Dual-Interval Optimization Modeling for the Planning of Natural Gas Pipeline Systems

A Thesis

Submitted to the Faculty of Graduate Studies and Research

in Partial Fulfillment of the Requirements

for the Degree of

Master of Applied Science

in Environmental Systems Engineering

University of Regina

by

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Regina, Saskatchewan

June, 2012

UNIVERSITY OF REGINA

FACULTY OF GRADUATE STUDIES AND RESEARCH

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Abstract

Natural gas (NG) pipeline network, a major mode of transportation, requires optimized operations and management in order to ensure stable and efficient gas supplies. To provide such optimal solutions, pipeline systems modeling is a widely used method. The interactions among upstream, midstream, and downstream sectors could be clearly defined and addressed by developing mathematical models for pipeline systems.

However, in the real world, the market demand of NG usually cannot be deterministic values, and floating demand is the more common situation. Furthermore, the range of floating demand also cannot be determined. Therefore, it involves dual-interval uncertainties.

Currently, in the field of energy systems planning, the studies of optimization models under dual-interval uncertainties are still limited, especially in NG pipeline transportation research. In order to address the issues of NG optimization modeling under dual-interval uncertainties, in this research, a dual-interval energy systems planning model (DIESPM) and a dual-interval NG pipeline systems planning model (DIPSPM) are developed. The DIESPM is to deal with the uncertainties expressed in dual-interval format in energy systems planning. The DIPSPM is applied to “Se Ning Lan” NG pipeline systems (SNLPS) in northwest China.

The optimized planning solutions for SNLPS indicate that the developed model can provide an integrative gas transmission plan to reflect the dual uncertainties of gas demand. Meanwhile, the model can be adaptable to various situations and could be applied to other NG pipeline networks by adjusting parameters.

Acknowledgements

I would like to express my sincere appreciation to Dr. Gordon Huang for his supervision. It is my honour to be a student of Dr. Huang. During the two years of research, his guidance, encouragement, and support helped me overcome all problems and complete this thesis. I am sure that the experience from the last two years is worth a lifetime of wealth.

I am heartily grateful to Dr. Qianguo Lin for his valuable advice and kind help during the past two years. I am also thankful to the Faculty of Graduate Studies and Research for providing me the opportunity to complete my research. I also appreciate the people in the China Petroleum and Petrochemical Engineering Institute for their assistance in data collection.

I wish to express my appreciation to all my colleagues from the Institute for Energy, Environment and Sustainable Communities at the University of Regina for their constructive suggestions to my study.

Finally, I would like to express my deep gratitude to my family for their unlimited and unconditional love and moral support.

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Chapter 1

Introduction

Energy and food are the two most important types of fuel for human society (W. Engdahl, 2004; W. F. Engdahl, 2007). Modern industries rely on stable energy supply delivered by different types of energy sources such as coal, firewood, oil, natural gas (NG), nuclear-, hydro-, wind-, and solar-power. In 2009, the energy supply achieved 12150 million tonnes of oil equivalents (Mtoe) (IEA, 2011). The majority of the total supply includes coal, oil, and NG. These three types of energy sources contribute to 81 percent of world energy supply (IEA, 2011).

Based on the statistic results (IEA, 2011), NG is the third most important energy source in the world. It is utilized by several activities including power generation, space heating, combustion, and transportation. Compared with the other two major energy sources, NG delivers higher energy density and lower emissions (EIA, 1999). Since climate change and greenhouse gas emission reduction are continuously attracting people's attention, there will be a great potential in NG development for the future.

According to the IEA (International Energy Agency) world energy statistics, NG accounted for 20 percent of the world total energy consumption (IEA, 2005). With increasing demand from the market, the share of NG in world energy market increased to 22% in 2008 (EIA, 2011). Furthermore, some researchers indicate that the demand of NG is projected to increase by 30 to 40 percent in 2020 while the world total energy demand reaches approximately 15300 Mtoe (EIA, 2011; IEA, 2005).

As a result of rapidly growing demand in the NG market, sufficient and reliable NG supply is critical to satisfy the market's requirements. In recent years, investments have been made to reservoir exploration, production technology innovation, and distribution systems construction. Since 2000, the world proved reserves of NG have increased to 186.6 trillion cubic metres from 154.3 trillion cubic metres. At the end of 2010, the world total production of NG raised to 3.193 trillion cubic metres, which is a 32% increase compared to the production level in 2000 (BP, 2011). In order to deliver the growing amount of NG, the total length of NG pipeline networks all over the world was doubled from what it was in 1990 (0.58 million kilometres) and reached 1.2 million kilometres in 2010 (CIA, 2000, 2010).

NG pipeline systems is the primary means of gas transportation because of its efficiency and capability in delivering a large amount of gas (Kelkar, 2008; Speight, 2007). It plays a significant role in collecting NG from wellheads and delivering the gas to all downstream customers. Therefore, studies about the pipeline system are important to NG pipeline design, development, and management.

Typically, a NG pipeline system consists of three components: gathering and pre-treatment facilities, transportation pipelines, and distribution networks (Speight, 2007). Reliable gas delivery relies on effective integration of the three components. For some customers, it is essential to ensure uninterruptible gas supply. On the other hand, maintaining pipeline operation requires a large amount of expense. To pipeline owners, it is an important task to reduce operation cost in order to maximize their profit. Generally, there is always a conflict between delivery amount and operation cost. Although a larger amount of gas delivered means a higher profit, the cost of transportation increases simultaneously. Therefore, comprehensive understandings of pipeline systems are necessary for NG transportation.

In order to integrate all of the components and to introduce various economical aspects, NG pipeline systems models are commonly used. Different types of pipeline models were developed by previous researchers in order to address a variety of issues associated with pipeline design, planning, and management. Generally, there are two types of pipeline models: simulation models and management/optimization models.

The simulation models mainly focus on studying pipeline fluid mechanics and simulating system response for a specific input. These models can reveal how NG flows through pipelines and are therefore helpful tools in aiding pipeline designs. The management/optimization models contain two sub categories: one concerns a single component (gathering, transportation, or delivery) of pipeline networks; the other one attempts to provide an overall solution. The objectives of the management/optimization models are to identify the balance point between system profit and system cost.

A significant issue in pipeline modeling is the uncertain parameters that often cause inaccuracy of modeling results. In NG pipeline modeling, issues with uncertainty usually include unpredictable demand, flexible price, and variable cost of transportation.

To address such issues, the uncertain variables can be expressed as a specific range. In this way, the values of the uncertain variables can be quantified as intervals instead of deterministic values. However, in some circumstances, boundaries of the intervals may not be deterministic. For instance, it is difficult to predict the annual demand of NG for next ten years within a specific range. In order to overcome such an issue, the upper and lower boundaries can also be represented as intervals, thereby introducing dual-interval uncertainties.

In China, the studies of NG pipeline planning modeling are very limited, especially under dual uncertainties. In this thesis, a dual-interval NG pipeline systems planning model (DIPSPM) is developed to reflect issues of dual uncertainties in optimizing a NG pipeline system and is applied to the “Se Ning Lan” NG pipeline system (SNLPS).

The SNLPS connects “Se Bei” gas field to Qinghai Province and Gansu Province in China. The maximum flow rate of the pipeline system is 6.8 billion cubic metres per year. 18 major customers are located mainly in the cities of Xi Ning and Lan Zhou, which are the capital cities of Qinghai Province and Gansu Province, respectively. The customers can be categorized into residential, commercial, and industrial sectors. Continuous gas supply to domestic and industrial customers is a critical task for pipeline operators. On the other hand, for such a large amount of delivered gas, minimizing annual operation cost is important in the generation of profit. Thus, NG pipeline systems modeling method is helpful to identify the optimum spot between profit and cost.

Since 2008, the demand of NG has dramatically increased in Qinghai Province and Gansu Province. In China's 12th Five-Year Plan (2011-2015) (DRCG, 2011; DRCQ, 2011), both of the two provinces are planning to promote the utilization of NG in the next 10 years. Due to the increasing demands of NG, the owner of SNLPS, China National Petroleum Corporation (CNPC) is under pressure to deliver sufficient NG while maintaining profitable operation.

However, due to difficulties in predicting the demand of NG, the increases of NG demand in the two provinces by the end of 2020 could be expressed in dual-interval format. In this model, the increase of NG demand is [(50, 93), (98, 126)]%. A NG pipeline systems planning method can deal with such dual-interval uncertainties and thereby is helpful to optimize the pipeline operation and achieve a maximized profit.

Therefore, the objectives of this research include:

- Development of a dual-interval energy systems planning model (DIESPM).
- Development of a dual-interval NG pipeline systems planning model (DIPSPM).
- Application of the developed DIPSPM to the planning of "Se Ning Lan" NG pipeline system in China.

Chapter 2

Literature Review

2.1 Energy systems planning under uncertainties

Energy systems optimization is complicated when coupled with a variety of uncertainties. For example, energy demand of a specific region may fluctuate with variations in population and economy. Similar effects also appear regarding factors such as power-plant operating costs, electricity transmitting costs, and facility expansion costs.

To deal with such uncertainties, various energy systems planning methods were developed. Liu et al. (2000) and Guo et al. (2008) developed chance-constrained programming models to optimize the management of energy sources. Cai et al. (2008) and Lin et al. (2011) developed dynamic energy management models that take uncertainties into account. Lin and Huang (2010) introduced a stochastic linear programming model for optimizing energy management models. Lin and Huang (2008) and Cai et al. (2009) developed energy management models through interval chance-constrained linear programming. Chedid et al. (1999) and Lin et al. (2009) presented fuzzy linear programming energy management models. Lin et al. (2010) developed an energy management model with combined interval linear programming and chance constrained programming. Cao et al. (2010) introduced a random interval integer programming energy model to optimize municipal power systems. Li et al. (2011)

combined fuzzy linear programming with stochastic linear programming and developed a regional energy system model. These studies could address the effects of uncertainties by introducing different methodologies including fuzzy, stochastic, and interval programming.

Stochastic and fuzzy programming methods can address uncertainties expressed as probabilistic distributions and/or fuzzy sets (Lin & Huang, 2008). Interval parameter linear programming (ILP) can deal with uncertainties in interval format. It can handle uncertainties through defining the related parameters in a range with lower and upper boundaries. Compared to the other methods, the ILP method doesn't need distribution information of the variables. Therefore, it requires less effort in data collection.

2.2 Optimization under dual-interval uncertainties

However, in real-world problems, the boundaries of many interval variables may not be deterministic due to various complexities that exist in the information acquisition process. As a result, additional uncertainties (i.e., dual uncertainties) may be involved. In order to address such uncertainties, the method of optimization under multiple uncertainties was proposed by various researchers.

2.2.1 Linear programming under multiple uncertainties

Cheng et al. (2009) combined interval linear programming method and stochastic programming method and introduced an integrated solid waste management model under interval-stochastic uncertainties. Cai et al. (2009) applied the concept of multiple uncertainties to energy systems modeling and developed a fuzzy-random interval programming energy management model. In 2009, Guo et al. (2010) developed a fuzzy-stochastic programming method for water resources management under multiple uncertainties. Zhang et al. (2010) introduced an integrated solid waste management model under interval-possibilistic uncertainties. In 2011, Li et al. (2010) developed a water resource management model combining interval and fuzzy uncertainties. In addition, different models under multiple uncertainties were introduced to support environmental systems decision making (Y. P. Li, Huang, Guo, Yang, & Nie, 2010; Y. P. Li, Huang, Nie, & Chen, 2011).

These studies integrate two or three types of programming methods and develop a new approach under multiple uncertainties. Although the studies can reflect the complexity in systems optimization, they require great effort to collect distribution information of variables. Therefore, use of these methods might not obtain reliable results when information is limited.

2.2.2 Dual-interval linear programming

In order to overcome the disadvantages of the previous studies, Liu and Huang (2009) developed a dual-interval two-stage optimization model for flood management. Then, Liu et al. (2009) applied this method to solid waste management planning.

For the interval linear programming, the inexact variables are express as interval numbers. An interval number represent a specific range. Obviously, providing a range of an unknown variable is much easier than collecting distribution information of the variable. Therefore, the ILP method is widely applied in optimization research.

An interval number is usually denoted as D = [A, B] where A and B respectively represent the lower bound and the upper bound of the interval D. Consider A and B are two interval numbers, where A = [a, b], and B = [c, d]. Then, the interval, I, turns into [(a, b), (c, d)], which is an interval with inexact boundaries.

2.3 Modeling of NG pipeline systems

2.3.1 Simulation

In general, there are two types of NG pipeline models: simulation models, and management/optimization models. The simulation models focus on the characteristics of NG flow through the pipeline networks. Nimmanonda et al. (2004) introduced a computer aided simulation model to simulate the flow of NG within pipeline networks. Zhang and Gao (2007) developed a simulation model to discover the NG behaviour in gathering systems of the “Se Bei” gas field. Woldeyohannes and Majid (2011) developed a model to research flow characteristics under different pressures.

2.3.2 Optimization

Transportation cost is one of the most significant costs in NG transportation. The majority of transportation cost is the operation cost of compressors. Therefore, many optimization models were developed by different researchers in order to reduce the operation cost of compressors. Ainouche (2003) developed a linear programming model to optimize the operation of compressors. The model provided an optimized operation plan for the compressors to reduce the transportation cost. Uraikul et al. (2004) proposed an optimization model to select the most economical compressors for a gas pipeline in Saskatchewan, Canada. Garcia-Hernandez and Brun (2012) developed a gas pipeline systems model to minimize transportation cost. In the model, they focused on optimizing the operation of compressors, thereby reducing energy usage in NG transportation. In addition, similar optimization models were developed by various researchers (Borraz-Sanchez & Rios-Mercado, 2005; Chebouba et al., 2009).

In addition to the above models, Contesse et al. (2005) developed an optimization model to optimize NG distribution for a downstream distribution company. Wu, Lai et al. (2007) introduced an optimization model to minimize cost for downstream distribution pipeline networks. These distribution optimization models are generally simpler than the models focusing on upstream networks because the distribution system doesn’t include gathering stations and compressors (Wu, et al., 2007).

2.4 Summary

In China, the studies of NG pipeline systems models are still limited. In 2001, Li (2001) proposed a pipeline systems model to simulate NG flow within pipelines. Meanwhile, she also developed pipeline simulation software. He et al. (2006) developed an optimization model for a NG pipeline system in southwest China. The objective of the model is to achieve maximum profit by regulating the operation of compressors. Su et al. (2010) developed an optimization model to determine the most economical expansion option for the “Se Ning Lan” NG pipeline systems (SNLPS).

Although there were a number of studies related to NG pipeline modeling, the previous research could hardly reflect the complexities of NG pipeline system planning. There was no study about pipeline optimization under highly uncertain demand.

In order to reflect the uncertainties in NG demand, dual-interval uncertainties can be used to represent NG demand. Currently, there is no optimization model that can reflect the uncertainties in NG demand in China. Therefore, in this research, a dual-interval NG pipeline systems model was developed for the SNLPS.

Chapter 3

Dual-Interval Energy Systems Planning Model

In order to address the dual-interval uncertainties issues in NG pipeline systems modeling, a dual-interval energy systems optimization model is developed. The objective is to explore and verify the dual-interval linear programming approach in energy systems optimization.

3.1 Background

Energy system modeling is an effective tool for energy planning in a region. However, it is highly complicated when coupled with a variety of uncertain factors. When conducting a model study of energy systems, it is difficult to determine the amount of energy supply due to the complexity of demand variation. Previously, various research and studies have proposed plenty of valuable methods to address the uncertainties in systems optimization. For example, the fuzzy linear programming method and stochastic linear programming method are introduced to deal with the probabilistic and possibilistic uncertainties, etc.

However, most of the previous approaches require great effort in the data collecting process. When available data is limited, the interval linear programming (ILP) method can make data collection easier by narrowing the variable value to an acceptable range. However, the greatest shortcoming of the ILP method is the definition of “acceptable range”. If the range is too small, then it will be easily violated. On the other hand, it is not very meaningful if the range is too large.

In addition to the ILP method, some researches introduced a dual-interval linear programming (DILP) method. DILP express the two boundaries of an interval number as two intervals. In other words, in DILP, the boundaries of an interval are uncertain and, therefore, the second level of uncertainty is introduced. Meanwhile, interpolation methods are developed to convert a dual-interval number into a group of interval numbers, while each of the interval numbers will be assigned a specific possibility.

Conversely, inherent in the DILP method is the possibility of precisely deciding “the acceptable range.” During data collecting for a target variable, a group of interval numbers are collected without regard for the range of each interval number. Then, decision makers can review the collected interval numbers and determine their possibilities. Finally, these interval numbers can be converted into a dual-interval number. The possibility distribution of the converted dual-interval number can be developed using the pre-determined possibilities. In this way, the DILP method can robustly reflect the high complexity of variables in reality.

In energy systems studies, the amount of energy supply highly depends on the energy demand. Although the actual energy demand in the future is very difficult to estimate, the DILP method can be helpful in addressing such uncertainty issues.

Therefore, in this study, a dual-interval energy systems planning model (DIESPM) is developed.

In DIESPM, the lower and upper bounds of many uncertain variables are expressed as intervals. Compared to other uncertain-boundary interval optimization methods, DIESPM can more robustly reflect complexities of the effects from the dual uncertainties. Meanwhile, it also does not require boundary distributional information for the uncertain parameters, resulting in improved information availability and computational simplicity.

3.2 Complexities in energy generation and allocation planning

The concept of the model is to minimize total system cost with engineering optimization. Three categories of cost are introduced in the model including operation cost, facility expansion cost, and electricity import cost. The total system cost can be calculated by summing all the categories of operation cost, facility expansion cost, and electricity import cost. Three time periods are covered in this model. For each time period, a five-year study time is used. Therefore, a fifteen-year time span is covered in this model. The time horizon setting represents scopes of typical energy policies. The three time periods are assigned with different ranges of energy demand in order to reflect variations in an economy.

Six facilities are considered to describe operation cost. These facilities are different due to their energy source: coal, NG, nuclear, water, wind, and solar. The operation cost of each power generating facility is defined by a variable called unit operation cost, which reflects the cost of generating a certain amount of electricity. Therefore, the operation cost for each facility in each time period can be calculated by multiplying the electricity generated with the unit operation cost of the facility.

