.5	150	157.5
7	6	BPK-Oil	Baht/Liter	17.6	22	26.4
		RB-Oil	Baht/Liter	20.9	22	23.1
8	2	KA-Oil	Baht/Liter	24	30	36
		KN-Oil	Baht/Liter	28.5	30	31.5
9	46	Diesel	Baht/Liter	20	25	30
		J-Gas N-Gas W-Gas	Baht/MMBTU	237.5 142.5 380	250 150 400	262.5 157.5 420

In 24-unit system, we would establish 3 scenarios of operational selection, namely case 1.1, case 1.2, and case 1.3. Case 1.1 describes the selective optimization of 2 fuel types used for one generator. In the similar way, 3 types of fuel will be considered in case 1.2. Therefore, each type of fuel in each case has its own fluctuation level of price. In detail of case 1.1, one examined unit has 2 types fuel of coal, coal 1, and coal 2. The fluctuation of fuel price sequentially has 2 levels, specifically low, and high. The price fluctuation becomes to be 3 levels with coal type 1, coal type 2, and coal type 3 in case 1.2, respectively. Case 1.3 gives the conduct of selecting 2 fuel types, but a little difference between the constant prices is considered. The fuel with lower price would have higher fluctuation and it is on the contrary for the remaining fuel. In case of 204-unit system, there is an increase in number of unit with actual fluctuation levels in fuel price. The proposed solution method is implemented by IBM ILOG CPLEX optimizer on version 12.6.1. A computer with processor of 1.8 GHz Intel Core i5 CPU is used for modeling and computational testing.

4.2 Results and Discussion

4.2.1 Case 1 - 24-unit system

Taking the data set of large-scale model, the 24-unit system is simulated to verify the efficiency of model by the fluctuation behaviors of fuel selection. All referred types of unit and a few types of fuel extracting from large-scale model are used for execution. In this case, each type of fuel with its imprecise price is examined in both two cases to evaluate how fuzzy model generates by deciding fuel type and fluctuation level. The solution would be low variance while types of fuel are having the same price but different fluctuation level.

4.2.1.1 Case 1.1

As shown in Table 4.2, the sensitivity analysis is performed on units BLCP-T1, NPO-GT11, KA-T1, and each unit has its fuel type which has different price variance. The results getting from LB and UB model are first calculated to determine the objective boundaries for α model. The results of fuzzy boundaries and optimal solution are displayed in Table 4.4, respectively.

Varying from 2,409.10 MTHB to 2,631.85 MTHB, the total cost is defined at 2,514.95 MTHB and the fuel cost equals to 2,507 MTHB. At the optimal point, value reaches to 0.525. It is remarkable that the optimal solution tends to the lower total cost whereby the efficiency of model is manifested. Comparing to deterministic model, the total cost and the fuel cost of Fuzzy MILP model are obtained lower than those of the deterministic model. Figure 4.2 presents the comparisons of Fuzzy MILP model and deterministic model.

Table 4.4 Optimal solution and computational performance of Fuzzy MILP model in 24-unit system (Case 1.1)

Statistic	Deterministic model	Fuzzy model		
		LB	UB	α
α value	-	-	-	0.525
Total cost (MTHB)	2,541.29	2,409.10	2,631.85	2,514.95
Fuel cost (MTHB)	2,533.34	2,402.62	2,623.89	2,507.00
Start-up cost (MTHB)	7.95	6.48	7.96	7.95
Delivery cost (MTHB)	0.001	0.001	0.003	0.001
Constraints	10,196	10,196	10,196	10,199
Binary variables	2,570	2,570	2,570	2,570
Continuous variables	3,783	3,783	3,783	3,784
Non-zero coefficients	26,876	26,876	26,876	28,708
Computational time (minute)	4.82	4.12	5.13	43.00

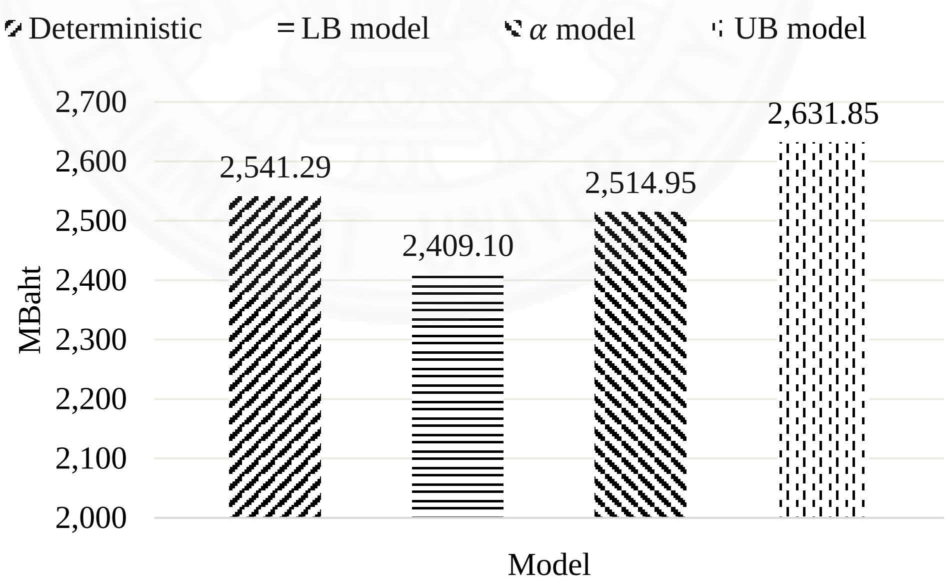

Figure 4.2 Total cost of deterministic model and Fuzzy MILP model in 24-unit system for case 1.1