The cost associated with facility expansion is determined by three factors: capital cost for capacity expansion, expansion options, and an integer decision variable that indicates whether expansion activities would occur. If the integer decision variable indicates no action would be taken, then it is not necessary to consider the other two factors. If the integer decision variable indicates there would be expansion actions, then the other two factors will be calculated to obtain expansion cost. The decision variable is determined by compromising between facility expansion and electricity import. A detailed description about this variable will be given after introducing the electricity import factor.

The theory of expansion cost calculation is similar to the calculation of operation cost. The first factor, capital cost, represents the amount of capital investment for facility expansion for a certain amount of electricity. This factor differs among various facilities. For example, a big investment is required to design and construct a nuclear power plant compared to a solar power station that usually needs a lesser work load.

The expansion options indicate various amounts of capacity expansion in giga-watts (GW). For each facility, three different options are available in this model. Therefore, if expansion activity occurs, then the capital cost is multiplied by expansion options to obtain the total expansion cost. However, there might be some arguments about expansion cost. For instance, in the model, three options (0.2GW, 0.3GW, and 0.4 GW) are available for expanding a coal power plant. The expansion cost can be calculated by multiplying the capital cost by one of the options. Therefore, it is obvious that the expansion cost for a certain facility is directly proportional to the expansion options. In the real world, this relation might not be correct. In this paper, the primary objective is to demonstrate the application of dual-interval programming in energy planning model. Thus, it is assumed that the expansion cost is directly proportional to the expansion options.

In order to determine the cost of imported electricity, two factors are involved: the amount of imported electricity and the price of imported electricity. These two factors are used to calculate the cost of imported electricity by multiplying them together. In this model, the electricity price is assigned with a specific range for each time period. Therefore, the amount of imported electricity is the decision variable deciding the electricity import cost.

As mentioned before, the objective of this model is to derive the minimum range of the total cost. As the system demand increases, the current electricity supply cannot satisfy it. In order to increase supply, actions should be taken including facility expansion and electricity importing. To obtain an optimized solution, the costs of the two actions should be considered simultaneously. The concept is to cover the electricity shortage with the lowest cost. Thus, facility expanding is usually suitable for a large supply, while imported electricity is more appropriate to cover a small shortage. In some cases, both of the two actions might be selected to satisfy the increasing demand.

3.3 Development of dual-interval energy systems optimization method

The dual-interval energy systems optimization method uses interval decision variables that define the upper limits and the lower limits for the corresponding parameters. These variables are denoted with the symbol "±". Three categories of cost on the right of the equation represent operation cost, expansion cost, and electricity import cost. The equation's objective is to achieve the lowest cost and the objective function could be formulated as follows:

$$\text{Min } f^{\pm} = \sum_{k=1}^{3}\sum_{j=1}^{6} P_{jk}^{\pm} X_{jk}^{\pm} + \sum_{k=1}^{3}\sum_{j=1}^{6}\sum_{i=1}^{3} C_{jik}^{\pm} E_{jik} Y_{jik}^{\pm} + \sum_{k=1}^{3} H_{k}^{\pm} I_{k}^{\pm} \tag{3-1}$$

(Operational cost + capital cost + electricity import cost)

The objective function is subject to five constraints that restrict the potential solutions. The constraints include: (1) mass balance constraint, (2) imported electricity rate constraint, (3) renewable electricity rate constraint, (4), capacity expansion constraints, and (5) non-negativity constraints.

These constraints provide restrictions for solving the model. In the model, electricity supply over a given time period should always be greater than system demand. As the demand increases, expansion to current facilities or electricity import should be initiated in order to cover the power shortage. Another way to overcome supply shortage is electricity import. However, due to economic issues, the maximum level of electricity import is restricted to 5% of the total supply. Considering the environmental aspect, renewable energy is more environmentally friendly and could decrease greenhouse gas emission. Therefore, a certain amount of electricity is required to be generated from renewable energy which includes hydro power, wind power, and solar power.

Mass balance constraint (electricity supply greater than demand):

$$\sum_{j=1}^{6} X_{jk}^{\pm} + I_k^{\pm} \geq \tilde{\tilde{D}}_k \qquad (3\text{-}2)$$

Imported electricity rate constraint (upper bound of electricity import):

$$I_k^{\pm} \leq I_k^{0}, \ \forall k \qquad (3\text{-}3)$$

Renewable electricity rate constraint (lower bound of electricity from renewable % of total electricity demand):

$$\sum_{j=4}^{6} X_{jk}^{\pm} \geq \eta_k \tilde{\tilde{D}}_k, \ \forall\, k \qquad (3\text{-}4)$$

Capacity expansion constraints:

$$\sum_{i=1}^{3} Y_{jik}^{\pm} \leq 1, \ \forall j, k \qquad (3\text{-}5a)$$

$$O_j^{\pm} + \sum_{i=1}^{3} E_{ji1} Y_{ji1}^{\pm} U \geq X_{j1}^{\pm} \qquad (3\text{-}5b)$$

$$O_j^{\pm} + \sum_{i=1}^{3} E_{ji1} Y_{ji1}^{\pm} U + \sum_{i=1}^{3} E_{ji2} Y_{ji2}^{\pm} U \geq X_{j2}^{\pm} \qquad (3\text{-}5c)$$

$$O_j^{\pm} + \sum_{i=1}^{3} E_{ji1} Y_{ji1}^{\pm} U + \sum_{i=1}^{3} E_{ji2} Y_{ji2}^{\pm} U + \sum_{i=1}^{3} E_{ji3} Y_{ji3}^{\pm} U \geq X_{j3}^{\pm} \qquad (3\text{-}5d)$$

Non-negativity constraints:

$$Y_{jik}^{\pm} = 0, 1 \text{ or } [0, 1], \ \forall j, i, k \qquad (3\text{-}6a)$$

$$X_{jk}^{\pm} \geq 0, \ \forall i, k \qquad (3\text{-}6b)$$

$$I_k^{\pm} \geq 0, \forall k \qquad (3\text{-}6c)$$

where:

i = capacity expansion options, i = 1, 2, 3;

j = electricity generation facilities, j = 1, 2, 3, 4, 5, 6;

k = time periods, k = 1, 2, 3;

$X_{jk}^{\pm}$ = decision variables representing annual electricity from facility j in period k (PJ);

E_{ijk} = expansion options for facility j in period k (GW);

$I_k^{\pm}$ = decision variables representing imported electricity in period k (PJ);

$Y_{jik}^{\pm}$ = binary-interval decision variables for facility j with option i in period k;

I_k^0 = the maximum imported electricity in period k (PJ);

$H_k^{\pm}$ = electricity import price in period k (million$/PJ);

η_k = the minimum rate of renewable energy supplied electricity in period k;

$\tilde{\bar{D}}_k$ = the total electricity demand in time k (PJ);

$P_{jk}^{\pm}$ = operation cost of facility j in time k (million$/PJ);

$C_{jik}^{\pm}$ = capital cost for capacity expansion option i of facility j in period k (million$/GW);

In this model, the total energy demand is considered as a dual-interval parameter. The possibilities for each sub-model are all set to be 33.3%. In the real world applications, the possibilities for each sub-model could vary since they are determined by decision makers with specific confident levels.

3.4 Issues of energy supplies and demands

The hypothetical case study is designed to illustrate the application of the DILP method in energy systems modeling. The model describes the energy supply and demand of a region for three five-year periods. Both non-renewable energy sources (coal, NG, and nuclear power) and renewable energy sources (water, wind, and solar) are considered in this study. The expected outcome of the study is to obtain a valid energy supply scheme with the lowest cost for the whole study period. The regional energy demand is uncertain and is set as a dual-interval number. In the first period, the energy demand is [(100, 110), (130, 143)] (PJ/year) in dual-interval format. Then, it increases to [(110, 121), (143, 157.3)] (PJ/year), which is a ten percent increment. In the last period, the energy demand reaches [(121, 133.1), (157.3, 173.03)] (PJ/year).

In this study, the unit operation costs are assigned with specific values. In the real energy system, the unit operation cost for a power plant varies with time, economic conditions, and aging facilities. Meanwhile, regional policy for an energy market might cause a change in operation cost. However, these uncertainties have minor impacts on the model algorithm. Therefore, they can be neglected in this model to simplify the calculation.

Coal, as an important conventional power generating resource, usually comes with high production, easy accessibility, and low cost. In this model, the unit operation cost of a coal-powered power plant is 0.35 million dollars / PJ. The initial power generating capability is set to 1.5 GW.

Compared to coal, NG can be classified as a clean energy source since the only emission from NG combustion is carbon dioxide and water. However, more issues would arise during gas transportation and storage. Although NG can be compressed from a gaseous state to a liquid state, it still cannot compete with the accessibility of coal. Therefore, in this model, the initial electricity generating capacity of a gas power plant is set to 0.3 GW, and the unit operation cost is 0.4 million dollars / PJ.

Nuclear power has a low emission amount and does not require a large amount of cost due to resource transportation. Meanwhile, compared to new energy sources, nuclear power is characterized with a remarkable high energy density. Wind turbines and solar panels usually occupy a significant amount of land in order to produce a large amount of power. Considering the tremendous amount of power output from nuclear power, a nuclear power plant takes much less land area than the other two energy sources. In addition, the power output will not be disrupted by changing weather conditions. Therefore, a stable electricity supply can be achieved.

Although nuclear power carries the above advantages, development of nuclear power plants is often restricted by cost of construction, technology availability, sources of nuclear fuel, regional policies, and public acceptance. In addition, disposal of nuclear wastes, and the impacts of nuclear crises such as those that occurred in Chernobyl and Fukushima have increased negative attitudes toward nuclear power development.

In the hypothetic region, a nuclear power plant is assumed to exist due to concerns about energy source variability. The initial installed capacity is set to be 1 GW, and the unit operation cost is 2.9 million dollars/PJ.

Besides the above conventional energy sources, hydro power, wind power, and solar power are also considered in this model. The three energy sources are not only renewable energy sources. But they can also be categorized as clean energy sources, since there are no direct emissions from converting these three types of energy to electricity.

From the Kyoto Protocol to the 2009 Copenhagen Climate Conference, the energy industry advocates using clean energy to reduce emissions. For years, the proportion of clean energy in the total energy supply has been gradually increasing. In order to simulate this scenario, in this study, a parameter, η_k is defined to restrict the percentage of new energy proportion in the total energy consumption. For the three periods, η_k is defined as greater than 10%, 15%, and 20%, respectively. The increasing percentage refers to the increasing requirement of replacing the conventional energy sources with newer and cleaner energy sources.

Among the three energy sources, the initial installed capacity for hydro power is 0.4GW. The unit operation cost of hydro power plant is 0.6 million dollars / PJ. For the wind power, the initial installed capacity is set to be 0.012GW, and its unit operation cost is 1.81 million dollars / PJ. For the solar power, the initial installed capacity is 0.01GW, and its unit operation cost is 0.01 million dollars / PJ.

When the current energy supply cannot satisfy the regional energy demand, there are be two options available, expanding current facilities or importing electricity from other regions. Thus, the expansion cost and electricity import cost should be addressed.

There are two parameters related to facility expansion, capital costs for expansion and expansion options. Table 3-1 lists the expansion costs and expansion options for each facility. Sometimes, it is more economical to import electricity from other regions than to expand the current facilities. External energy dependence is an important factor in examining the local energy security of supply. In this model, this factor is assumed to be 5% of the total energy supply in order to restrict the maximum amount of electricity imports. The electricity import price is set to be [25, 35], [25, 36], [25, 37] million dollars / PJ for the three periods.

3.5 Planning of energy management systems

To solve the dual-interval problem, Joslyn (2003) proposed a solution to interpret a DILP model into a number of ILP sub-models. According to Joslyn's algorithm, there are two possible approaches to solving DILP problems.

When the collected information is in dual-interval format, the first approach can be applied. The approach is to convert the dual-interval variables to sub-models. Specific possibilities are assigned to every sub-model. Thus, the sub-models can be equivalent to the DILP model. Then, solutions for each sub-model can be obtained through the ILP algorithm, which was developed by Huang et al. (1992). The ILP method has been clearly defined and applied in many studies (Huang, 1996; Huang, Baetz, & Patry, 1997; Huang & Moore, 1993). It was demonstrated that the ILP method can reflect the uncertainty of environmental systems without distribution information. Finally, the solutions of the sub-models are formulated under the specific possibility distributions to obtain the DILP solutions.

Table 3-1

Expansion cost of each facility (million $/GW)

Time Periods	Capital Cost					
	Coal	NG	Nuclear	Hydro	Wind	Solar
1					2300	3400
2	1051.3	750	2654	1450.3	2100	2900
3					1900	2400

When the collected information is in interval format, the second approach can be applied. The interval variables can be considered as sub-models, and they need to be assigned with specific possibilities. With the assigned possibilities, the possibility distribution of the dual-interval can be obtained. After the sub-models are solved with ILP method, the dual-interval solution can be obtained by formulating the sub-models under the possibility distribution. The solution processes of the two approaches are shown in Figure 3-1 and Figure 3-2.

As mentioned in section 3.4, the information on energy demand is in dual-interval format. Thus, according to the first approach, the dual-interval model will be transformed into three sub-models. The possibility of each sub-model is 33%, as mentioned in section 3.3. Finally, the three sub-models are calculated for each time period.

The energy demands of each sub-model for the three periods are listed as follows: for Sub-model 1, they are (100, 130), (110, 143), and (121, 157.3) PJ/year. For Sub-model 2, they are (110, 130), (121, 143), and (133.1, 157.3) PJ/year. For Sub-model 3, they are (110, 143), (121, 157.3), and (133.1, 173.03) PJ/year. Then, all nine sub-models can be solved with the ILP solution algorithm. The solutions are shown in Tables 3-2, 3-3 and 3-4. These solutions describe energy production plans for the three sub-models. The plans provide detail instructions about how much energy should be delivered from the six different facilities and how much electricity should be imported during each time period. Also, the solutions provide suggestions about the optimized system cost. With these solution tables, the overall solution can be achieved by combining the solutions of the sub-models. Table 3-3 demonstrates the solution of the DILP model.

The energy production solution draws a blueprint of the energy supply in the studied region for the next three periods. It can be considered a regional power supply plan. For each facility in each period, this plan provides an optimized interval of power generation. Based on the results shown above, it is demonstrated that this model is capable of providing a reasonable energy planning solution under dual uncertainty for a region with a variety of power facilities.

Since the objective of the model is to minimize the total system cost while satisfying energy demand, it can be expected that the model tends to select the most affordable resource for power supply. Under this assumption, the six different power sources can be ranked by their cost. Here, the most affordable power source means the one that has the least operational costs. If there were no other constraints, the model is supposed to select the most affordable energy facility until it reaches its installed capacity. Then, the second most affordable facility will join the supply sequence. However, there is a “renewable energy” constraint that requires at least a fraction of energy to be delivered from renewable energy sources. Thus, separately, all the renewable energy sources are selected based on their affordability to satisfy the proportion of the “renewable” energy demand.

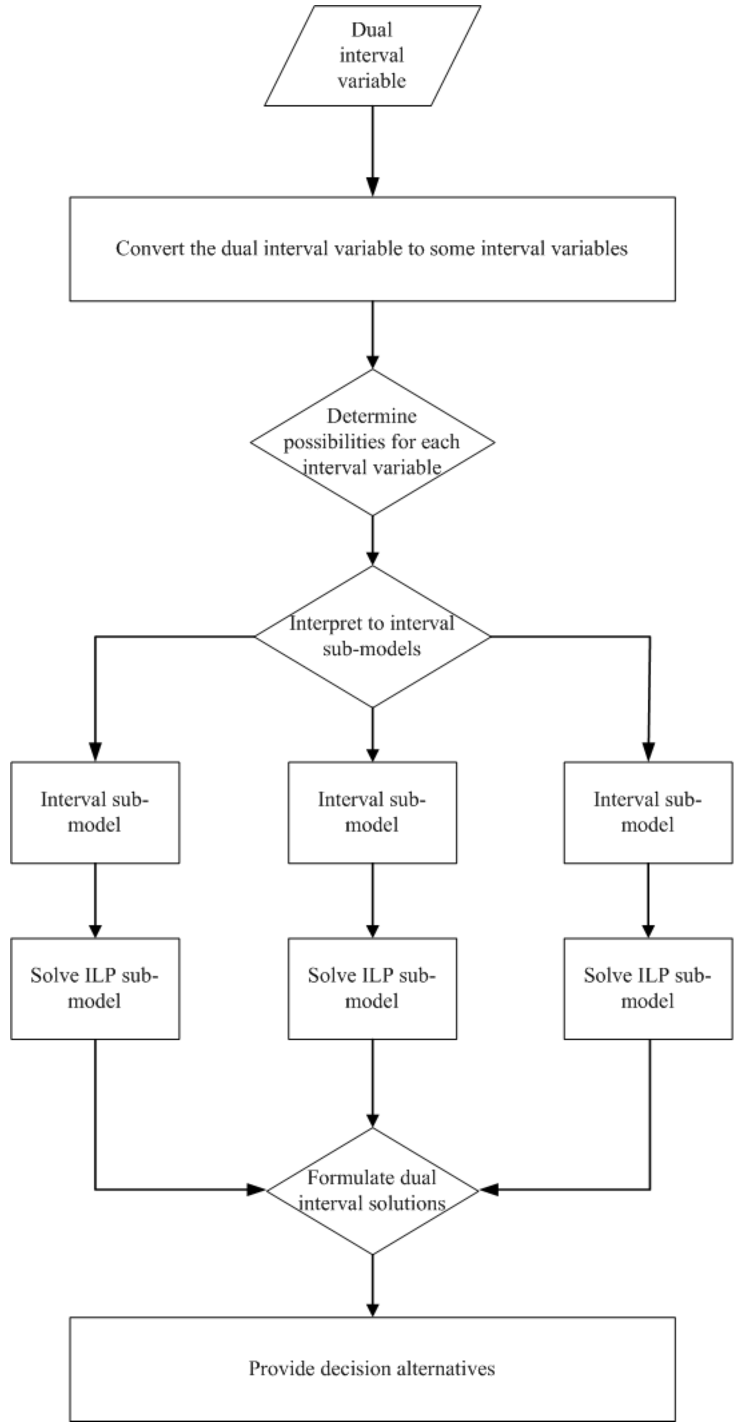

Figure 3-1 Solution process of the first approach

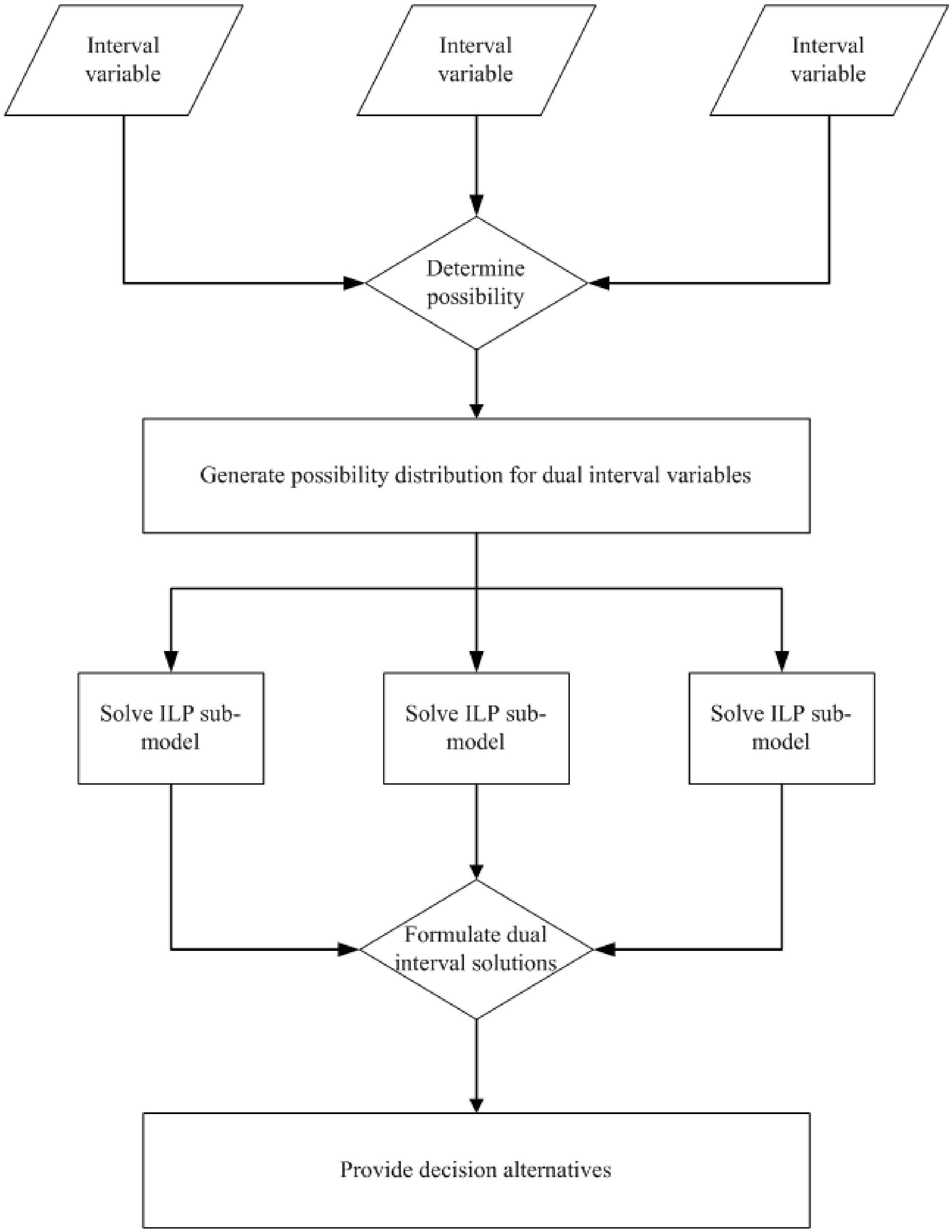

Figure 3-2 Solution process of the second approach

Table 3-2

ILP solution for the three sub-models (PJ/year)

Facilities	Period	Sub-model 1		Sub-model 2		Sub-model 3	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal	1	47.3	59.92	47.3	59.92	47.3	59.92
	2	47.3	72.53	47.3	66.23	47.3	69.38
	3	47.3	72.53	47.3	66.23	47.3	69.38
NG	1	13.56	13.56	13.56	13.56	13.56	13.56
	2	15.55	17.66	17.66	17.66	17.66	17.66
	3	15.55	20.66	21.76	21.76	21.76	21.76
Nuclear	1	13.21	26.81	23.21	26.81	23.21	31.54
	2	21.23	22.15	30.11	30.11	30.11	30.11
	3	31.54	31.54	31.54	31.54	31.54	31.54
Hydro	1	25.23	28.38	25.23	28.38	25.23	28.38
	2	25.23	28.38	25.23	28.31	25.23	38.51
	3	25.23	28.38	25.23	28.38	25.23	41.00
Wind	1	0.38	1.01	0.38	1.01	0.38	1.32
	2	0.38	1.96	0.38	0.38	0.38	0.38
	3	0.38	2.9	1.32	2.9	1.32	1.32
Solar	1	0.32	0.32	0.32	0.32	0.32	1.26
	2	0.32	0.32	0.32	0.32	0.32	1.26
	3	0.32	0.32	0.32	0.32	0.32	1.26
Electricity Import	1	0	0	0	0	0	7.02
	2	0	0	0	0	0	0
	3	0.69	0.98	5.63	6.18	5.63	6.77
System Cost		1048.46	2422.23	1436.56	2446.95	1436.56	3432.05

Table 3-3

DILP solution for the energy model (PJ/year)

<table>
<tr><th rowspan="2">Facilities</th><th rowspan="2">Period</th><th colspan="2">Lower Bound</th><th colspan="2">Upper Bound</th></tr>
<tr><th>Lower Bound</th><th>Upper Bound</th><th>Lower Bound</th><th>Upper Bound</th></tr>
<tr><td rowspan="3">Coal</td><td>1</td><td colspan="2">47.30</td><td colspan="2">59.92</td></tr>
<tr><td>2</td><td colspan="2">47.30</td><td>66.23</td><td>72.53</td></tr>
<tr><td>3</td><td colspan="2">47.30</td><td>66.23</td><td>72.53</td></tr>
<tr><td rowspan="3">NG</td><td>1</td><td colspan="2">13.56</td><td colspan="2">13.56</td></tr>
<tr><td>2</td><td colspan="2">15.55</td><td colspan="2">17.66</td></tr>
<tr><td>3</td><td colspan="2">15.55</td><td colspan="2">21.76</td></tr>
<tr><td rowspan="3">Nuclear</td><td>1</td><td>13.21</td><td>23.21</td><td>26.81</td><td>31.54</td></tr>
<tr><td>2</td><td colspan="2">21.23</td><td colspan="2">30.11</td></tr>
<tr><td>3</td><td colspan="2">31.54</td><td colspan="2">31.54</td></tr>
<tr><td rowspan="3">Hydro</td><td>1</td><td colspan="2">25.23</td><td colspan="2">28.38</td></tr>
<tr><td>2</td><td colspan="2">25.23</td><td>28.31</td><td>38.51</td></tr>
<tr><td>3</td><td colspan="2">25.23</td><td>28.38</td><td>41.00</td></tr>
<tr><td rowspan="3">Wind</td><td>1</td><td colspan="2">0.38</td><td>1.01</td><td>1.32</td></tr>
<tr><td>2</td><td colspan="2">0.38</td><td colspan="2">1.96</td></tr>
<tr><td>3</td><td colspan="2">0.38</td><td colspan="2">2.90</td></tr>
<tr><td rowspan="3">Solar</td><td>1</td><td colspan="2">0.32</td><td colspan="2">1.26</td></tr>
<tr><td>2</td><td colspan="2">0.32</td><td colspan="2">1.26</td></tr>
<tr><td>3</td><td colspan="2">0.32</td><td colspan="2">1.26</td></tr>
<tr><td rowspan="3">Electricity Import</td><td>1</td><td colspan="2">0.00</td><td colspan="2">7.02</td></tr>
<tr><td>2</td><td colspan="2">0.00</td><td colspan="2">0.00</td></tr>
<tr><td>3</td><td colspan="2">0.69</td><td colspan="2">6.77</td></tr>
<tr><td colspan="2">System Cost (million $)</td><td>1048.46</td><td>1436.557</td><td>2422.23</td><td>3432.054</td></tr>
</table>

Table 3-4

Facility expansion (giga-watts)

Facilities	Periods	Sub-models 1		2		3	
		Low	High	Low	High	Low	High
Coal	1	0	0.6	0	0.6	0	0.6
	2	0	0.6	0	0.3	0	0.45
	3	n/a		n/a		n/a	
NG	1	0.13	0.13	0.13	0.13	0.13	0.13
	2	0.063	0.13	0.13	0.13	0.13	0.13
	3	0	0.095	0.13	0.13	0.13	0.13
Nuclear	1	n/a		n/a		n/a	
	2	n/a		n/a		n/a	
	3	n/a		n/a		n/a	
Hydro	1	0.4	0.5	0.4	0.5	0.4	0.5
	2	n/a		n/a		0	0.4
	3	n/a		n/a		n/a	
Wind	1	0	0.02	0	0.02	0	0.03
	2	0	0.03	0	0.03	n/a	
	3	0	0.03	0.03	0.03	0.03	n/a
Solar	1	n/a		n/a		0	0.03
	2	n/a		n/a		n/a	
	3	n/a		n/a		n/a	

Consider the lower-bound scenario of Sub-model 1. The increasing energy demand is based on 10% increments through three periods and is from 100 PJ/year to 121 PJ/year. Since the initial capacity of electricity supply is 101.6 PJ/year, facility expansions or electricity imports should be scheduled to fulfill the energy demand.

In Tables 3-2 and 3-4, detailed expansion activities are listed. The capacity of the NG facility is increased to 13.56 PJ/year in the first period and is increased to 15.55 PJ/year in the second period; the capacity of the hydro-power facility is increased to 25.23 PJ/year from 12.62 PJ/year. Besides the expansions, 0.69 PJ/year of electricity is imported in the third period.

Theoretically, the expansions and electricity imports are directed by the principle of minimal cost. Compared with the other facilities, the natural-gas based facility has the lowest capital cost of expansion so it rates the highest expansion priority. An interesting finding in Table 3-4 is the expansion in hydro-power facility. According to the initial data, the hydro-power facility has higher expansion cost and operation cost than the coal-powered facility. However, in the solution, investments pass over coal-powered facility and are directed into hydro-power facility expansion. It seems that the result contradicts the principle of minimal cost. Such a contradiction can be addressed by including a renewable energy constraint.

In the DIESPM, the parameter η_k is defined to restrict the minimum fraction of renewable energy supplied electricity in the total electricity supply. In the model, this parameter requires at least a certain amount of electricity must be delivered from renewable energy sources (water, wind, and solar). Assuming the coal-powered facility obtained investment instead of hydro-powered facility, then, in the third period, the renewable energy delivered electricity will only take 11% of the total energy demand (13.32 PJ/year of 121 PJ/year). Referring to Chapter 3.1, the fraction must be greater than 10%, 15%, and 20% for the three periods. In the model solution, the renewable energy constraint parameter η_k is 25.9%, 23.6%, and 21.4%, respectively (As shown in Table 3-5). Therefore, it is clear that the purpose of the expansion of hydro-powered facility is to satisfy the renewable energy constraint. Although the primary target of the energy model is to minimize system cost, the model is capable to compromise between the primary goal and the requirements from constraints.

According to Table 3-5, the percentage of renewable energy-based electricity satisfies the requirements for all of the scenarios. Moreover, the expansion of NG facility should be considered. From the solution (Tables 3-2 and 3-4), the expansions take place in the first and the second period, and the total increasing of capacity is 6.09 PJ/year. However, it is noticeable that the nuclear-powered facility is operated under its capacity limit in the first two periods. Thus, the question becomes one of why the model decides to expand current facilities while they are working under stress.

Table 3-5

Percentage of renewable energy-based electricity (%)

		Sub-models						
		1		2		3		
	Periods	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound	Requirement ≥
	1	25.93	22.85	23.57	22.85	23.57	21.65	10
η	2	23.57	21.44	21.43	20.29	21.43	25.52	15
	3	21.43	20.09	20.19	20.09	20.19	25.19	20

To answer this question, firstly, the energy supply structure for the last period must be analyzed. Without considering NG facility and electricity imports, the total energy supply is 104.77 PJ/year, while all the other facilities are generating electricity at their supply capacity. Thus, an additional amount of 16.23 PJ/year of electricity is required to meet the 121 PJ/year demand. The NG-powered facility can provide 9.462 PJ/year of electricity without any expansion. Then, the energy gap is reduced to 6.768 PJ/year. In Chapter 3.2, I_k^0 defines the threshold for the amount of imported electricity. In the model, this amount is set to be 5% for all scenarios. For 121 PJ/year of demand in the third period, the maximum amount of imported electricity is 6.05 PJ/year, which is less than the energy gap. As a result, there is still a shortage of 0.718 PJ/year even if the maximum amount of electricity is imported. Thus, current facilities have to expand their capacity to cover the energy gap. As the facility with lowest expansion cost, the NG facility is the primary option so that minimal costs can be achieved. Referring to Table 3-4, the expansion of 1.99 PJ/year (the second expansion of NG) could cover the energy gap.

Then, the next question would become one of why there are two expansions for the NG facility. In answer, as mentioned above, with the expansion of 1.99 PJ/year, the energy demand can be satisfied by maximizing the local supply capacity in addition to the electricity imports. Although the imported electricity is expensive, however, comparing the cost of facility expansion with the cost of electricity imports can answer the above question.

In Table 3-4, the first expansion of the NG facility is 0.13 GW, which can be converted to 4.1 PJ/year. Without this expansion, 4.78 PJ/year of electricity would have to be imported to cover the energy gap. The cost of expansion and electricity imports is 97.5 million dollars and 119.5 million dollars, respectively. Obviously, expanding the NG facility is more economical. Consequently, the model considers conditions across different periods and generates optimized solutions for energy supply.

Similarly, based on the analysis of the lower-demand scenario of Sub-model 1, the other scenarios can also be verified. Table 3-6 illustrates the percentage of imported electricity also meets the requirements for all the scenarios. From the above analysis, it can be conclude that the model can provide optimized solutions for energy planning with compromise among different constraints and help to generate optimized solutions based on the whole period of study.

The next stage of results analysis is to integrate all the sub-models to a dual-interval model. Among the solutions presented in Table 3-3, seven parameters are dual-interval numbers: X_{12}, X_{13}, X_{31}, X_{42}, X_{43}, X_{51}, and F_{opt}. Therefore, focus is placed on these dual-interval variables. By the DILP algorithm, each sub-model is assigned a specific possibility before the solution assembling process. Thus, all of the seven dual-interval variables have their specific possibility distributions.

Table 3-6

Percentage of imported electricity (%)

		Sub-models						
		1		2		3		
	Periods	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound	Requirement ≤
	1	0	0	0	0	0	4.91	
I	2	0	0	0	0	0	0	5
	3	0.57	0.62	4.23	3.93	4.23	3.91	

In this study, the possibility for each sub-model is assumed to be 33.3%. Based on this possibility distribution, Figure 3-3 to Figure 3-9 present possibility distributions for the dual-interval variables and illustrate the dual-interval solutions for the power production planning parameters and total system cost.

Figure 3-3 shows the dual-interval solution for the coal-powered facility in the second period. For energy demand varying from 100 PJ/year to 173.03 PJ/year, the coal-delivered electricity should guarantee an output of [47.3, 66.23] (PJ/year). For 66.6% of the scenarios, the amount of coal-delivered electricity should be between [47.3, 69.38] (PJ/year). For 33.3% of the scenarios, the interval should be extended to [47.3, 72.53] (PJ/year).

Such situations require decision makers to compromise between total cost and supply reliability with further information, such as, for example, profit goals, local policy, and regional economy. The option of [47.3, 66.23] (PJ/year) results in the least cost and the lowest reliability. On the other hand, the option of [47.3, 72.53] (PJ/year) is another alternative. The conservative option could guarantee electricity supply for all demands; however, it results in over investment for lower-demand scenarios such as [47.3, 66.23] (PJ/year) and [47.3, 69.38] (PJ/year).