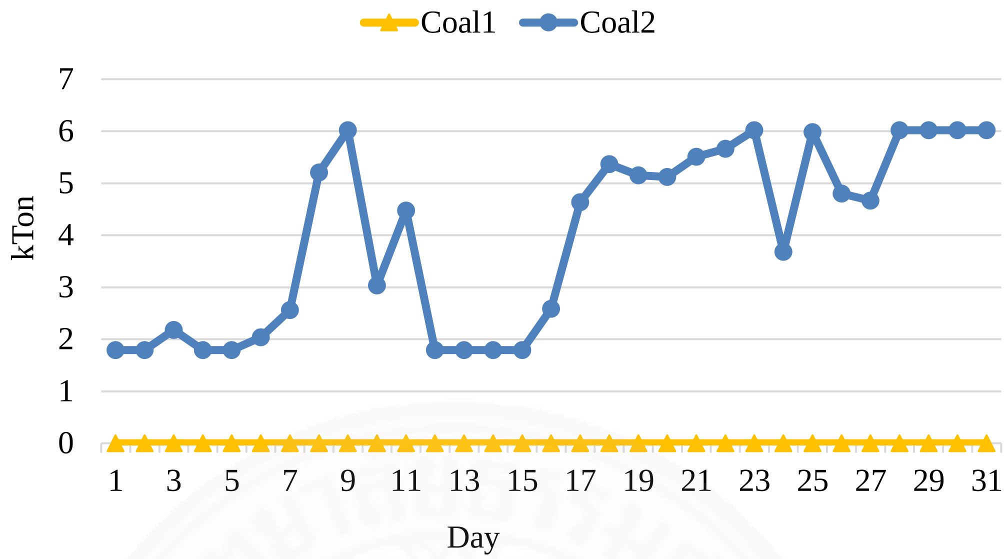

Figure 4.3 The optimal fuel usage for unit BLCP-T1 in Fuzzy MILP solution for case 1.1

Dealing with fluctuation of fuel price, the thermal unit BLCP-T1 which has coal type 1 and coal type 2 for selective optimization. Both of them are having the same price but different fluctuation level. Particularly, coal type 1 has low fluctuation level whereas this level is high for coal type 2. The behavior presented in Figure 4.3 explicitly indicates that the fuzzy model preferred to the low fluctuation level of coal type 2.

4.2.1.2 Case 1.2

This scenario is proposed in order to enhance the objectivity of formulated model and avoid the confusing consistency while selecting between only 2 types of fuel in the same unit. The thermal unit considered to have coal 1 and coal 2 in case 1.1 is modified to have 3 types fuel of coal, namely coal 1, coal 2, and coal 3. The results are all shown in Table 4.5, respectively. The comparison between deterministic model and fuzzy model is also indicated in Figure 4.4. Satisfaction degree α reaches to 0.503 at the optimal point. It is acceptable to state that the optimal solution leads to the low cost. Similar results are found, whereas the total cost and the fuel cost incurred lower than in deterministic model.

Table 4.5 Optimal solution and computational performance of Fuzzy MILP model in 24-unit system (Case 1.2)

Statistic	Deterministic model	Fuzzy model		
		LB	UB	α
α value	-			0.503
Total cost (MTHB)	2,469.88	2,204.17	2,602.52	2,401.96
Fuel cost (MTHB)	2,461.97	2,197.75	2,594.59	2,395.52
Start-up cost (MTHB)	7.91	6.42	7.93	6.43
Delivery cost (MTHB)	0	0	0.002	0.002
Constraints	10,489	10,489	10,489	10,492
Binary variables	2,601	2,601	2,601	2,601
Continuous variables	3,969	3,969	3,969	3,970
Non-zero coefficients	27,570	27,570	27,570	29,495
Computational time (minute)	4.43	4.82	5.90	45.07

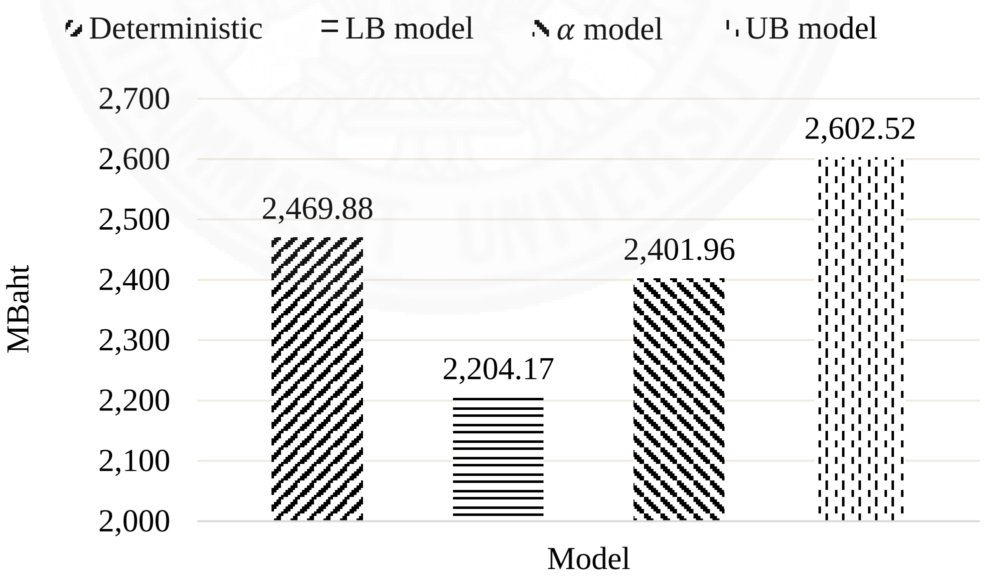

Figure 4.4 Total cost of deterministic model and Fuzzy MILP model in 24-unit system for case 1.2