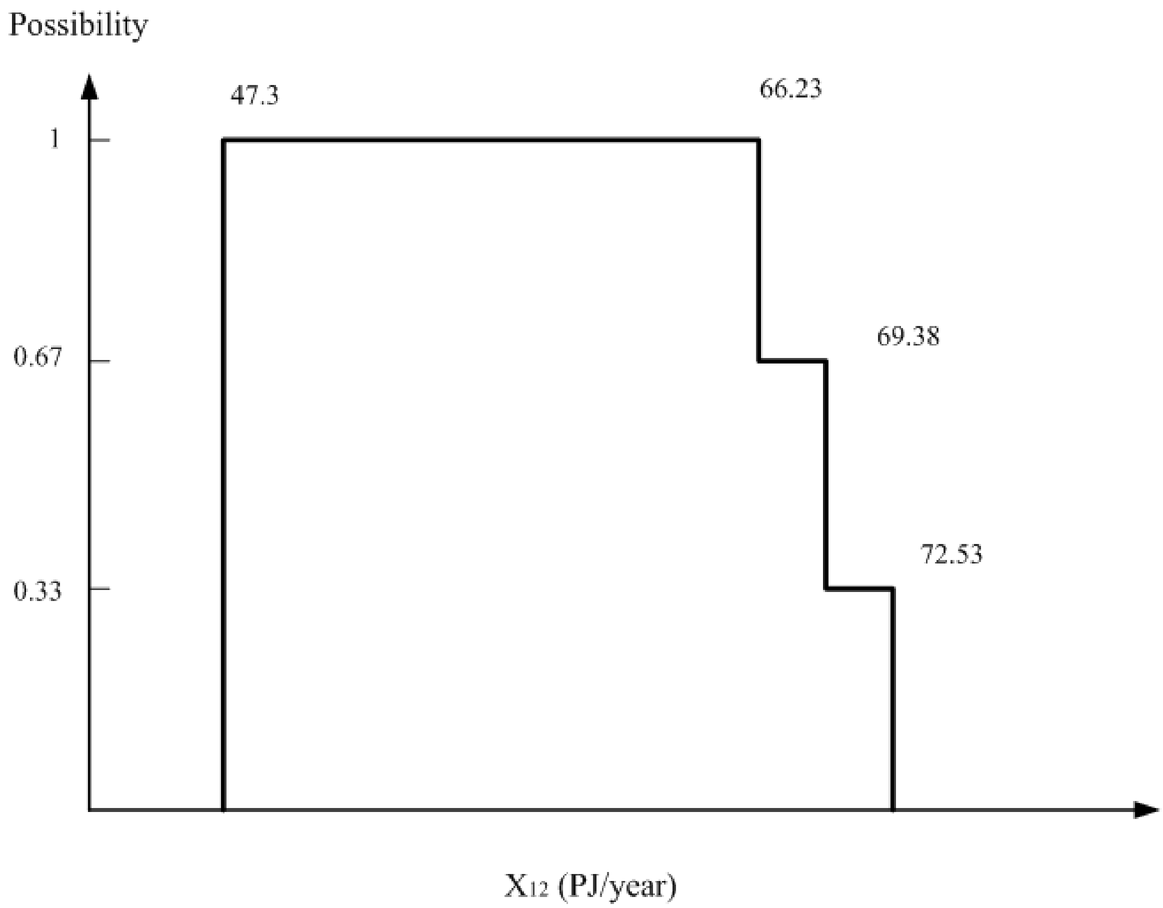

Figure 3-3 Possibility distribution of X_{12} (PJ/year)

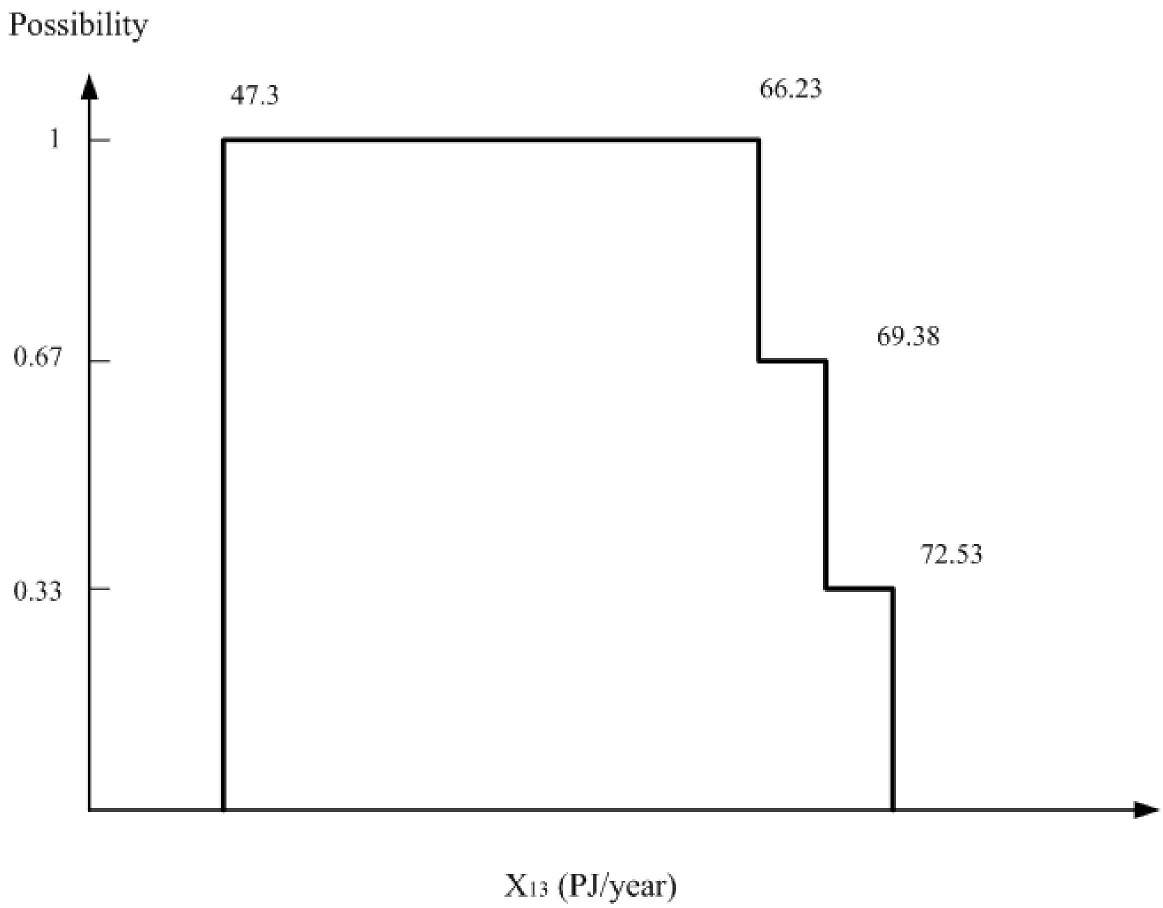

Figure 3-4 Possibility distribution of X_{13} (PJ/year)

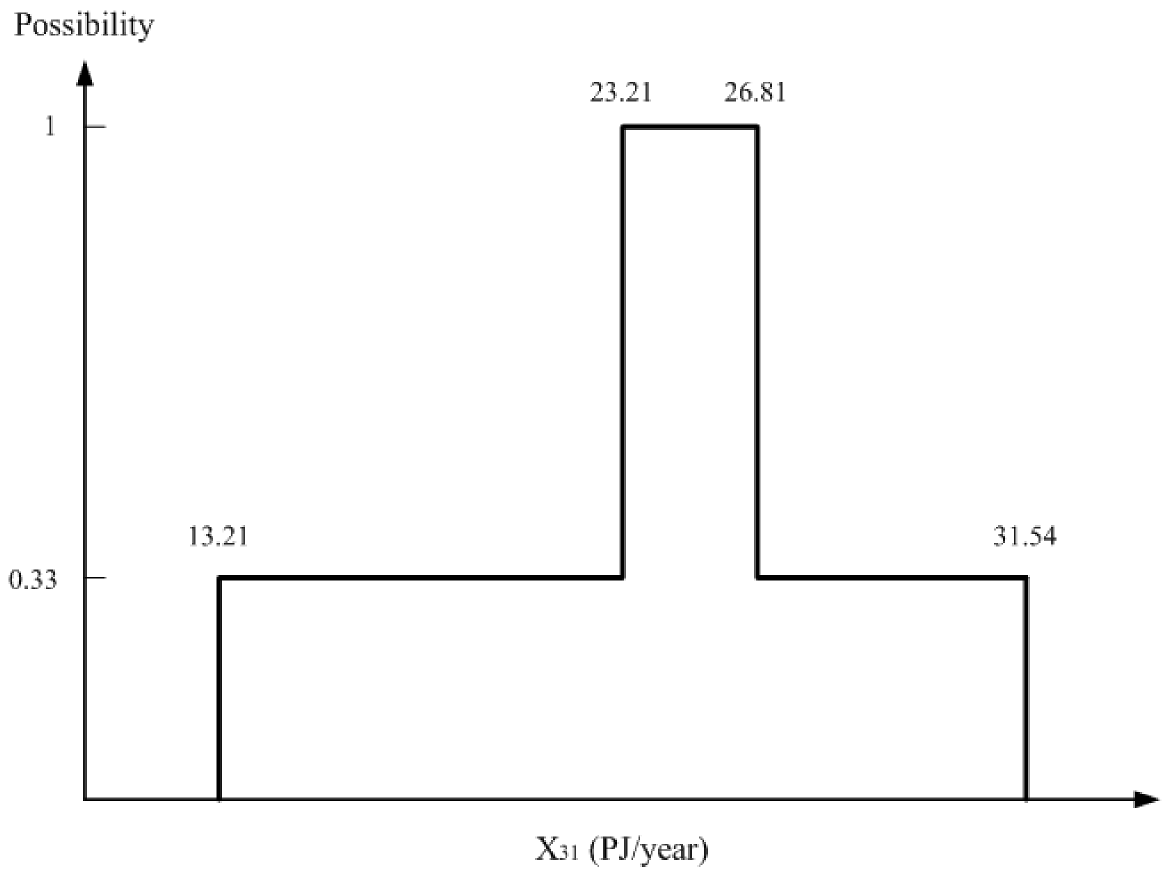

Figure 3-5 Possibility distribution of X_{31} (PJ/year)

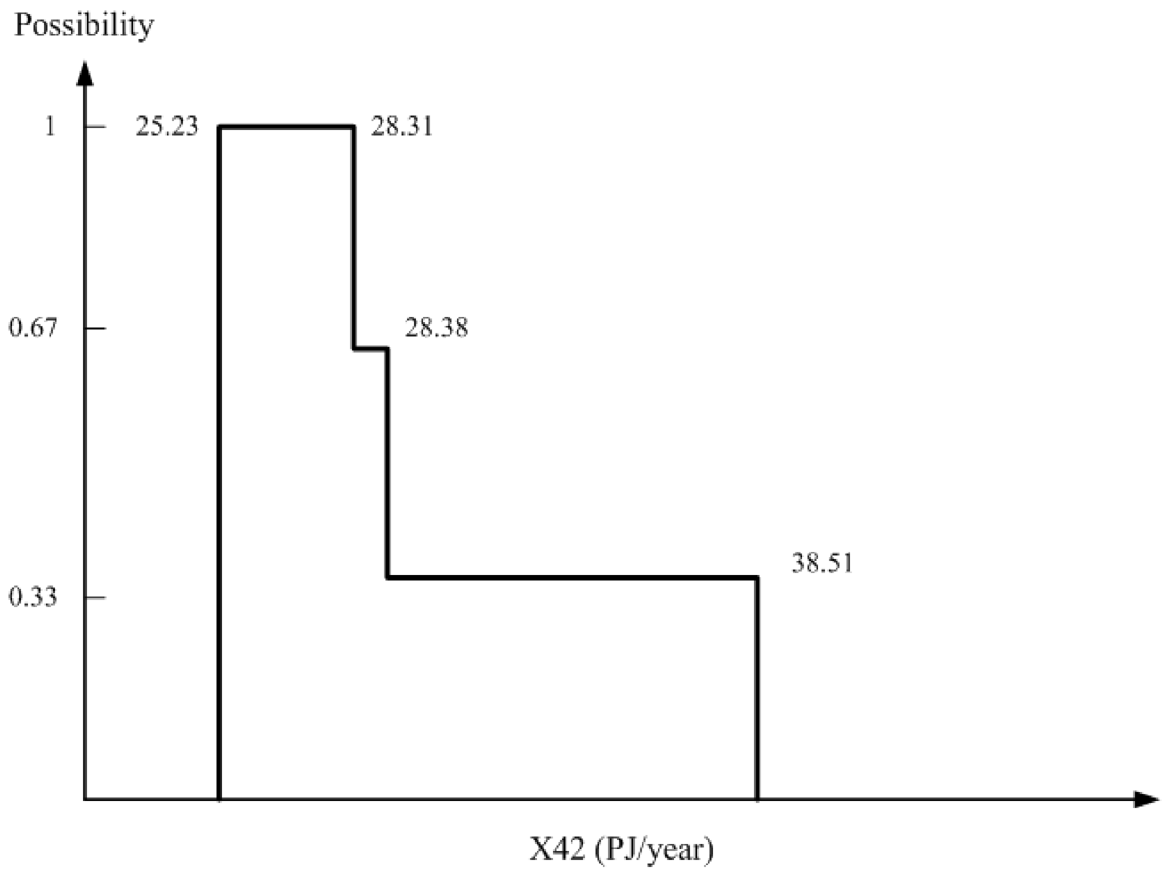

Figure 3-6 Possibility distribution of X_{42} (PJ/year)

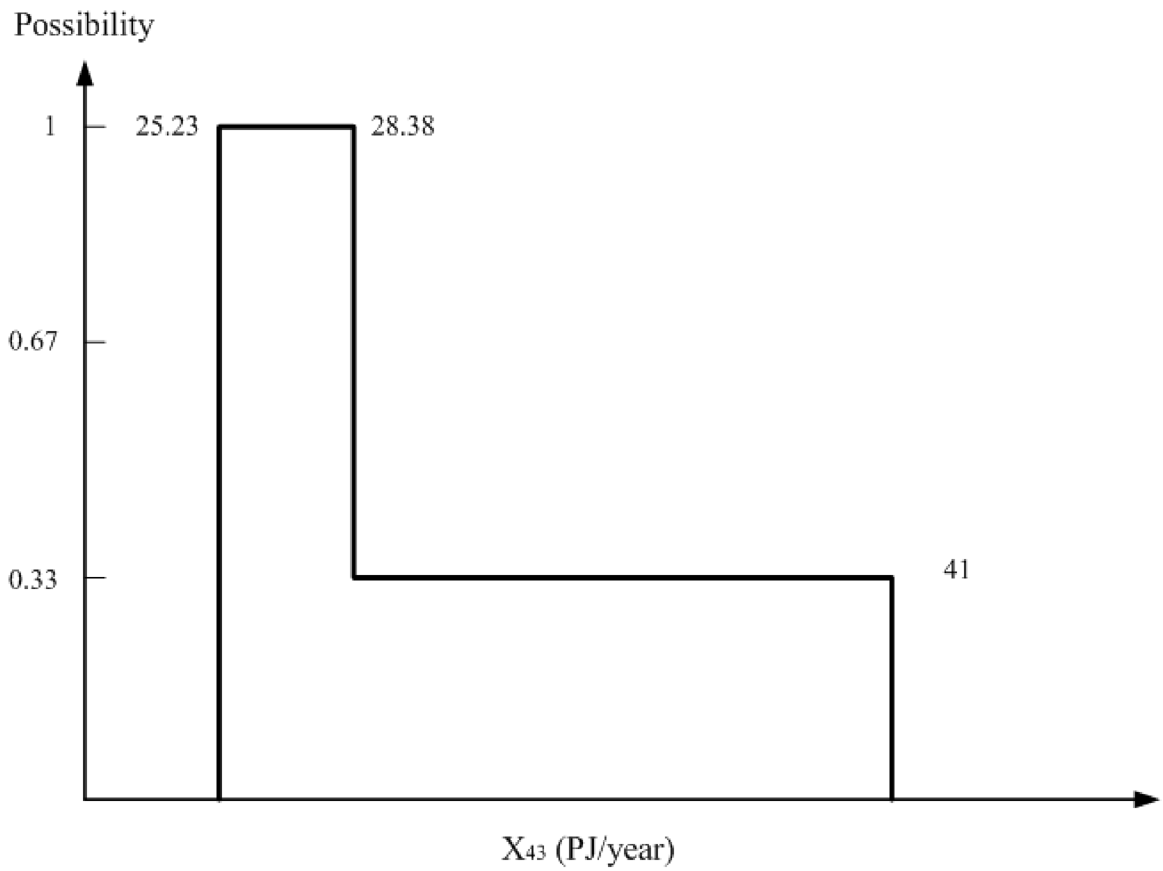

Figure 3-7 Possibility distribution of X_{43} (PJ/year)

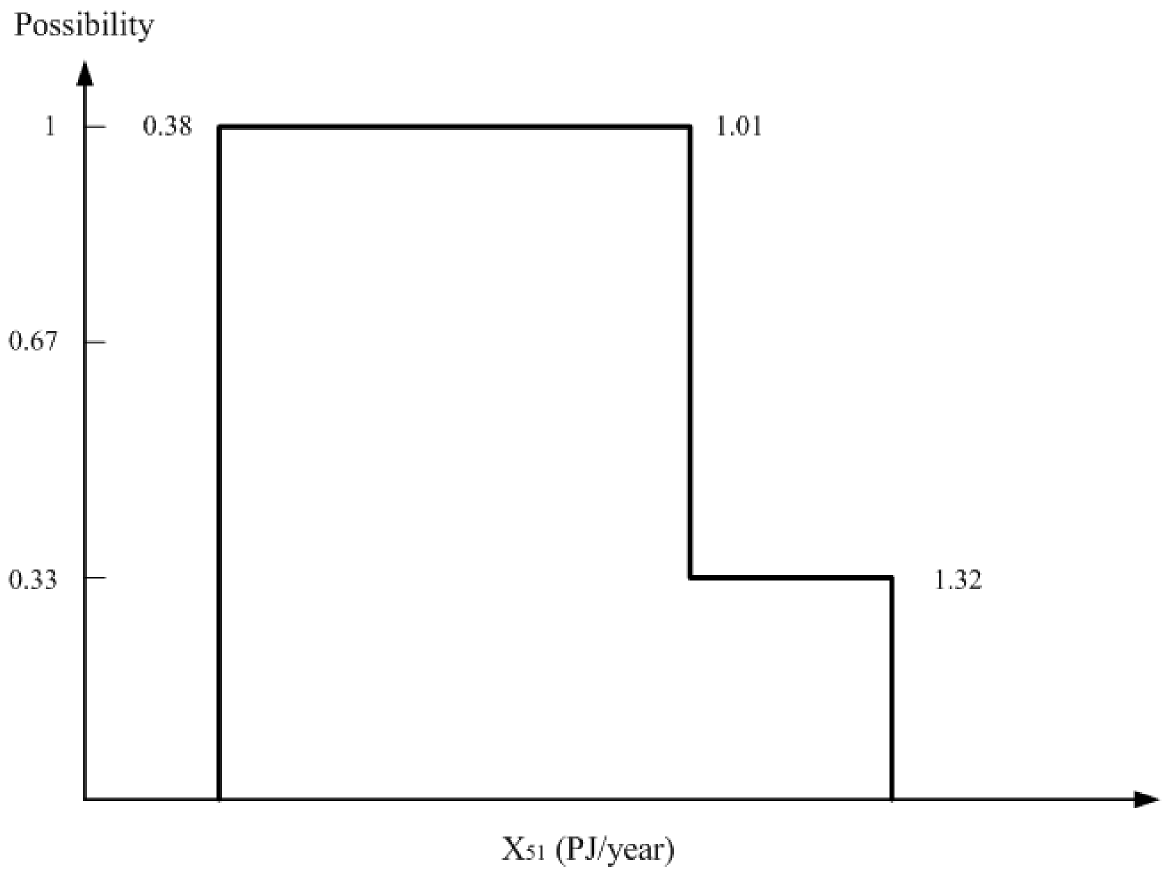

Figure 3-8 Possibility distribution of X_{51} (PJ/year)

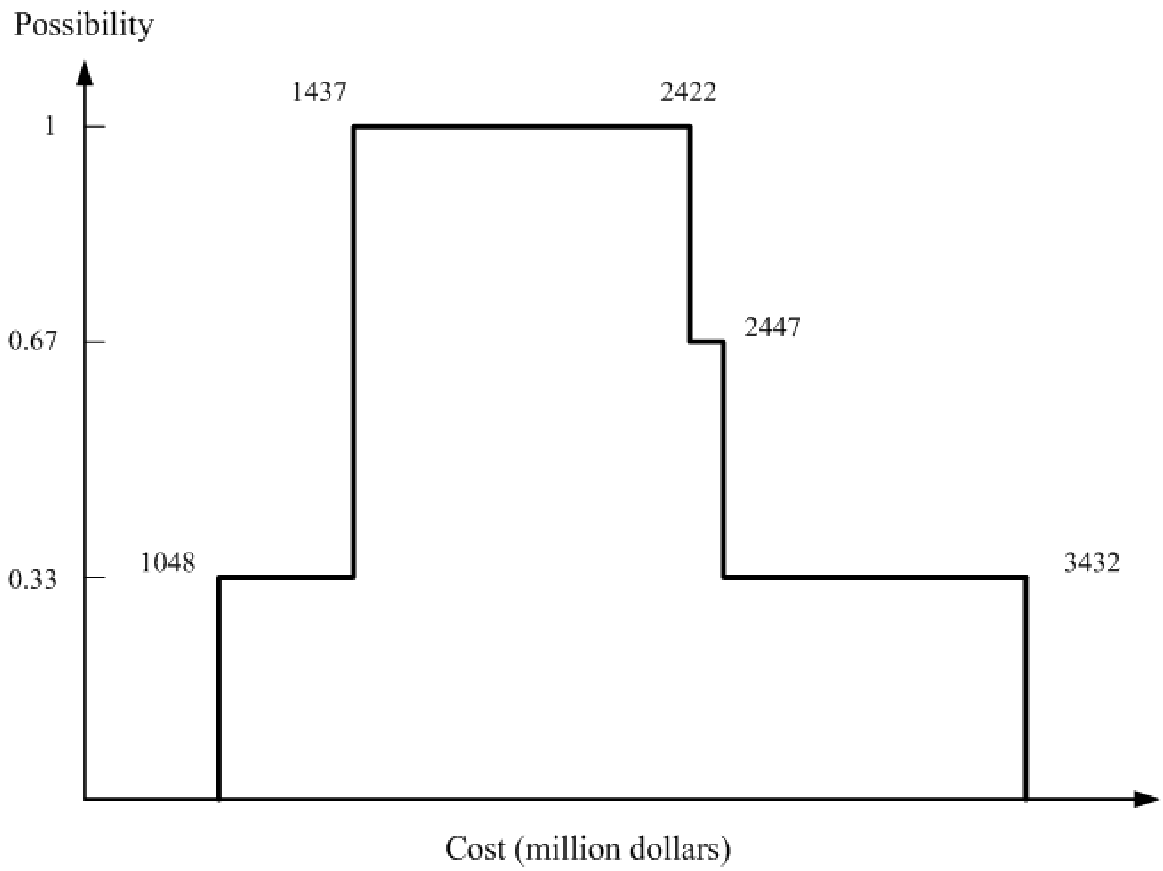

Figure 3-9 Possibility distribution of total cost (million dollars)

All of the dual-interval parameters shown in Figure 3-3 to Figure 3-8 are facing this type of compromise. It is complicated to obtain an overall optimal solution by picking up alternatives separately. Considering these six parameters to be a part of the energy model, then an evaluation of the total system cost is not only a short cut to achieving an optimal solution, but also is more meaningful.

Figure 3-9 shows the possibility distribution of the total system cost. The figure shows that the solution is [(1048.45, 1436.56), (2422.23, 3432.05)] (million dollars). For all demand-scenarios, the total cost will fall in [1437, 2422] (million dollars). Two thirds of scenarios result in system costs increasing to 2447 million dollars. Meanwhile, there is a 33% possibility that the total cost will be as low as 1048 million dollars and as high as 3432 million dollars.

The solution and the corresponding analysis are based on the premise that the possibility for each sub-model is 33.3% (one third). The possibility for each sub-model is adjustable when applying the model to different case studies (Table 3-2). In this study, the energy demand, types of facilities, and the weights for each sub-model are all hypothetical. In a real world case study, the regional energy demand can be determined by surveying and trend analysis of historical data and market expectation. In this way, a more reliable energy demand interval can be addressed. After data collection and preparation, the interval of energy demand will be interpreted into sub-models. Then, decision makers can assign each sub-model with a weighted value, which could reflect real-world cases. With decision makers bringing in real information and data, then, the dual-interval energy model could be established to optimize regional energy planning.

3.6 Summary

In this study, a dual-interval energy systems planning model (DIESPM) was developed. Through integrating dual-interval programming and mixed integer programming techniques with energy management systems, the model can deal with not only uncertainty expressed as a dual-interval format, but also the dynamics of facility expansion. The developed model was then applied to a hypothetical case study. The results suggested that DIESPM can provide solid decision alternatives for supporting power systems management toward a sustainable energy future.

In this study, DIESPM was applied into a hypothetical case study. Six different facilities and their potential expansions were considered. The model then generated an electricity generating plan for the study region under dual uncertainties. This study is the first openly published study in the energy field under dual-interval uncertainties. The results indicate that the dual-interval programming method is valuable in addressing corresponding issues during energy modeling.

In order to reflect the energy supply and demand system in the real world, further improvements to this model are necessary for the future studies: (a) the model in this paper does not consider energy/electricity export. Thus, profits from electricity export could be added to the model in the future; (b) while dealing with the expansion cost, the model does not consider the cost variation among different options. Although it does not affect the algorithm, it could be introduced if there were further requirements regarding this issue; (c) Different types of facilities do not usually coexist in the same region. Meanwhile, the capacity of certain facilities cannot increase as much as demand. The availability issue of energy resources should be reflected; (d) Restriction on greenhouse gas emissions is also another important issue in the energy planning field and could be carried out in future studies.

Chapter 4

Dual-Interval NG Pipeline Systems Planning Model (DIPSPM)

4.1 The "Se Ning Lan" NG pipeline systems

4.1.1 Project background

By the end of the 1990's in China, the level of development in the eastern (coastal) region was significantly higher than that in the western (inland) region. According to the survey data from the National Bureau of Statistics of China, the real GDP per capita in Shanghai, a coastal city, was ten times higher than it was in Gansu Province, which is located in the inland part of China. In 1999, the GDP per capita in Shanghai was 30805 Chinese Yuans (CNY). The GDP per capita in Gansu province was 3668 CNY (NBS, 2000). In order to improve living quality in western provinces, China initiated a long-term program known as the Strategy for the Development of the Western Region. The program includes projects such as infrastructure improvements, business development, and environment protection.

Both Qinghai Province and Gansu Province are located in western China. As a part of implementing the new development program, the local governments planned to promote the use of NG due to the increasing energy demand. As a result, in 2000, China

National Petroleum Corporation started a project known as “Se Ning Lan NG pipeline system” (SNLPS) to connect the “Se Bei” gas field and the two provinces.

Although the “Se Bei” gas field was originally discovered in 1964, the production of NG did not begin until 1995, after the “Se Bei-Golmud” pipeline system was finished. By the end of 2005, the proved NG reserve of the “Se Bei” gas field (including the No.1, No.2, and No.3 gas fields) had increased to 3.5 trillion cubic metres since 1964. Today, the “Se Bei” gas field has became one of the top four gas field in China.

4.1.2 Facts of the SNLPS

The SNLPS started at the “Se Bei No.1” gas field and its total length is over 900 kilometres. The first phase of the project was completed in 2001. The designed annual flow rate is 2 billion cubic metres. In 2005, the second phase of the project was started and it was completed two years later. During the second phase, the pipeline pressure was increased because of pump station improvements, and the annual pipeline flow rate was raised to 3 billion cubic metres. By the end of 2007, the total investment for the SNL NG pipeline system was 2.9 billion CNY.

In 2008, the SNLPS could hardly provide enough NG to satisfy the increasing gas demands caused by local economy booming. Therefore, CNPC started an expansion project on the SNL NG pipeline system with a total investment of 3.7 billion CNY. After the expansion, in 2010, the SNLPS is capable of delivering 6.4 billion cubic metres of NG per year to downstream customers.

4.1.3 Regional NG demand

The SNL NG pipeline system is one of the most important energy supply systems in western China. The pipeline is responsible for the supply of NG for Qinghai Province and Gansu Province. In Qinghai Province and Gansu Province, NG is mainly used in cooking, space heating, electricity generating, vehicle fuelling, and fertilizer production (DRCG, 2011).

Currently, there are 18 major customers from residential, commercial, and industrial sectors. Most of these customers are located in the City of Xi Ning and the City of Lan Zhou, which are the capital cities of Qinghai Province and Gansu Province. Figure 4-1 shows the locations of the 18 customers along the pipeline. In recent years, the NG demand of the two provinces has increased significantly (CPPEI, 2010). Table 4-1 shows the amount of NG delivered to the 18 major customers from 2008 to 2010. From Table 4-1, the total NG demand can be calculated. In 2010, the total NG demand is over two times greater than the demand in 2008.

According to China's Twelfth Five-year Plan and China's Thirteenth Five-year Plan, the development of NG will be continuously promoted in western China. According to "2010-2020 China's Regional Energy Demand Forecast (CREDF)", the NG demand for Qinghai Province and Gansu Province is projected to increase 50% to 98% by the end of 2020 (CAS, 2006). However, a different estimation is given by CNPC, which is the owner and operator of the SNLPS. In 2011, CNPC completed a report named "China's

NG Development Outlook (CNGDO)" (CNPC, 2011). In the report, the NG demand for the two provinces is estimated to increase by 6.8% to 8.5% per year.

Assuming that the annual increase in NG demand is even, the results from CREDF can be converted to a 4.1% - 7.1% increase per year. As a result, two intervals of NG demand increase are introduced. The two intervals can be expresses as [4.1%, 7.1%] and [6.8%, 8.5%], respectively.

4.1.4 Dual-interval uncertainties in NG demands

For easy presentation, in the model, the scenario regarding the research of CREDF is assigned as Scenario 1. The other research, which is from CNDGO, is assigned as Scenario 2. Cases 1 to 4 are assigned to represent different demand increase levels. In Table 4-2, the possibility of every case and scenario are shown. Since the collected information is in interval format, according to the algorithm described in section 3.5, the second DILP approach is applied. The two scenarios are treated as two sub-models that can be solved using an interval linear programming method. Then, the solutions of the two sub-models can be formulated in dual-interval format according to their assigned possibilities. The whole solution process is shown in Figure 3-2.

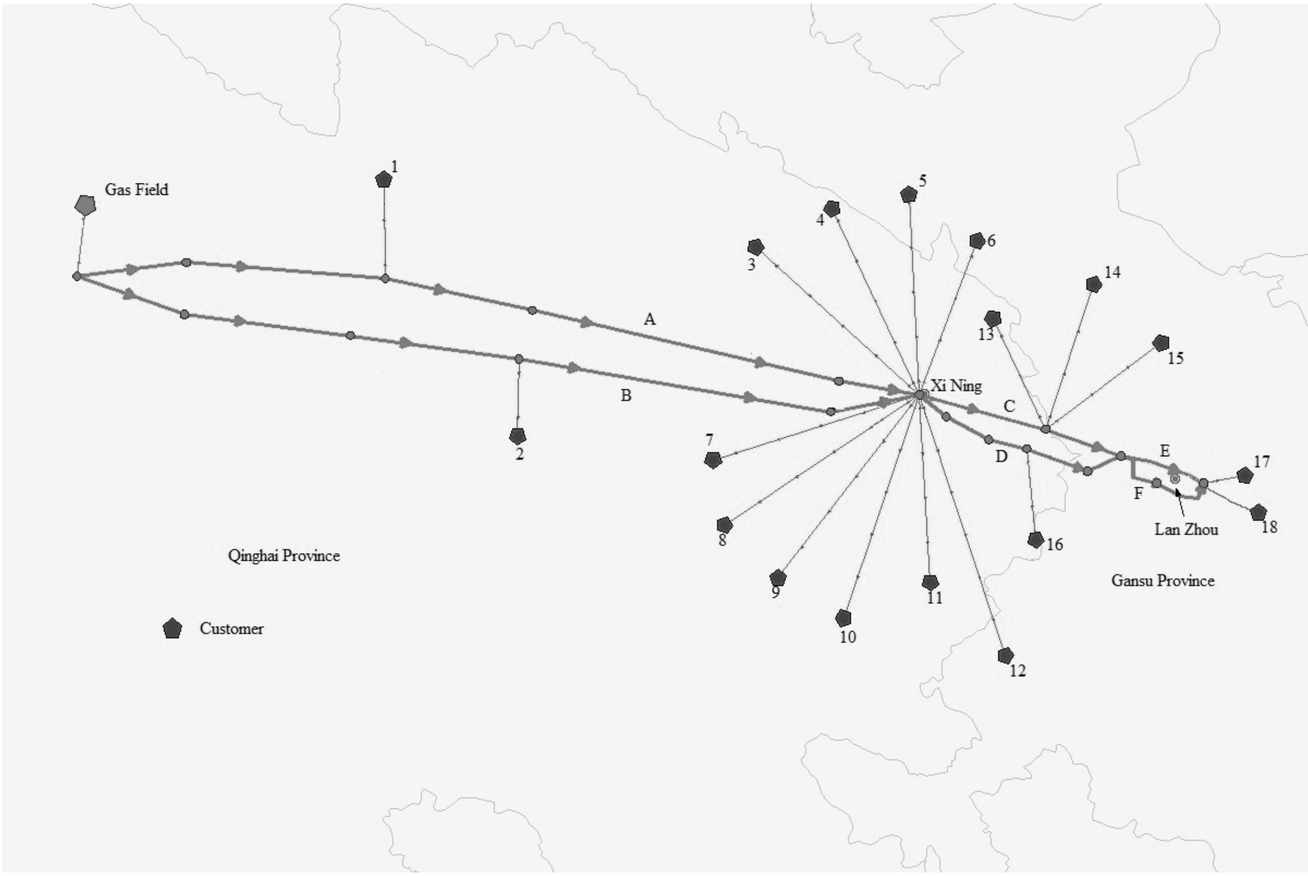

Figure 4-1 Major customers in the area

Table 4-1

NG demand of the major customers during 2008 to 2010 (10^5 m^3/year)

Customer	NG Demand		
	2008	2009	2010
1	1358	1358	1358
2	0	0	370
3	1800	3000	4000
4	57000	63100	65100
5	2200	2700	2800
6	0	3500	16000
7	0	0	300
8	0	0	4500
9	0	0	4000
10	0	18000	28000
11	0	0	3500
12	0	0	8000
13	439	600	1000
14	300	350	500
15	1550	1600	1800
16	0	0	2000
17	0	0	112800
18	105000	120000	130000
Total	169647	214208	386028

Table 4-2

Possibilities of different scenarios

	Scenario 1 (CREDF)		Scenario 2 (CNDGO)	
	Case 1	Case 2	Case 3	Case 4
Demand Increase	4.1%	7.1%	6.8%	8.5%
Possibility	33%	33%	67%	67%

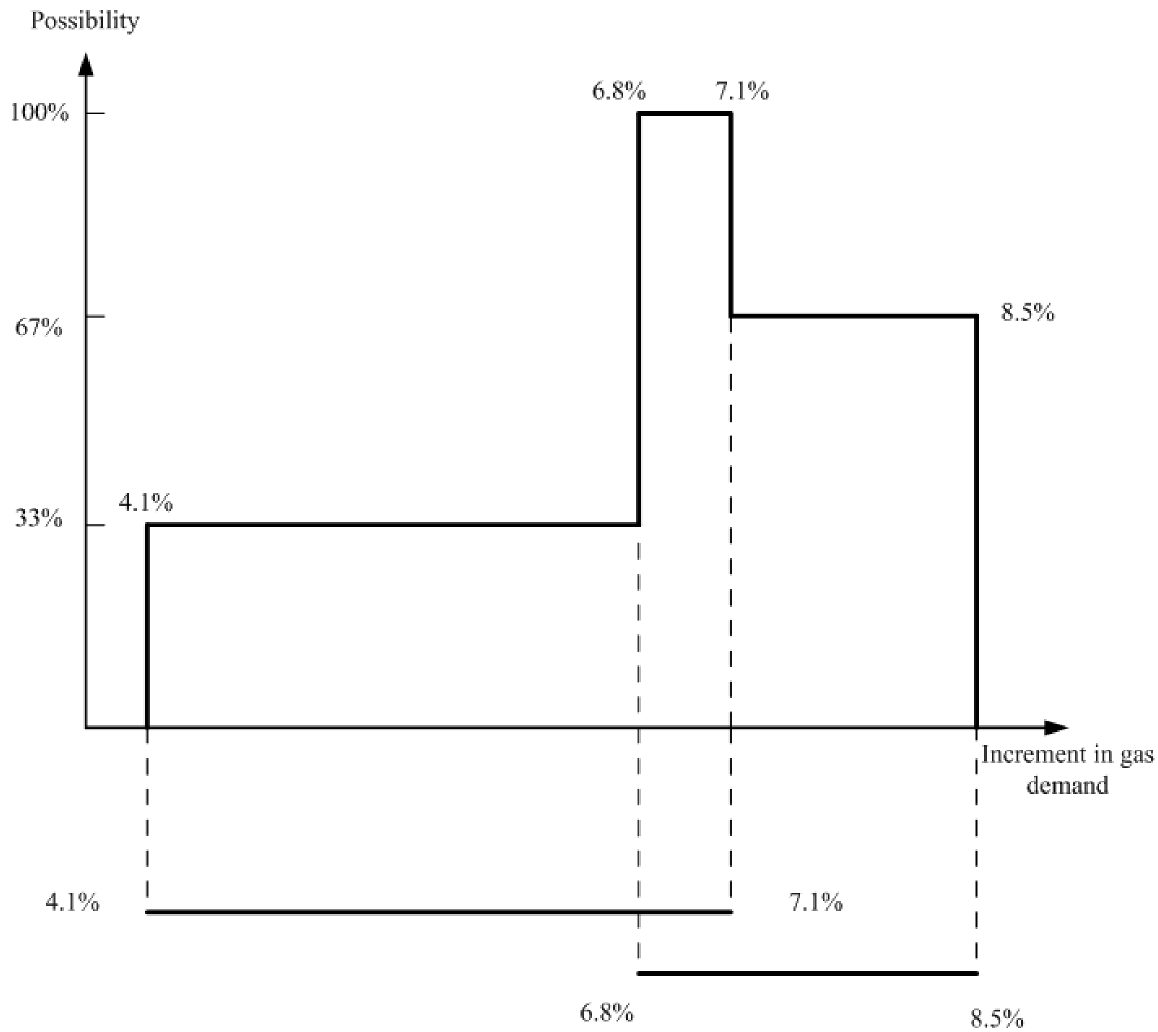

Figure 4-2 Possibility distribution of the demand in dual-interval format

As mentioned in the second DILP approach, the possibility for each interval is required to formulate the two sub-models in dual-interval format. Thus, suitable possibility should be assigned. The CNDGO was conducted by the CNPC Economics and Technology Research Institute (ETRI). This internal research can be used in directing NG production and designing strategies under different scenarios. In the model, the possibility of the CNDGO (Scenario 2) is assigned to be 67%.