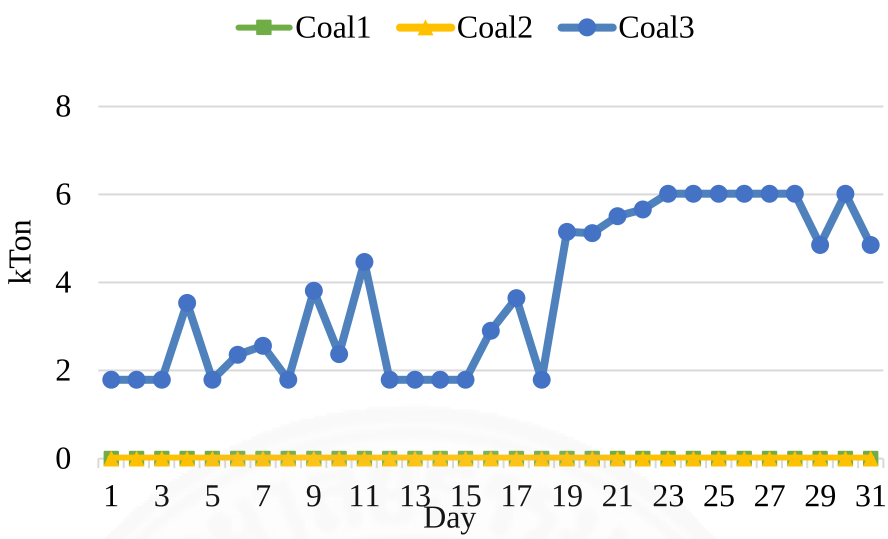

Figure 4.5 The optimal fuel usage for unit BLCP-T1 in Fuzzy MILP solution for case 1.2

In this case, the thermal unit BLCP-T1 is modified to have 3 types of coal, namely coal type 1, type 2, and type 3. In such problem, the fluctuation is defined as high, medium and low level for coal 1, coal 2 and coal 3, respectively. As revealed in Figure 4.5, coal type 3 with lowest level of fluctuation is selected to generate for unit BLCP-T1. In general, this strongly demonstrates the robustness of fuzzy model in respect of dealing with price uncertainty.

4.2.1.3 Case 1.3

In order to generally evaluate how model deals with fuel price and its deviation, case 1.3 is considered with different constant prices of 2 fuel types. Unit NPO-GT11 and KA-T1 have similarity of 2-fuel-type selection for generation and each fuel type specifically has most likely price as well as fluctuation level. Meanwhile, the fuel type with lower price is assumed to have higher fluctuation and the higher-price fuel type has lower variance.

The feasible solutions revealed from LB model and UB model are also the boundary conditions in definition of fuzzy set of optimal solution. Table 4.6 displays those results and the performance of model is also presented. Optimal total cost and fuel cost are 2,579.78 MTHB and 2,570.40 MTHB, respectively. The comparison of total cost between deterministic model and fuzzy model given in Figure 4.6 indicates that the total cost is moving from 2,433.19 MTHB to 2,748.62 MTHB at the optimal point (0.535).

Table 4.6 Optimal solution and computational performance of Fuzzy MILP model in 24-unit system (Case 1.3)

Statistic	Deterministic model	Fuzzy model		
		LB	UB	α
α value	-	-	-	0.535
Total cost (MTHB)	2,607.93	2,433.19	2,748.62	2,579.78
Fuel cost (MTHB)	2,598.55	2,423.80	2,740.70	2,570.40
Start-up cost (MTHB)	9.39	9.38	7.92	9.38
Delivery cost (MTHB)	0	0	0.002	0
Constraints	10,943	10,943	10,943	10,946
Binary variables	2,663	2,663	2,663	2,663
Continuous variables	4,279	4,279	4,279	4,280
Non-zero coefficients	28,144	28,144	28,144	30,193
Computational time (minute)	4.60	5.52	5.05	42.23