The other research, the CREDF, was conducted by the Forecast and Research Centre of China's Academy of Science in 2006. The research mainly focuses on the macroscopic level, and it describes energy prospects for various regions of China. In the model, the possibility of the CREDF (Scenario 1) is assumed to be 33%. The possibility of the two scenarios can be further formulated to express the dual-interval parameter. The formulated possibility is shown in Figure 4-2.

So far, there is no study of optimization modeling for the SNLPS. In order to optimize pipeline management, in this thesis, a NG pipeline systems model is developed under dual-interval uncertainties. In the solution, the model will provide a NG transmission plan and an expansion strategy. The modeling horizon will be from 2011 to 2020 regarding China's Twelfth Five-year Plan and the China's Thirteenth Five-year Plan. Some assumptions are made in this research:

1. The annual increase of NG demand is even for the modeling horizon (2011-2020).
2. The possibility of CNGDO's scenario is assumed to be 67% while the possibility of the other scenario is assumed to be 33%.

3. In the model, currency inflation and price change are not involved. The operation cost and NG selling price remain constant for the modeling horizon.
4. The mass of NG is conservative. It is assumed that there are no leaking or other kinds of loss.

4.2 Model structure

The objective of this model is to maximize profit for the entire time horizon. In the model, the time horizon covers 2011 to 2020. The modeling period is designed to reflect China's Twelfth Five-year Plan and China's Thirteenth Five-year Plan.

In order to develop a model of the "Se Ning Lan" NG pipeline systems (SNLPS), the SNLPS is divided into four different components: (1) production; (2) transportation; (3) distribution; (4) expansion. In this chapter, detailed descriptions about the four segments will be provided.

The SNLPS includes two major pipelines. In order to develop the DIPSPM, the two pipelines are divided into six segments: Pipeline A to Pipeline F. The first major pipeline is composed of Pipeline A, C, and E. The second major pipeline is composed of Pipeline B, D, and F. Meanwhile, each pipeline segment contains several sections and nodes. The nodes represent compressors and pump stations. The sections are the parts of pipeline between different nodes. In Figure 4-3, a connection map of SNLPS is sketched.

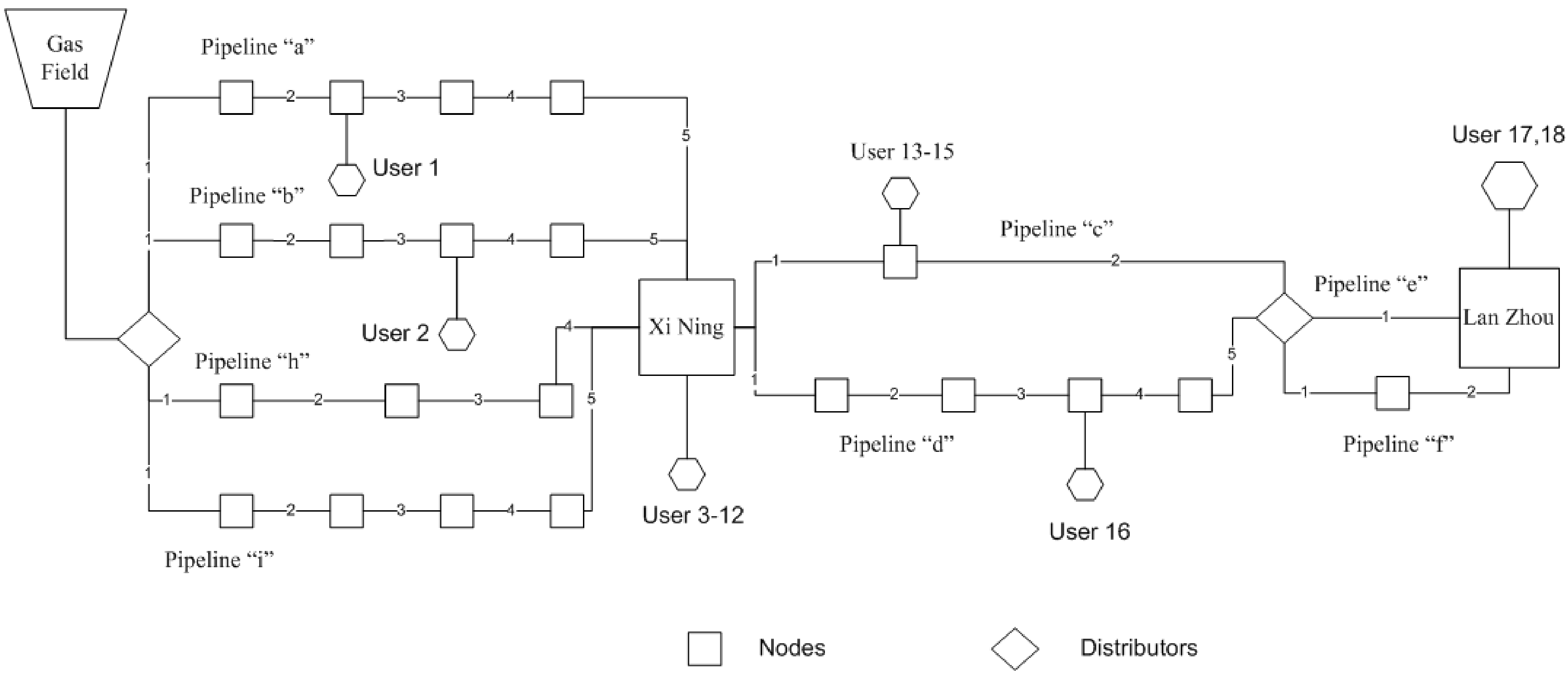

Figure 4-3 Connection map of SNLPS

In Figure 4-3, Pipeline H and I are the two expansion pipeline options to support the high gas demand in the future. In this model, a decision will be made as to whether expansion is necessary. Then, if expansion is required, the model will select one of the options to achieve higher profit.

4.2.1 NG production

At the "Se Bei" gas field, there are plenty of gas extraction wells. The recovered NG is collected through four gathering stations. Then, the gas will be distributed into the two major pipelines. In this model, the four gathering stations are included in the production sector. The four gathering stations receive NG from the "Se Bei" No.1 to No.4 gas fields. The gate prices of each gathering station are slightly different. The maximum gas production of each gas field is restricted by a parameter that describes the maximum annual production ability. In addition, the total production of the four gas fields is also restricted. The actual production through each gathering station is determined by the model.

4.2.2 NG transportation

In the model, an assumption about mass conservation is made: the amount of NG through each section is conserved. In NG pipeline systems, it is estimated that 3-5% of gas is consumed by the compressors (Woldeyohannes & Abd Majid, 2011). Therefore, in this model, the amount of gas flow into a pipe section should be equal to the sum of gas flow out and the amount of gas consumed.

The portion of gas consumed in each pipeline section can be calculated using a coefficient. In the model, the total gas consumed in the major pipeline is assumed to be 5%. In Table 4-5 (4.4 Data Collections), the coefficient of gas consumption for each section is listed. Finally, depending on the cost of transportation, the amount of gas flow through each section is optimized by the model.

4.2.3 Customer distribution

Eighteen major customers are located along the SNLPS. In Qinghai province and Gansu province, the customers include municipal, commercial, and industrial users. In reality, there are distributing pipelines that connect transportation pipeline systems and customers. The NG is first delivered to the distributor (gate) of the distributing pipelines and then sent to the users. In the SNLPS, most of the distribution pipelines are between 5-20 kilometres. As a result, the distributing cost is a small fraction compared to the transportation cost (the two major pipelines are over 1800 kilometres). Therefore, in this model, the distributing pipelines are not included.

4.2.4 Future expansion

In the model, two expansion options are provided. Currently, the maximum loads of pipelines between Xi Ning and Lan Zhou are less than 40%. Although the NG demand of Xi Ning and Lan Zhou will grow up to 226% simultaneously compared to the current demand (if they increase by 8.5% per year), the expansion of downstream pipelines is not necessary. Thus, both of the two options are to construct a pipeline from the “Se Bei” gas field to the City of Xi Ning.

The first option is to construct a pipeline with a maximum annual flow rate of 2 billion cubic metres. The other option comes with a higher flow rate of 3.5 billion cubic metres. In addition, the first option includes a future pressure boost. After the pressure boost, the flow rate of the first option can increase to 3 billion cubic metres per year. At the end of the model, an optimized expansion plan can be determined in order to maximize profit.

4.3 Modeling formulation

The goal of the dual-interval NG pipeline systems management model is to maximize profit for the entire study horizon. The objective function of the model incorporates four components: production cost, transportation cost, expansion cost, and profit. The parameters in the four components are represented as interval parameters that are denoted by “±”. The objective function is formulated in terms of the following equations:

$$\text{Max } f^{\pm} = \begin{array}{l} \sum_{u=1}^{18}\sum_{k=1}^{8} P_{uk}V_{uk}^{u\pm} - \sum_{w=1}^{4}\sum_{k=1}^{8} C_{wk}^{p}V_{wk}^{p\pm} - \sum_{a=1}^{5}\sum_{k=1}^{8} C_{ak}^{ta}V_{ak}^{ta\pm} \\ -\sum_{b=1}^{5}\sum_{k=1}^{8} C_{bk}^{tb}V_{bk}^{tb\pm} - \sum_{c=1}^{2}\sum_{k=1}^{8} C_{ck}^{tc}V_{ck}^{tc\pm} - \sum_{d=1}^{5}\sum_{k=1}^{8} C_{dk}^{td}V_{dk}^{td\pm} \\ -\sum_{e=1}^{1}\sum_{k=1}^{8} C_{ek}^{te}V_{ek}^{te\pm} - \sum_{f=1}^{2}\sum_{k=1}^{8} C_{fk}^{tf}V_{fk}^{tf\pm} - \sum_{h=1}^{4}\sum_{k=1}^{8} C_{hk}^{th}V_{hk}^{th\pm} \\ -\sum_{i=1}^{5}\sum_{k=1}^{8} C_{ik}^{ti}V_{ik}^{ti\pm} - \sum_{k=1}^{8} C_{k}^{eh}(\sum_{k=1}^{k} E_{k}^{h\pm}) - \sum_{k=1}^{8} C_{k}^{ei}(\sum_{k=1}^{k} E_{k}^{i\pm}) - \sum_{k=1}^{8} C_{k}^{ph}(\sum_{k=1}^{k} E_{k}^{ph\pm}) \end{array} \quad (4\text{-}1)$$

(Revenue – production cost – transportation cost for each section – expansion cost for each option)

Six categories of constraints are introduced to restrict the objective function: (1) production constraints, (2) mass balance constraints, (3) gas loss constraints, (4) flow rate constraints, (5) demand constraints, and (6) expansion constraints.

(1) Production constraints:

The production constraints restrict the maximum level of total NG production for each period (4-2a). In addition, the production levels for every gas field (gathering station) are also defined (4-2b). Another constraint is the minimum production level of each gas field (4-2c).

In the SNLPS, the production cost of every gas field decreases when the production amount is increasing. When the production level is very low, the production would be not economical due to the high production cost (Chen, 2006). Therefore, in 4-2c, a threshold of production is introduced, which is suggested by the Economics and

Development Research Institute of (EDRI) China National Petroleum Corporation (CNPC).

$$\sum_{w=1}^{4} V_{wk}^{p\pm} \le L_{k}^{total}, \forall k \tag{4-2a}$$

$$V_{wk}^{p\pm} \le L_{w,k}^{\max}, \forall w,k \tag{4-2b}$$

$$V_{wk}^{p\pm} \ge L_{w,k}^{\min}, \forall w,k \tag{4-2c}$$

(2) Mass balance constraints:

In this model, it is assumed that total amount of NG in the system is conserved. Therefore, the total gas production is equal to the sum of gas delivered and the gas consumed by compressors. In order to implement the assumption, various constraints are used to quantify the gas flow within the system.

- Mass balance at starting point

At the starting point, the total amount of production equals to the amount of NG distributed into Pipeline A, B, H (if constructed), and I (if constructed).

$$\sum_{w=1}^{4} V_{wk}^{p\pm} = V_{1,k}^{ta\pm} + V_{1,k}^{tb\pm} + V_{1,k}^{th\pm} + V_{1,k}^{ti\pm}, \forall k \tag{4-3a}$$

For the mass balance in pipelines, the flow rate of inflow to every pipeline section equals to the amount of NG flow out the pipeline section, the amount of NG delivered to customers, and the amount of NG consumed by the compressor in the section.

For the mass balance of the two cities, the total amount of NG from upstream pipelines is equal to the amount of NG distributed to customers and downstream pipelines.

- Mass balance in Pipeline A

$$V_{ak}^{ta\pm} = V_{a+1,k}^{ta\ \ \pm} + V_{ak}^{la\pm}, \forall k, a = 1, 3, 4 \tag{4-3b}$$

$$V_{2,k}^{ta\ \pm} = V_{3,k}^{ta\ \pm} + V_{2,k}^{la\ \pm} + V_{1,k}^{u\ \ \pm}, \forall k \tag{4-3c}$$

- Mass balance in Pipeline B

$$V_{bk}^{tb\pm} = V_{b+1,k}^{tb\ \ \pm} + V_{bk}^{lb\pm}, \forall k, b = 1, 2, 4 \tag{4-3d}$$

$$V_{3,k}^{tb\ \pm} = V_{4,k}^{tb\ \pm} + V_{3,k}^{lb\ \pm} + V_{2,k}^{u\ \ \pm}, \forall k \tag{4-3e}$$

- Mass balance in Pipeline H

$$V_{hk}^{th\pm} = V_{h+1,k}^{th\ \ \pm} + V_{hk}^{lh\pm}, \forall k, 1 \le h \le 3 \tag{4-3f}$$

- Mass balance in Pipeline I

$$V_{ik}^{ti\pm} = V_{i+1,k}^{ti\ \pm} + V_{ik}^{li\pm}, \forall k, 1 \le i \le 4 \tag{4-3g}$$

- Mass balance in the City of Xi Ning

$$V_{5,k}^{ta\pm} + V_{5,k}^{tb\pm} + V_{4,k}^{th\pm} + V_{5,k}^{ti\pm} - V_{5,k}^{la\pm} - V_{5,k}^{lb\pm} - V_{4,k}^{lh\pm} - V_{5,k}^{li\pm} = V_{1,k}^{tc\pm} + V_{1,k}^{td\pm} + \sum_{u=3}^{12} V_{uk}^{u\pm}, \forall k \tag{4-3h}$$

- Mass balance in Pipeline C

$$V_{1,k}^{tc\pm} = V_{2,k}^{tc\pm} + V_{1,k}^{lc\pm} + \sum_{u=13}^{15} V_{uk}^{u\pm}, \forall k \tag{4-3i}$$

- Mass balance in Pipeline D

$$V_{d,k}^{td\pm} = V_{d+1,k}^{td\ \pm} + V_{d,k}^{ld\pm}, \forall k, d = 1, 2, 4 \tag{4-3j}$$

$$V_{3,k}^{td\pm} = V_{4,k}^{td\pm} + V_{3,k}^{ld\pm} + V_{16,k}^{u\ \pm}, \forall k \tag{4-3k}$$

- Mass balance at gathering station

$$V_{2,k}^{tc\pm} + V_{5,k}^{td\pm} - V_{2,k}^{lc\pm} - V_{5,k}^{ld\pm} = V_{1,k}^{te\pm} + V_{1,k}^{tf\pm}, \forall k \tag{4-3l}$$

- Mass balance in Pipeline F

$$V_{1,k}^{tf\pm} = V_{2,k}^{tf\pm} + V_{1,k}^{lf\pm}, \forall k \tag{4-3m}$$

- Mass balance in the City of Lan Zhou

$$V_{1,k}^{te\pm} + V_{2,k}^{tf\pm} - V_{1,k}^{le\pm} - V_{2,k}^{lf\pm} = \sum_{u=17}^{18} V_{uk}^{u\pm}, \forall k \quad \text{(4-3n)}$$

(3) Gas loss constraints (gas consumed by compressors):

As mentioned before, this group of constraints was designed to reflect the NG consumed by compressors. The amount of NG consumed can be calculated by multiplying the flow rate of a pipeline with a coefficient. The values of the coefficient are listed in Table 4-5.

$$V_{ak}^{la\pm} = L^a V_{ak}^{ta\pm}, \forall a, k \quad \text{(4-4a)}$$

$$V_{bk}^{lb\pm} = L^b V_{bk}^{tb\pm}, \forall b, k \quad \text{(4-4b)}$$

$$V_{ck}^{lc\pm} = L^c V_{ck}^{tc\pm}, \forall c, k \quad \text{(4-4c)}$$

$$V_{dk}^{ld\pm} = L^d V_{dk}^{td\pm}, \forall d, k \quad \text{(4-4d)}$$

$$V_{ek}^{le\pm} = L^e V_{ek}^{te\pm}, \forall e, k \quad \text{(4-4e)}$$

$$V_{fk}^{lf\pm} = L^f V_{fk}^{tf\pm}, \forall f, k \quad \text{(4-4f)}$$

$$V_{hk}^{lh\pm} = L^h V_{hk}^{th\pm}, \forall h, k \quad \text{(4-4g)}$$

$$V_{ik}^{li\pm} = L^i V_{ik}^{ti\pm}, \forall i, k \quad \text{(4-4h)}$$

(4) Flow rate constraints:

The flow rate constraints are used to restrict the maximum and minimum flow rate of every pipeline. The maximum flow rate constraints define the maximum load of every pipeline. They are constant numbers after the pipeline is constructed. The minimum flow rate constraints represent the lowest economical operating flow rate. The transportation cost is not economical if the flow rate is below the specific value (Chen, 2006). The coefficients used to calculate the minimum flow rate are suggested by the CNPC Economics and Technology Research Institute.