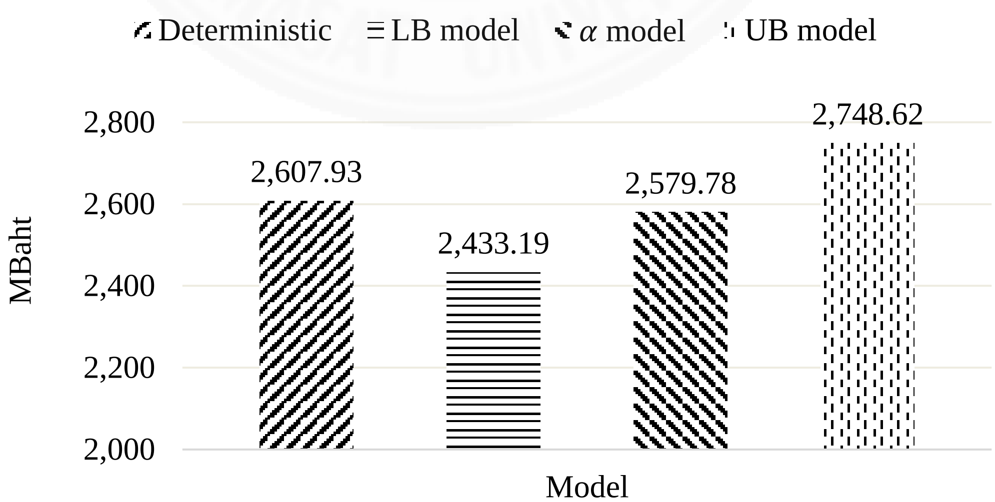

Figure 4.6 Total cost of deterministic model and Fuzzy MILP model in 24-unit system for case 1.3

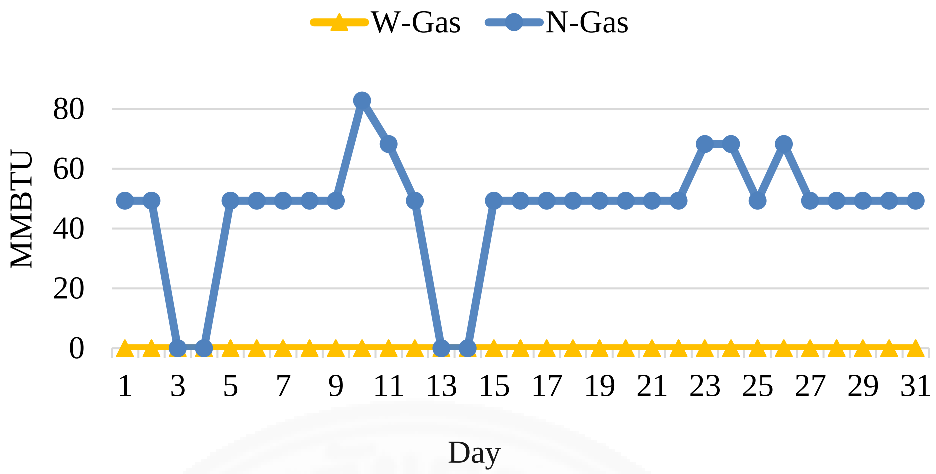

Figure 4.7 The optimal fuel usage for unit NPO-GT11 in Fuzzy MILP solution for case 1.3

Considering unit NPO-GT11 which are available to N-Gas and W-Gas, the result shown in Figure 4.7 exposes that model tends to select fuel with cheaper price although its fluctuation is higher than the expensive price. Insignificant deviation between these two prices (150 Baht/MMBTU and 160 Baht/MMBTU) could cause the tradeoff between price and fluctuation.

4.2.2 Case 2 - 204-unit system

This case is used to demonstrate the model dimension and ability of technique in addition to obtain the optimal solution. The data set with national system is used to implemented. In similar way to above cases model, LB and UB objective are initially calculated. For Fuzzy MILP, the results are displayed in Table 4.7 and the dimension of model for execution is also shown.

The Fuzzy MILP model is employed by using the feasible solution from boundaries. The optimal solution and its satisfaction degree are illustrated in Figure 4.8. It shows that the degree of possibility of solution is satisfied with 0.592. Thus, the optimal total cost is close to positive-solution value. Moreover, it points out the fluctuation of fuel price is optimized, which lead to optimizing the total cost in flexibility environment.

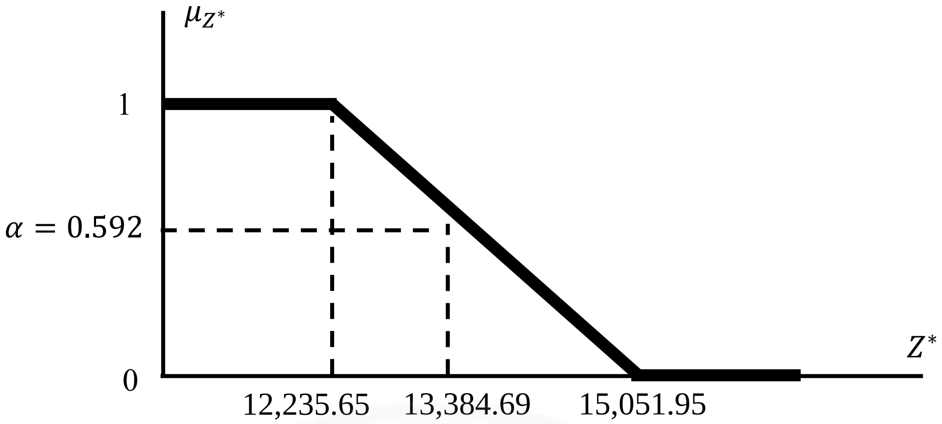

Figure 4.8 Satisfaction degree (α) and the optimal solution (Z^*) in Fuzzy MILP solution of 204-unit system

Table 4.7 Optimal solution and computational performance of Fuzzy MILP model in 204-unit system