In 4-5g, 4-5h, 4-5o, and 4-5p, the flow rates of the expansion pipelines are defined. Further descriptions will be provided after the expansion constraints are presented.

- Maximum flow rate constraints

$$V_{ak}^{ta\pm} \leq 300000, \forall a, k \tag{4-5a}$$

$$V_{bk}^{tb\pm} \leq 340000, \forall b, k \tag{4-5b}$$

$$V_{ck}^{tc\pm} \leq 300000, \forall c, k \tag{4-5c}$$

$$V_{dk}^{td\pm} \leq 340000, \forall d, k \tag{4-5d}$$

$$V_{ek}^{te\pm} \leq 300000, \forall e, k \tag{4-5e}$$

$$V_{fk}^{tf\pm} \leq 340000, \forall f, k \tag{4-5f}$$

$$V_{hk}^{th\pm} \le 200000 \times \sum_{k=1}^{k} E_k^{h\pm} + 100000 \times \sum_{k=1}^{k} P_k^{h\pm}, \forall h, k \tag{4-5g}$$

$$V_{ik}^{ti\pm} \le 350000 \times \sum_{k=1}^{k} E_k^{i\pm}, \forall i, k \tag{4-5h}$$

- Minimum flow rate constraints

$$V_{ak}^{ta\pm} \ge 300000 \times C^a, \forall a, k \tag{4-5i}$$

$$V_{bk}^{tb\pm} \ge 340000 \times C^b, \forall b, k \tag{4-5j}$$

$$V_{ck}^{tc\pm} \ge 300000 \times C^c, \forall c, k \tag{4-5k}$$

$$V_{dk}^{td\pm} \ge 340000 \times C^d, \forall d, k \tag{4-5l}$$

$$V_{ek}^{te\pm} \ge 300000 \times C^e, \forall e, k \tag{4-5m}$$

$$V_{fk}^{tf\pm} \ge 340000 \times C^f, \forall f, k \tag{4-5n}$$

$$V_{hk}^{th\pm} \ge (200000 \times \sum_{k=1}^{k} E_k^{h\pm} + 100000 \times \sum_{k=1}^{k} P_k^{h\pm}) \times C^h, \forall h, k \tag{4-5o}$$

$$V_{ik}^{ti\pm} \ge 350000 \times \sum_{k=1}^{k} E_k^{i\pm} \times C^i, \forall i \tag{4-5p}$$

(5) Expansion constraints

The expansion constraints are designated to plan expansion events. From 4-6a to 4-6c, three binary decision variables are defined. They are used to determine the expansion option from Pipeline H and Pipeline I and the pressure boost of Pipeline H. In 4-6d, only one pipeline will be constructed (either Pipeline H or Pipeline I). 4-6e ensures that the pressure boost is less than once. In addition, the pressure boost cannot happen in the first year because it can only occur after Pipeline H is constructed. Therefore, 4-6f and 4-6g were developed to reflect this fact.

Besides these constraints, the sums of the three binary decision (4-6a, 4-6b, and 4-6c) variables are also calculated separately. They can be used to determine if expansion events have occurred. Again with respect to the flow rate constraints 4-5g, 4-5h, 4-5o, and 4-5p, the sums of the three binary decision variables are included in calculating the maximum and minimum flow rate of the expansion pipelines. If the expansion of the pipeline is selected by the model, then the flow rate of the pipeline will be registered. If there is no expansion of the pipeline, then the flow rate of the pipeline will remain at zero.

$$E_k^{h\pm} = 0,1, \forall k \tag{4-6a}$$

$$E_k^{i\pm} = 0,1, \forall k \tag{4-6b}$$

$$P_k^{h} = 0,1, \forall k \tag{4-6c}$$

$$\sum_{k=1}^{8} E_k^{h\pm} + \sum_{k=1}^{8} E_k^{i\pm} \le 1 \tag{4-6d}$$

$$\sum_{k=1}^{8} P_k^{h\pm} \leq 1 \tag{4-6e}$$

$$P_1^{h\pm} = 0 \tag{4-6f}$$

$$P_k^{h\pm} \leq \sum_{k=1}^{k-1} E_k^{h\pm}, 2 \leq k \leq 8 \tag{4-6g}$$

(6) Demand constraint

This constraint restricts the amount of NG delivered to customers so that it must be greater than the demand of the customers.

$$V_{u,k}^{u\ \pm} \geq D_{u,k}^{u\ \pm}, \forall u, k \tag{4-7a}$$

a = sections of Pipeline A, where $1 \leq a \leq 5$;

b = sections of Pipeline B, where $1 \leq b \leq 5$;

c = sections of Pipeline C, where $1 \leq c \leq 2$;

d = sections of Pipeline D, where $1 \leq d \leq 5$;

e = sections of Pipeline E, where $e = 1$;

f = sections of Pipeline F, where $1 \leq f \leq 2$;

h = sections of expansion Pipeline H, where $1 \leq h \leq 4$;

i = sections of expansion Pipeline I, where $1 \leq I \leq 5$;

k = time period, where $1 \le k \le 8$;

u = customers, where $1 \le u \le 18$;

w = NG field, where $1 \le w \le 4$;

L_k^{total} = the total production level in period “k” (10^5 m^3);

$L_{w,k}^{\max}$ = the maximum production level for gas field “w” in period “k” (10^5 m^3);

$L_{w,k}^{\min}$ = the minimum production level for gas field “w” in period “k” (10^5 m^3);

P_{uk} = gas selling price for user “u” in period “k” (CNY/m^3);

$V_{uk}^{u\pm}$ = gas supplied to user “u” in period “k” (10^5 m^3);

C_{wk}^{p} = cost of production for gas field “w” in period “k” (CNY/m^3);

$V_{wk}^{p\pm}$ = volume of production for gas field “w” in period “k” (10^5 m^3);

C_{ak}^{ta} = cost of gas transportation through Pipeline A in period “k” (CNY/m^3);

C_{bk}^{tb} = cost of gas transportation through Pipeline B in period “k” (CNY/m^3);

C_{ck}^{tc} = cost of gas transportation through Pipeline C in period “k” (CNY/m^3);

C_{dk}^{td} = cost of gas transportation through Pipeline D in period “k” (CNY/m^3);

C_{ek}^{te} = cost of gas transportation through Pipeline E in period “k” (CNY/m^3);

C_{fk}^{tf} = cost of gas transportation through Pipeline F in period “k” (CNY/m^3);

C_{hk}^{th} = cost of gas transportation through Pipeline H in period “k” (CNY/m^3);

C_{ik}^{ti} = cost of gas transportation through Pipeline I in period “k” (CNY/m^3);

$V_{ak}^{ta\pm}$ = volume of gas transmitted through Pipeline A in period “k” (10^5 m^3);

$V_{bk}^{tb\pm}$ = volume of gas transmitted through Pipeline B in period “k” (10^5 m^3);

$V_{ck}^{tc\pm}$ = volume of gas transmitted through Pipeline C in period “k” (10^5 m^3);

$V_{dk}^{td\pm}$ = volume of gas transmitted through Pipeline D in period “k” (10^5 m^3);

$V_{ek}^{te\pm}$ = volume of gas transmitted through Pipeline E in period “k” (10^5 m^3);

$V_{fk}^{tf\pm}$ = volume of gas transmitted through Pipeline F in period “k” (10^5 m^3);

$V_{hk}^{th\pm}$ = volume of gas transmitted through Pipeline H in period “k” (10^5 m^3);

$V_{ik}^{ti\pm}$ = volume of gas transmitted through Pipeline I in period “k” (10^5 m^3);

C_{k}^{eh} = cost of expansion for Pipeline H in period “k” (10^5 CNY/year);

C_{k}^{ei} = cost of expansion for Pipeline I in period “k” (10^5 CNY/year);

C_{k}^{ph} = cost of pressure increasing for Pipeline H in period “k” (10^5 CNY);

$E_k^{h\pm}$ = binary-interval decision variables for the expansion of Pipeline H;

$E_k^{i\pm}$ = binary-interval decision variables for the expansion of Pipeline I;

$E_k^{ph\pm}$ = binary-interval decision variables for the pressure increasing of Pipeline H;

$V_{ak}^{la\pm}$ = volume of gas consumed by compressors along Pipeline A in period “k” (10^5 m^3);

$V_{bk}^{lb\pm}$ = volume of gas consumed by compressors along Pipeline B in period “k” (10^5 m^3);

$V_{ck}^{lc\pm}$ = volume of gas consumed by compressors along Pipeline C in period “k” (10^5 m^3);

$V_{dk}^{ld\pm}$ = volume of gas consumed by compressors along Pipeline D in period “k” (10^5 m^3);

$V_{ek}^{le\pm}$ = volume of gas consumed by compressors along Pipeline E in period “k” (10^5 m^3);

$V_{fk}^{lf\pm}$ = volume of gas consumed by compressors along Pipeline F in period “k” (10^5 m^3);

$V_{hk}^{lh\pm}$ = volume of gas consumed by compressors along Pipeline H in period “k” (10^5 m^3);

$V_{ik}^{li\pm}$ = volume of gas consumed by compressors along Pipeline I in period “k” (10^5 m^3);

In the model, the NG demands of the 18 customers are under dual-interval uncertainties. As mentioned in Chapter 4.1, the NG demand for the modeling horizon will increase by [(4.1%, 6.8%), (7.1%, 8.5%)] per year. Then, from the gas demand data of 2010, the gas demand for the modeling period can be calculated.

4.4 Data collection

As listed in Chapter 5.1, there are four components in the model, which are production, transportation, customers, and expansion. The parameters of the four components are important to solving the model. In this thesis research, the data were collected by conducting literature reviews, surveys, and interviews with CNPC, ETRI, and China Petroleum and Petrochemical Engineering Institute (CPPEI). In the following section, the parameters of the four components are described.

The production sector contains three important parameters: (1) the total production ability, (2) the production ability of every gas field, and (3) the gas price of every gathering station that receives NG from one of the gas fields. There are four gas fields in the "Se Ning Lan" gas field, and they are denoted as gas fields No.1 to No.4. In the model, the total production ability is the maximum amount of NG production by the four gas fields. Due to investments from CNPC, the production ability of the SNL gas field is increasing gradually.

In the model, the production cost of the four gas fields is the cost of NG at the gathering station. Thus, it represents not only the production cost of extracting a unit volume of NG, but also the transportation cost from the well heads to the gathering station. In Table 4-3, the production capacity and the production cost of the four gas fields are listed. The transportation cost includes pipeline operation cost, maintenance cost, labour cost, and cost of NG which is consumed by the compressors. In Table 4-4, the transportation cost of every section in the SNLPS is shown. In Table 4-5, the coefficient of gas consumption is listed. There is only one parameter in the distribution sector: the gas selling price. Table 4-6 shows the gas selling price for the 18 major customers.

In the model, there are two expansion options. The 1st option is to construct an auxiliary pipeline that has a maximum capacity of 2 billion cubic metres per year. The 2nd option is to construct a major pipeline that could carry 4 billion cubic metres of gas per year. In the low-demand scenarios, only the 2nd option is available, while both of the options are available in high-demand scenarios. In addition, the 1st option is open to a potential pressure boost. The pressure boost brings in a one-time upgrade charge. After the pipeline is upgraded, the total capacity will increase to 3 billion cubic metres per year.

Refer to the previous study (Tang, 2008), in the model, the cost of the two options is expressed as the annual repayment to commercial loans. Table 4-7 lists the expansion cost of the two options and the upgrade.

Table 4-3

Production cost and production ability

Gas Field	Gate Price (CNY/m^3)	Maximum Production Potential ($10^5/m^3$)	Year	Total Production Ability ($10^5/m^3$)
			2011	450000
			2012	500000
No.1	0.7	250000	2013	600000
			2014	700000
No.2	0.75	250000	2015	800000
			2016	900000
No.3	0.82	300000	2017	950000
			2018	1000000
No.4	0.8	300000	2019	1050000
			2020	1100000

Table 4-4

Transportation cost of pipelines (CNY/m^3)

Pipeline	Nodes					Total Transportation Cost (CNY/m^3)
	1	2	3	4	5	
A	0.0626	0.0435	0.03988	0.0783	0.03464	0.25892
B	0.06264	0.04466	0.04104	0.08048	0.03524	0.26406
C	0.04539	0.02306				0.06845
D	0.01784	0.00899	0.01784	0.02045	0.0029	0.06802
E	0.0087					0.0087
F	0.00487	0.0029				0.00777
H	0.0720	0.0507	0.0465	0.0913		0.2605
I	0.06262	0.04408	0.04046	0.07939	0.03444	0.26099

Table 4-5

Gas consumption coefficient of pipelines

Pipeline	Per Section (%)	Number of Sections	Pipeline Gas Loss (%)
A	0.4	5	2
B	0.4	5	2
C	1.0	2	2
D	0.4	5	2
E	1.0	1	1
F	0.5	2	1
H	0.5	4	2
I	0.4	5	2
Gas Loss of the first major pipeline (A, C, E)			5
Gas Loss of the second major pipeline (B, D, F)			5

Table 4-6

NG selling price (CNY/m^3)

Customer	Gas Selling Price	Customer	Gas Selling Price
1	1.167	10	1.232
2	1.197	11	1.212
3	1.228	12	1.321
4	1.220	13	1.258
5	1.228	14	1.258
6	1.319	15	1.258
7	1.258	16	1.258
8	1.228	17	1.357
9	1.321	18	1.256

Table 4-7

Expansion cost (10^5 CNY)

Expansion options	Cost
Pipeline H	12500/year for the flowing 10 years
Pipeline I	25000/year for the following 10 years
Pressure Boost	100000

4.5 Result analysis

In the model, the dual-interval variables are the NG demand of the 18 major customers. According to Ch.4.1.4, the annual increase of gas demand in dual-interval format is expressed as [(4.1%, 6.8%), (7.1%, 8.5%)]. Then, the dual-interval parameter can be transformed to [4.1%, 7.1%] (Scenario 1) and [6.8%, 8.5%] (Scenario 2) as two sub-models. In fact, the two sub-models are interval models for the two scenarios. Based on the gas demand in 2010, the NG demand can be calculated (Table 4-8 to Table 4-11). Then, the two sub-models can be solved using interval linear programming method. The model will attempt to obtain the most profitable solution while satisfying the customers' demand. In this section, analysis of the optimized solution is presented.

The solution includes:

1. The amount of NG recovered from each gas field.
2. The amount of NG flow through each pipeline section.
3. The amount of NG consumed at each pipeline section.
4. The expansion options.

In the model, the mass of NG is assumed to be conservative in the pipelines. Therefore, once the NG flow rate at the starting point is determined, the amount of NG flow through every section can be calculated. Thus, the gas flow rates at the first section in Pipeline A to Pipeline I are the most important decision variables in the model. In this section, the solutions of the two sub-models and the dual-interval solutions will be discussed.

Table 4-8

NG demand of Sub-model 1 (Cases 1 and 2) from 2011 to 2015 (10^5 m^3/year)

Customer	2011		2012		2013		2014		2015	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
1	1413.678	1454.418	1471.639	1557.682	1531.976	1668.277	1594.787	1786.725	1660.173	1913.582
2	385.17	396.27	400.962	424.4052	417.4014	454.5379	434.5149	486.8101	452.33	521.3736
3	4164	4284	4334.724	4588.164	4512.448	4913.924	4697.458	5262.812	4890.054	5636.472
4	67769.1	69722.1	70547.63	74672.37	73440.09	79974.11	76451.13	85652.27	79585.63	91733.58
5	2914.8	2998.8	3034.307	3211.715	3158.713	3439.747	3288.221	3683.969	3423.038	3945.53
6	16656	17136	17338.9	18352.66	18049.79	19655.69	18789.83	21051.25	19560.22	22545.89
7	312.3	321.3	325.1043	344.1123	338.4336	368.5443	352.3094	394.7109	366.754	422.7354
8	4684.5	4819.5	4876.565	5161.685	5076.504	5528.164	5284.64	5920.664	5501.311	6341.031
9	4164	4284	4334.724	4588.164	4512.448	4913.924	4697.458	5262.812	4890.054	5636.472
10	29148	29988	30343.07	32117.15	31587.13	34397.47	32882.21	36839.69	34230.38	39455.3
11	3643.5	3748.5	3792.884	4014.644	3948.392	4299.683	4110.276	4604.961	4278.797	4931.913
12	8328	8568	8669.448	9176.328	9024.895	9827.847	9394.916	10525.62	9780.108	11272.94
13	1041	1071	1083.681	1147.041	1128.112	1228.481	1174.365	1315.703	1222.513	1409.118
14	520.5	535.5	541.8405	573.5205	564.056	614.2405	587.1823	657.8515	611.2567	704.559
15	1873.8	1927.8	1950.626	2064.674	2030.601	2211.266	2113.856	2368.266	2200.524	2536.412
16	2082	2142	2167.362	2294.082	2256.224	2456.962	2348.729	2631.406	2445.027	2818.236
17	117424.8	120808.8	122239.2	129386.2	127251	138572.6	132468.3	148411.3	137899.5	158948.5
18	135330	139230	140878.5	149115.3	146654.5	159702.5	152667.4	171041.4	158926.7	183185.3
Total	401855.1	413436	418331.2	442789.9	435482.8	474228	453337.6	507898.2	471924.4	543959

Table 4-9

NG demand of Sub-model 1 (Cases 1 and 2) from 2016 to 2020 (10^5 m^3/year)