Statistic	Deterministic model	Fuzzy model		
		LB	UB	α
α value	-	-	-	0.592
Total cost (MTHB)	14,197.93	12,235.65	15,051.95	13,384.69
Fuel cost (MTHB)	14,179.72	12,217.45	15,033.75	13,365.44
Start-up cost (MTHB)	18.21	18.19	18.20	19.23
Delivery cost (MTHB)	0.009	0.011	0.010	0.028
Constraints	83,541	83,541	83,541	83,544
Binary variables	20,552	20,552	20,552	20,552
Continuous variables	26,413	26,413	26,413	26,414
Non-zero coefficients	235,064	235,064	235,064	249,048
Computational time (minute)	18.33	9.15	20.92	62.37

Analyzing the results of deterministic model as shown in Table 4.7 and Figure 4.9, the optimal total cost of Fuzzy MILP model shows obviously lower than the deterministic model. The gap between two solution is 813.24 million Baht in term of total cost and 814.28 million Baht of fuel cost. Besides, the start-up cost and delivery cost are comparable inversely. While attempting to minimize total cost and fuel cost, however, this compromise is generally insignificant. Taking over one hour, the computation performance of Fuzzy MILP model clearly yields the magnitude of modeling fuzzy optimization in large-scale power system, including the additional works for defining the boundaries of fuzzy set.

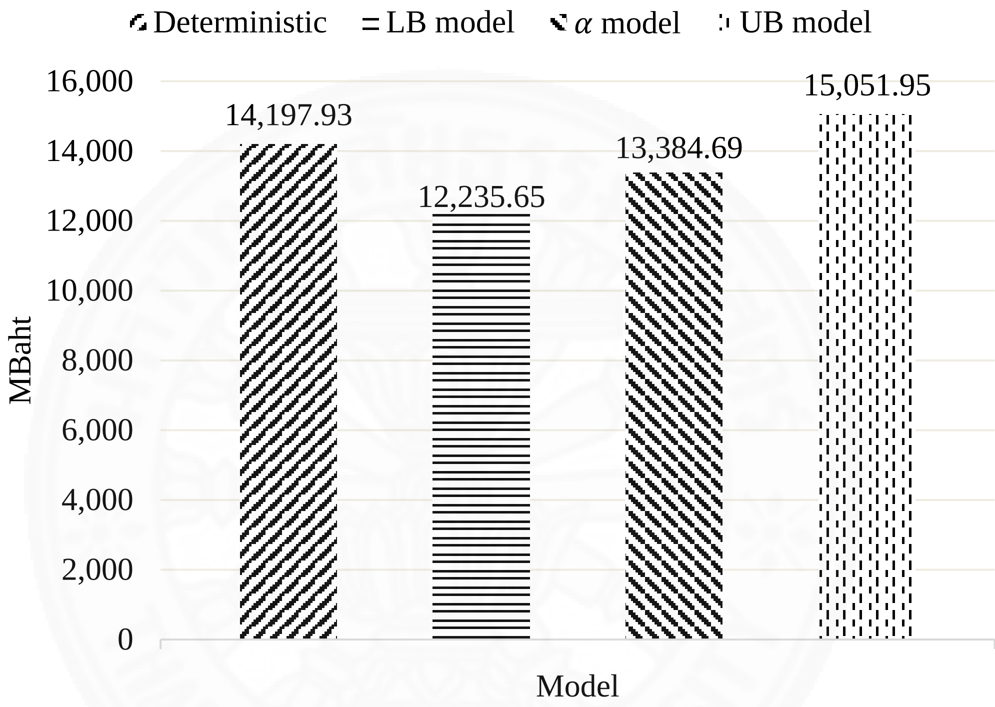

Figure 4.9 Total cost of deterministic model and Fuzzy MILP model in 204-unit system

CHAPTER 5
CONCLUSION AND FURTHER RESEARCH

5.1 Conclusion

The monthly unit commitment problem focusing on fluctuation of fuel price in the large-scale power system is investigated in this research. Fuzzy Mixed Integer Linear Programming model is proposed to determine the optimal solution with its satisfaction degree. The solution method consists of 3 MILP models: lower-bound model, upper-bound model, and α model. Experimental results based on optimization technique clearly manifest the reliability of model and the efficiency involve with fluctuation behaviors of fuel selection. At the optimal point, the satisfaction degree illustrates that optimal solution is satisfied with closing to the low-cost boundary of fuzziness. The model sensitivity analysis by small case studies revealed a behavior in aspect of selecting fuel types for generation based on price variation. Fuzzy model preferred the low fluctuation price. Meanwhile, the model tended to select the cheaper price in case of the prices are a bit different. Using MILP technique for solving Fuzzy MILP, it is simply applicable and efficient to handle the large-scale monthly unit commitment model with the plenty of energy system.

5.2 Further research

The proposed fuzzy monthly unit commitment model in this thesis based on the deterministic forecasted demand and known renewable energy, namely output hydro power. Therefore, the further research could be explored with uncertain demand and include uncertain output of renewable energy. The formulated model could be applied for the other energy resources such as renewable energies. On the other hand, the proposed Fuzzy MILP model could be solved by other solution methods: probability theory in stochastic optimization, other empirical approaches in fuzzy optimization.

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APPENDIX

No.	Unit	Unit type	Minimum capacity (MW)	Maximum capacity (MW)	Operating capacity (MW)	Minimum uptime (Day)	Minimum downtime (Day)	Start-up cost (THB)
1	BLCP-T1	Thermal	161	673.25	660	14	2	1,484,255
2	BLCP-T2	Thermal	161	673.25	660	14	2	1,484,255
3	GOC-T1	Thermal	210	660	650	14	2	1,484,255
4	BPK-T1	Thermal	0	280	526.5	510	14	627,676
5	BPK-T2	Thermal	0	280	526.5	510	14	627,676
6	BPK-T3	Thermal	0	280	576	560	14	627,676
7	BPK-T4	Thermal	0	280	576	560	14	627,676
8	HSA-T1	Thermal	286	551	492	14	2	627,676
9	HSA-T2	Thermal	286	580	485	14	2	627,676
10	HSA-T3	Thermal	286	491	485	14	2	627,676
11	KA-T1	Thermal	0	145	315	315	14	627,676
12	KN-T2	Thermal	0	60	70.2	70.2	14	627,676
13	MM-T10	Thermal	0	162	270	270	14	627,676
14	MM-T11	Thermal	0	162	270	270	14	627,676
15	MM-T12	Thermal	0	162	270	270	14	627,676
16	MM-T13	Thermal	0	162	270	270	14	627,676
17	MM-T4	Thermal	0	132	140	140	14	627,676

No.	Unit	Unit type	Minimum capacity (MW)	Maximum capacity (MW)	Operating capacity (MW)	Minimum uptime (Day)	Minimum downtime (Day)	Start-up cost (THB)
18	MM-T5	Thermal	0	132	140	140	14	627,676
19	MM-T6	Thermal	0	132	140	140	14	627,676
20	MM-T7	Thermal	0	132	140	140	14	627,676
21	MM-T8	Thermal	0	162	270	270	14	627,676
22	MM-T9	Thermal	0	162	270	270	14	627,676
23	RB-T1	Thermal	0	220	720	700	14	627,676
24	RB-T2	Thermal	0	220	720	700	14	627,676
25	SB-T4	Thermal	0	140	250	250	14	627,676
26	SB-T5	Thermal	0	140	250	250	14	627,676
27	CHN21	SCGT	0	232	383	380	0	3,785
28	CHN22	SCGT	0	232	383	380	0	3,785
29	EPEC	SCGT	0	275	350	340	30	3,785
30	GLOW1	SCGT	0	275	354	343	30	3,785
31	GLOW2	SCGT	0	275	354	343	30	3,785
32	KN-S21	SCGT	0	270	488	450	0	3,785
33	KN-S22	SCGT	0	270	488	450	0	3,785
34	LKB-GT1	SCGT	0	10	14.85	14	0	3,785

No.	Unit	Unit type	Minimum capacity (MW)	Maximum capacity (MW)	Operating capacity (MW)	Minimum uptime (Day)	Minimum downtime (Day)	Start-up cost (THB)
35	LKB-GT11	SCGT	0	40	119.9	116	0	3,785
36	LKB-GT2	SCGT	0	10	19	19	0	3,785
37	LKB-GT3	SCGT	0	10	19	19	0	3,785
38	LKB-GT4	SCGT	0	10	19	19	0	3,785
39	LKB-GT5	SCGT	0	10	19	19	0	3,785
40	LKB-GT6	SCGT	0	10	19	19	0	3,785
41	LKB-GT9	SCGT	0	10	19	19	0	3,785
42	NB-S21	SCGT	0	254	435	405	0	3,785
43	NB-S22	SCGT	0	254	435	405	0	3,785
44	SRT-GT1	SCGT	0	40	116	110	0	3,785
45	SRT-GT2	SCGT	0	40	116	110	0	3,785
46	BPK-GT31	CCGT	0	59.4	103	99	3	3,785
47	BPK-GT32	CCGT	0	59.4	103	99	3	3,785
48	BPK-GT41	CCGT	0	59.4	103	99	3	3,785
49	BPK-GT42	CCGT	0	59.4	103	99	3	3,785
50	BPK-GT51	CCGT	0	125	231	230	6	3,785
51	BPK-GT52	CCGT	0	125	231	230	6	3,785

No.	Unit	Unit type	Minimum capacity (MW)	Maximum capacity (MW)	Operating capacity (MW)	Minimum uptime (Day)	Minimum downtime (Day)	Start-up cost (THB)
52	CHN-GT11	CCGT	0	117	225	225	6	3,785
53	CHN-GT12	CCGT	0	117	225	225	6	3,785
54	GNS-GT11	CCGT	0	137	257	247	0	3,785
55	GNS-GT12	CCGT	0	137	257	247	0	3,785
56	GNS-GT21	CCGT	0	137	257	247	0	3,785
57	GNS-GT22	CCGT	0	137	257	247	0	3,785
58	GPG-GT11	CCGT	0	125	228	220	6	3,785
59	GPG-GT12	CCGT	0	125	228	220	6	3,785
60	GPG-GT21	CCGT	0	125	228	220	6	3,785
61	GPG-GT22	CCGT	0	125	228	220	6	3,785
62	GPS-GT11	CCGT	0	120	230	230	6	3,785
63	GPS-GT12	CCGT	0	120	230	230	6	3,785
64	GUT-GT11	CCGT	0	137	260	247	0	3,785
65	GUT-GT12	CCGT	0	137	260	247	0	3,785
66	GUT-GT21	CCGT	0	137	260	247	0	3,785
67	GUT-GT22	CCGT	0	137	260	247	0	3,785
68	KN-GT11	CCGT	0	70	105	100	6	3,785

No.	Unit	Unit type	Minimum capacity (MW)	Maximum capacity (MW)	Operating capacity (MW)	Minimum uptime (Day)	Minimum downtime (Day)	Start-up cost (THB)
69	KN-GT12	CCGT	0	70	105	100	6	3,785
70	KN-GT13	CCGT	0	70	105	100	6	3,785
71	KN-GT14	CCGT	0	70	105	100	6	3,785
72	NB-GT11	CCGT	0	117.5	220	217	6	3,785
73	NB-GT12	CCGT	0	117.5	220	217	6	3,785
74	NPO-GT11	CCGT	0	60	110	105	6	3,785
75	NPO-GT12	CCGT	0	60	110	105	6	3,785
76	NPO-GT21	CCGT	0	60	110	105	6	3,785
77	NPO-GT22	CCGT	0	60	110	105	6	3,785
78	RB-GT11	CCGT	0	150	211	207	6	3,785
79	RB-GT12	CCGT	0	150	209.7	207	6	3,785
80	RB-GT21	CCGT	0	150	209.7	202	6	3,785
81	RB-GT22	CCGT	0	150	208	202	6	3,785
82	RB-GT31	CCGT	0	150	213	206	6	3,785
83	RB-GT32	CCGT	0	150	213	206	6	3,785
84	RPCL-GT11	CCGT	0	152	225	220	6	3,785
85	RPCL-GT12	CCGT	0	152	225	220	6	3,785

No.	Unit	Unit type	Minimum capacity (MW)	Maximum capacity (MW)	Operating capacity (MW)	Minimum uptime (Day)	Minimum downtime (Day)	Start-up cost (THB)
86	RPCL-GT21	CCGT	0	152	225	220	6	3,785
87	RPCL-GT22	CCGT	0	152	225	220	6	3,785
88	RY-GT11	CCGT	0	81.68	97	93	3	3,785
89	RY-GT12	CCGT	0	83.46	96	93	3	3,785
90	RY-GT21	CCGT	0	81.23	94	93	3	3,785
91	RY-GT22	CCGT	0	82.79	97	93	3	3,785
92	RY-GT31	CCGT	0	77.01	96	93	3	3,785
93	RY-GT32	CCGT	0	77.01	95	93	3	3,785
94	RY-GT41	CCGT	0	82.24	97.5	93	3	3,785
95	RY-GT42	CCGT	0	77	98.29	93	3	3,785
96	SB-GT11	CCGT	0	97	99	98	3	3,785
97	SB-GT12	CCGT	0	97	99	98	3	3,785
98	SB-GT21	CCGT	0	132	184	178	6	3,785
99	SB-GT22	CCGT	0	132	184	178	6	3,785
100	SB-GT31	CCGT	0	140	225	225	6	3,785
101	SB-GT32	CCGT	0	140	225	225	6	3,785
102	TECO-GT11	CCGT	0	114	230	225	6	3,785

No.	Unit	Unit type	Minimum capacity (MW)	Maximum capacity (MW)	Operating capacity (MW)	Minimum uptime (Day)	Minimum downtime (Day)	Start-up cost (THB)
103	TECO-GT12	CCGT	0	114	230	225	6	3,785
104	W4-GT41	CCGT	0	130	246	240	0	3,785
105	W4-GT42	CCGT	0	130	246	240	0	3,785
106	WN-GT11	CCGT	0	130	212	205	3	3,785
107	WN-GT12	CCGT	0	130	212	205	3	3,785
108	WN-GT21	CCGT	0	130	212	205	3	3,785
109	WN-GT22	CCGT	0	130	212	205	3	3,785
110	WN-GT31	CCGT	0	120	230	225	3	3,785
111	WN-GT32	CCGT	0	120	230	225	3	3,785
112	BB-H1	HP	0	40	50	50	0	0
113	BB-H2	HP	0	40	50	50	0	0
114	BB-H3	HP	0	40	50	50	0	0
115	BB-H4	HP	0	40	50	50	0	0
116	BB-H5	HP	0	40	50	50	0	0
117	BB-H6	HP	0	40	50	50	0	0
118	BB-H7	HP	0	70	80	80	0	0
119	BB-H8	HP	0	123	130	130	0	0

No.	Unit	Unit type	Minimum capacity (MW)	Maximum capacity (MW)	Operating capacity (MW)	Minimum uptime (Day)	Minimum downtime (Day)	Start-up cost (THB)
120	BLG-H1	HP	0	15	24	24	0	0
121	BLG-H2	HP	0	15	24	24	0	0
122	BLG-H3	HP	0	15	24	24	0	0
123	BST-H1	HP	0	1.275	1.275	1.275	0	0
124	CLB-H1	HP	0	10	20	19	0	0
125	CLB-H2	HP	0	10	20	19	0	0
126	HK-H1	HP	0	1.06	1.06	1.06	0	0
127	KKC-H1	HP	0	19	19	19	0	0
128	LTK-H1	HP	0	210	250	250	0	0
129	LTK-H2	HP	0	210	250	250	0	0
130	MNG-H1	HP	0	4.5	4.5	4.5	0	0
131	MNG-H2	HP	0	4.5	4.5	4.5	0	0
132	NP-H1	HP	0	3	3	3	0	0
133	NP-H2	HP	0	3	3	3	0	0
134	PMN-H1	HP	0	5	34	32.3	0	0
135	PMN-H2	HP	0	5	34	32.3	0	0
136	PMN-H3	HP	0	5	34	34	0	0

No.	Unit	Unit type	Minimum capacity (MW)	Maximum capacity (MW)	Operating capacity (MW)	Minimum uptime (Day)	Minimum downtime (Day)	Start-up cost (THB)
137	PMN-H4	HP	0	5	34	34	0	0
138	RPB-H1	HP	0	60	80	80	0	0
139	RPB-H2	HP	0	60	80	80	0	0
140	RPB-H3	HP	0	60	80	80	0	0
141	SK-H1	HP	0	60	80	75	0	0
142	SK-H2	HP	0	60	80	75	0	0
143	SK-H3	HP	0	60	80	75	0	0
144	SK-H4	HP	0	60	80	75	0	0
145	SNR-H1	HP	0	80	120	110	0	0
146	SNR-H2	HP	0	80	120	110	0	0
147	SNR-H3	HP	0	80	120	110	0	0
148	SNR-H4	HP	0	149	150	150	0	0
149	SNR-H5	HP	0	149	150	150	0	0
150	SRD-H1	HP	0	10	12	12	0	0
151	SRD-H2	HP	0	10	12	12	0	0
152	SRD-H3	HP	0	10	12	12	0	0
153	TN-H1	HP	0	14	18	17.5	0	0

No.	Unit	Unit type	Minimum capacity (MW)	Maximum capacity (MW)	Operating capacity (MW)	Minimum uptime (Day)	Minimum downtime (Day)	Start-up cost (THB)
154	TN-H2	HP	0	14	18	17.5	0	0
155	UR-H1	HP	0	8.4	8.4	8.4	0	0
156	UR-H2	HP	0	8.4	8.4	8.4	0	0
157	UR-H3	HP	0	8.4	8.4	8.4	0	0
158	VRK-H1	HP	0	60	89	85	0	0
159	VRK-H2	HP	0	60	89	85	0	0
160	VRK-H3	HP	0	60	89	85	0	0
161	HHO-H1	Import	0	63	63	63	0	0
162	HHO-H2	Import	0	63	63	63	0	0
163	NNG2-H1	Import	0	150	198.867	198.867	0	0
164	NNG2-H2	Import	0	150	198.867	198.867	0	0
165	NNG2-H3	Import	0	150	198.867	198.867	0	0
166	NTN2-H1	Import	0	200	237	237	0	0
167	NTN2-H2	Import	0	200	237	237	0	0
168	NTN2-H3	Import	0	200	237	237	0	0
169	NTN2-H4	Import	0	200	237	237	0	0
170	THB-H1	Import	0	93	107	107	0	0

No.	Unit	Unit type	Minimum capacity (MW)	Maximum capacity (MW)	Operating capacity (MW)	Minimum uptime (Day)	Minimum downtime (Day)	Start-up cost (THB)
171	THB-H2	Import	0	93	107	107	0	0
172	THB-H3	Import	0	186	220	220	0	0
173	BPK-ST30	CCST	-	108	-	-	-	0
174	BPK-ST40	CCST	-	108	-	-	-	0
175	BPK-ST50	CCST	-	248	-	-	-	0
176	CHN-ST10	CCST	-	260	-	-	-	0
177	GNS-ST10	CCST	-	278	-	-	-	0
178	GNS-ST20	CCST	-	278	-	-	-	0
179	GPG-ST10	CCST	-	278	-	-	-	0
180	GPG-ST20	CCST	-	278	-	-	-	0
181	GPS-ST10	CCST	-	240	-	-	-	0
182	GUT-ST10	CCST	-	220	-	-	-	0
183	GUT-ST20	CCST	-	220	-	-	-	0
184	KN-ST10	CCST	-	220	-	-	-	0
185	NB-ST10	CCST	-	230	-	-	-	0
186	NPO-ST10	CCST	-	111	-	-	-	0
187	NPO-ST20	CCST	-	111	-	-	-	0

No.	Unit	Unit type	Minimum capacity (MW)	Maximum capacity (MW)	Operating capacity (MW)	Minimum uptime (Day)	Minimum downtime (Day)	Start-up cost (THB)
188	RB-ST10	CCST	-	264.3	-	-	-	0
189	RB-ST20	CCST	-	257.3	-	-	-	0
190	RB-ST30	CCST	-	255	-	-	-	0
191	RPCL-ST10	CCST	-	250	-	-	-	0
112	RPCL-ST20	CCST	-	250	-	-	-	0
193	RY-ST10	CCST	-	101	-	-	-	0
194	RY-ST20	CCST	-	96	-	-	-	0
195	RY-ST30	CCST	-	98	-	-	-	0
196	RY-ST40	CCST	-	106.21	-	-	-	0
197	SB-ST10	CCST	-	118	-	-	-	0
198	SB-ST20	CCST	-	194	-	-	-	0
199	SB-ST30	CCST	-	260	-	-	-	0
200	TECO-ST10	CCST	-	240	-	-	-	0
201	W4-ST40	CCST	-	188	-	-	-	0
202	WN-ST10	CCST	-	188	-	-	-	0
203	WN-ST20	CCST	-	188	-	-	-	0
204	WN-ST30	CCST	-	226	-	-	-	0

BIOGRAPHY

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Publications

Truong, Q. H., & Jeenanunta, C. (2019). *Mixed Integer Linear Programming Model for Monthly Unit Commitment in the National Level Power System.* The 11th International Conference on Information Technology and Electrical Engineering (ICITEE2019), 10-11 October, 2019, Pattaya, Thailand.