Customer	2016		2017		2018		2019		2020	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
1	1728.24	2049.447	1799.098	2194.957	1872.861	2350.799	1949.649	2517.706	2029.584	2696.463
2	470.8755	558.3912	490.1814	598.037	510.2788	640.4976	531.2003	685.9729	552.9795	734.677
3	5090.546	6036.661	5299.258	6465.264	5516.528	6924.298	5742.706	7415.923	5978.157	7942.454
4	82848.64	98246.66	86245.43	105222.2	89781.49	112693	93462.53	120694.2	97294.5	129263.4
5	3563.382	4225.663	3709.481	4525.685	3861.57	4847.009	4019.894	5191.146	4184.71	5559.718
6	20362.18	24146.65	21197.03	25861.06	22066.11	27697.19	22970.82	29663.69	23912.63	31769.82
7	381.791	452.7496	397.4444	484.8948	413.7396	519.3224	430.7029	556.1942	448.3617	595.684
8	5726.864	6791.244	5961.666	7273.422	6206.094	7789.835	6460.544	8342.914	6725.426	8935.261
9	5090.546	6036.661	5299.258	6465.264	5516.528	6924.298	5742.706	7415.923	5978.157	7942.454
10	35633.82	42256.63	37094.81	45256.85	38615.7	48470.09	40198.94	51911.46	41847.1	55597.18
11	4454.228	5282.079	4636.851	5657.106	4826.962	6058.761	5024.867	6488.933	5230.887	6949.647
12	10181.09	12073.32	10598.52	12930.53	11033.06	13848.6	11485.41	14831.85	11956.31	15884.91
13	1272.637	1509.165	1324.815	1616.316	1379.132	1731.075	1435.676	1853.981	1494.539	1985.613
14	636.3183	754.5827	662.4073	808.158	689.566	865.5373	717.8382	926.9904	747.2696	992.8067
15	2290.746	2716.498	2384.666	2909.369	2482.438	3115.934	2584.218	3337.165	2690.17	3574.104
16	2545.273	3018.331	2649.629	3232.632	2758.264	3462.149	2871.353	3707.962	2989.078	3971.227
17	143553.4	170233.9	149439.1	182320.5	155566.1	195265.2	161944.3	209129	168584	223977.2
18	165442.7	196191.5	172225.9	210121.1	179287.2	225039.7	186637.9	241017.5	194290.1	258129.7
Total	491273.3	582580.1	511415.5	623943.3	532383.6	668243.2	554211.3	715688.5	576934	766502.4

Table 4-10

NG demand of Sub-model 2 (Cases 3 and 4) from 2011 to 2015 (10^5 m^3/year)

Customer	2011		2012		2013		2014		2015	
	Case 3	Case 4	Case 3	Case 4	Case 3	Case 4	Case 3	Case 4	Case 3	Case 4
1	1450.344	1473.43	1548.967	1598.672	1654.297	1734.559	1766.789	1881.996	1886.931	2041.966
2	395.16	401.45	422.0309	435.5733	450.729	472.597	481.3786	512.7677	514.1123	556.353
3	4272	4340	4562.496	4708.9	4872.746	5109.157	5204.092	5543.435	5557.971	6014.627
4	69526.8	70633.5	74254.62	76637.35	79303.94	83151.52	84696.6	90219.4	90455.97	97888.05
5	2990.4	3038	3193.747	3296.23	3410.922	3576.41	3642.865	3880.404	3890.58	4210.239
6	17088	17360	18249.98	18835.6	19490.98	20436.63	20816.37	22173.74	22231.88	24058.51
7	320.4	325.5	342.1872	353.1675	365.4559	383.1867	390.3069	415.7576	416.8478	451.097
8	4806	4882.5	5132.808	5297.513	5481.839	5747.801	5854.604	6236.364	6252.717	6766.455
9	4272	4340	4562.496	4708.9	4872.746	5109.157	5204.092	5543.435	5557.971	6014.627
10	29904	30380	31937.47	32962.3	34109.22	35764.1	36428.65	38804.04	38905.8	42102.39
11	3738	3797.5	3992.184	4120.288	4263.653	4470.512	4553.581	4850.505	4863.224	5262.798
12	8544	8680	9124.992	9417.8	9745.491	10218.31	10408.18	11086.87	11115.94	12029.25
13	1068	1085	1140.624	1177.225	1218.186	1277.289	1301.023	1385.859	1389.493	1503.657
14	534	542.5	570.312	588.6125	609.0932	638.6446	650.5116	692.9294	694.7463	751.8283
15	1922.4	1953	2053.123	2119.005	2192.736	2299.12	2341.842	2494.546	2501.087	2706.582
16	2136	2170	2281.248	2354.45	2436.373	2554.578	2602.046	2771.717	2778.985	3007.313
17	120470.4	122388	128662.4	132791	137411.4	144078.2	146755.4	156324.9	156734.8	169612.5
18	138840	141050	148281.1	153039.3	158364.2	166047.6	169133	180161.6	180634	195475.4
Total	412277.9	418840.38	440312.8	454441.8	470254.1	493069.4	502231.3	534980.3	536383.1	580453.6

Table 4-11

NG demand of Sub-model 2 (Cases 3 and 4) from 2016 to 2020 (10^5 m^3/year)

Customer	2016		2017		2018		2019		2020	
	Case 3	Case 4	Case 3	Case 4	Case 3	Case 4	Case 3	Case 4	Case 3	Case 4
1	2015.242	2215.533	2152.279	2403.853	2298.634	2608.181	2454.941	2829.876	2621.877	3070.416
2	549.0719	603.643	586.4088	654.9526	626.2846	710.6236	668.872	771.0266	714.3553	836.5639
3	5935.913	6525.87	6339.555	7080.569	6770.645	7682.417	7231.048	8335.423	7722.76	9043.934
4	96606.98	106208.5	103176.3	115236.3	110192.2	125031.3	117685.3	135659	125687.9	147190
5	4155.139	4568.109	4437.688	4956.398	4739.451	5377.692	5061.734	5834.796	5405.932	6330.754
6	23743.65	26103.48	25358.22	28322.28	27082.58	30729.67	28924.19	33341.69	30891.04	36175.74
7	445.1935	489.4403	475.4666	531.0427	507.7983	576.1813	542.3286	625.1567	579.207	678.295
8	6677.902	7341.604	7131.999	7965.64	7616.975	8642.72	8134.929	9377.351	8688.105	10174.43
9	5935.913	6525.87	6339.555	7080.569	6770.645	7682.417	7231.048	8335.423	7722.76	9043.934
10	41551.39	45681.09	44376.88	49563.98	47394.51	53776.92	50617.34	58347.96	54059.32	63307.54
11	5193.924	5710.136	5547.11	6195.498	5924.314	6722.115	6327.167	7293.495	6757.415	7913.442
12	11871.83	13051.74	12679.11	14161.14	13541.29	15364.83	14462.1	16670.85	15445.52	18087.87
13	1483.978	1631.468	1584.889	1770.142	1692.661	1920.604	1807.762	2083.856	1930.69	2260.983
14	741.9891	815.7338	792.4443	885.0711	846.3306	960.3022	903.881	1041.928	965.345	1130.492
15	2671.161	2936.642	2852.8	3186.256	3046.79	3457.088	3253.972	3750.94	3475.242	4069.77
16	2967.956	3262.935	3169.777	3540.284	3385.322	3841.209	3615.524	4167.711	3861.38	4521.967
17	167392.7	184029.5	178775.4	199672	190932.2	216644.2	203915.6	235058.9	217781.8	255038.9
18	192917.2	212090.8	206035.5	230118.5	220045.9	249678.6	235009.1	270901.2	250989.7	293927.8
Total	572857.1	629792.1	611811.4	683324.5	653414.6	741407.1	697846.8	804426.7	745300.4	872802.9

4.5.1 Sub-model 1

In 2011, the NG demand of the 18 customers is [401855, 413436] (10^5 m^3). Because a small fraction of gas is consumed during pipeline transportation, [417466, 429494] (10^5 m^3) of NG is recovered. Table 4-12 shows the amount of gas production of every gas field. Most of the gas production is from the first two gas fields due to their lower production costs.

Then, the produced NG is distributed to pipeline A and pipeline B. Table 4-4 shows that the overall transportation cost of pipeline B is greater than that of pipeline A. Thus, more NG should flow through pipeline A. The solutions in Table 4-13 and Table 4-14 clearly verify this expectation. The flow rate of pipeline A stays at 300000 (10^5 m^3), which is the maximum value, regardless of the demand. The flow rate of pipeline B is 117466 (10^5 m^3) when the demand increases by 4.1% (Case 1), and the flow rate of pipeline B rises to 129494 (10^5 m^3) when the demand increases by 7.1% (Case 2).

Similar results can be observed in pipelines C, D, E, and F. The transportation costs of pipelines D and F are slightly lower than pipelines C and E. As a result, pipelines C and E only work at their minimum transportation rate while most of NG flows through pipelines D and F.

Table 4-12

NG production for Sub-model 1 (10^5 m^3/year)

Year	Gas Field				Total Production
	1	2	3	4	
2011	250000	[87466, 99494]	40000	40000	[417466, 429494]
2012	250000	[104578, 129981]	40000	40000	[434578, 459981]
2013	250000	[122391, 162632]	40000	40000	[452391, 492632]
2014	250000	[140935, 197602]	40000	40000	[470935, 527602]
2015	250000	[160240, 235055]	40000	40000	[490240, 565055]
2016	250000	[180336, 250000]	40000	[40000, 65167]	[510336, 605167]
2017	250000	[201255, 250000]	40000	[40000, 108152]	[531255, 648153]
2018	250000	[223033, 250000]	40000	[40000, 154224]	[553033, 694224]
2019	250000	[245703, 250000]	40000	[40000, 203566]	[575703, 743567]
2020	250000	250000	40000	[59303, 256412]	[599303, 796412]

In Case 2, when the gas demand increases by 7.1% per year, due to the increase in NG demand, pipeline H will participate in the pipeline network in 2017. Also in Case 2, pipeline H is more economical than pipeline I. It is capable of transporting sufficient NG until 2010.

In 2020, both pipelines A and H are working under their maximum flow rates, since the transportation cost of pipeline B is higher. Therefore, as presented in Table 4-15, pipeline H reaches its maximum capacity as soon as it has been constructed.

The model determines that pipeline H should be in service in 2007. In order to achieve this, the construction project would need to start in 2006, assuming the construction will require one year. Besides the above variables, the solutions for the flow rates of Pipelines C, D, E, and F are shown in Table 4-16 to Table 4-19. The amounts of gas consumed during transportation for every pipeline are shown in Table 4-20 to Table 4-26.

4.5.2 Sub-model 2

In Sub-model 2, the NG demand increases by [6.8%, 8.5%] every year. As a result, Pipelines A and B will not be able to transport sufficient NG downstream in 2018 or 2016, respectively, when the annual gas demand increment is 6.8% or 8.5%, respectively. Therefore, the model brings Pipeline I into service in 2018 and 2016, respectively.

Table 4-13

The amount of NG flow through Pipeline A (10^5 m^3/year)

Year	Nodes				
	1	2	3	4	5
2011	300000	298800	[296150, 296191]	[294966, 295006]	[293786, 293826]
2012	300000	298800	[296047, 296133]	[294863, 294949]	[293683, 293769]
2013	300000	298800	[295937, 296073]	[294753, 294889]	[293574, 293709]
2014	300000	298800	[295818, 296010]	[294635, 294826]	[293456, 293647]
2015	300000	298800	[295691, 295945]	[294508, 294761]	[293330, 293582]
2016	300000	298800	[295555, 295877]	[294373, 294693]	[293196, 293514]
2017	300000	298800	[295410, 295806]	[294228, 294622]	[293051, 293444]
2018	300000	298800	[295254, 295732]	[294073, 294549]	[292897, 293371]
2019	300000	298800	[295087, 295655]	[293907, 294473]	[292731, 293295]
2020	300000	298800	[294908, 295575]	[293729, 294393]	[292554, 293215]

Table 4-14

The amount of NG flow through Pipeline B (10^5 m^3/year)

Year	Nodes				
	1	2	3	4	5
2011	[117466, 129494]	[116996, 128976]	[116528, 128460]	[115677, 127550]	[115214, 127039]
2012	[134578, 159981]	[134039, 159341]	[133503, 158703]	[132568, 157644]	[132038, 157014]
2013	[152391, 192632]	[151782, 191862]	[151175, 191094]	[150153, 189875]	[149552, 189116]
2014	[170935, 227602]	[170252, 226692]	[169571, 225785]	[168458, 224395]	[167784, 223498]
2015	[190240, 265055]	[189479, 263995]	[188721, 262939]	[187514, 261366]	[186764, 260320]
2016	[210336, 305167]	[209494, 303946]	[208656, 302731]	[207351, 300961]	[206521, 299757]
2017	[148153, 231255]	[147560, 230330]	[146970, 229409]	[145784, 228001]	[145201, 227089]
2018	[194224, 253033]	[193447, 252021]	[192674, 251013]	[191262, 249498]	[190497, 248500]
2019	[243567, 275703]	[242592, 274600]	[241622, 273502]	[239970, 271877]	[239010, 270789]
2020	[296412, 299303]	[295227, 298106]	[294046, 296913]	[292135, 295173]	[290967, 293992]

Table 4-15

The amount of NG flow through Pipeline H* (10^5 m^3/year)

Year	Nodes			
	1	2	3	4
2011	0	0	0	0
2012	0	0	0	0
2013	0	0	0	0
2014	0	0	0	0
2015	0	0	0	0
2016	0	0	0	0
2017	200000	199000	198005	197015
2018	200000	199000	198005	197015
2019	200000	199000	198005	197015
2020	200000	199000	198005	197015

*Pipeline "H" only exists when the annual increment of gas demand is 7.1%. In the low demand scenario, where the annual increment of gas demand is 4.1%, the expansion is not implemented.

Table 4-16

The amount of NG flow through Pipeline C (10^5 m^3/year)

Year	Nodes	
	1	2
2011	[48925, 49025]	45000
2012	[49067, 49278]	45000
2013	[49215, 49549]	45000
2014	[49369, 49840]	45000
2015	[49530, 50152]	45000
2016	[49697, 50485]	45000
2017	[49871, 72387]	[45000, 66329]
2018	[50052, 101718]	[45000, 94988]
2019	[50240, 133132]	[45000, 125682]
2020	[50436, 166776]	[45000, 158555]

Table 4-17

The amount of NG flow through Pipeline D (10^5 m^3/year)

Year	Nodes				
	1	2	3	4	5
2011	[216695, 224272]	[215828, 223350]	[214965, 222457]	[212023, 219425]	[211175, 218547]
2012	[227439, 243389]	[226530, 242416]	[225624, 241446]	[222554, 238186]	[221663, 237233]
2013	[238624, 263890]	[237670, 262835]	[236719, 261783]	[233516, 258279]	[232582, 257246]
2014	[250267, 285847]	[249266, 284704]	[248269, 283565]	[244927, 279799]	[243948, 278680]
2015	[262388, 309363]	[261339, 308125]	[260293, 306893]	[256807, 302847]	[255780, 301635]
2016	[275006, 334548]	[273906, 333210]	[272810, 331877]	[269174, 327531]	[268097, 326221]
2017	[288141, 340000]	[286988, 338640]	[285840, 337285]	[282047, 332704]	[280919, 331373]
2018	[301814, 340000]	[300607, 338640]	[299404, 337285]	[295449, 332474]	[294267, 331144]
2019	[316048, 340000]	[314784, 338640]	[313525, 337285]	[309399, 332228]	[308162, 330899]
2020	[330866, 340000]	[329542, 338640]	[328224, 337285]	[323922, 331965]	[322627, 330637]

Table 4-18

The amount of NG flow through Pipeline E (10^5 m^3/year)

Year	Nodes
	1
2011	45000
2012	45000
2013	45000
2014	45000
2015	45000
2016	45000
2017	[45000, 55713]
2018	[45000, 83858]
2019	[45000, 114001]
2020	[45000, 146284]

Table 4-19

The amount of NG flow through Pipeline F (10^5 m^3/year)

Year	Nodes	
	1	2
2011	[209880, 217223]	[209041, 216354]
2012	[220327, 235834]	[219446, 234891]
2013	[231201, 255767]	[230277, 254744]
2014	[242522, 277115]	[241552, 276007]
2015	[254307, 299979]	[253289, 298779]
2016	[266574, 324466]	[265508, 323168]
2017	[279345, 340000]	[278228, 338640]
2018	[292640, 340000]	[291469, 338640]
2019	[306479, 340000]	[305253, 338640]
2020	[320886, 340000]	[319603, 338640]

Table 4-20

The amount of NG consumed from Pipeline A (10^5 m^3/year)

Year	Nodes				
	1	2	3	4	5
2011	1200.0	1195.2	[1184.6, 1184.8]	[1179.9, 1180.0]	[1175.1, 1175.3]
2012	1200.0	1195.2	[1184.2, 1184.5]	[1179.5, 1179.8]	[1174.7, 1175.1]
2013	1200.0	1195.2	[1183.7, 1184.3]	[1179.0, 1179.6]	[1174.3, 1174.8]
2014	1200.0	1195.2	[1183.3, 1184.0]	[1178.5, 1179.3]	[1173.8, 1174.6]
2015	1200.0	1195.2	[1182.8, 1183.8]	[1178.0, 1179.0]	[1173.3, 1174.3]
2016	1200.0	1195.2	[1182.2, 1183.5]	[1177.5, 1178.8]	[1172.8, 1174.1]
2017	1200.0	1195.2	[1181.6, 1183.2]	[1176.9, 1178.5]	[1172.2, 1173.8]
2018	1200.0	1195.2	[1181.0, 1182.9]	[1176.3, 1178.2]	[1171.6, 1173.5]
2019	1200.0	1195.2	[1180.3, 1182.6]	[1175.6, 1177.9]	[1170.9, 1173.2]
2020	1200.0	1195.2	[1179.6, 1182.3]	[1174.9, 1177.6]	[1170.2, 1172.9]

Table 4-21

The amount of NG consumed from Pipeline B (10^5 m^3/year)

Year	Nodes				
	1	2	3	4	5
2011	[469.9, 518.0]	[468.0, 515.9]	[466.1, 513.8]	[462.7, 510.2]	[460.9, 508.2]
2012	[538.3, 639.9]	[536.2, 637.4]	[534.0, 634.8]	[530.3, 630.6]	[528.2, 628.1]
2013	[609.6, 770.5]	[607.1, 767.4]	[604.7, 764.4]	[600.6, 759.5]	[598.2, 756.5]
2014	[683.7, 910.4]	[681.0, 906.8]	[678.3, 903.1]	[673.8, 897.6]	[671.1, 894.0]
2015	[761.0, 1060.2]	[757.9, 1056.0]	[754.9, 1051.8]	[750.1, 1045.5]	[747.1, 1041.3]
2016	[841.3, 1220.7]	[838.0, 1215.8]	[834.6, 1210.9]	[829.4, 1203.8]	[826.1, 1199.0]
2017	[592.6, 925.0]	[590.2, 921.3]	[587.9, 917.6]	[583.1, 912.0]	[580.8, 908.4]
2018	[776.9, 1012.1]	[773.8, 1008.1]	[770.7, 1004.1]	[765.1, 998.0]	[762.0, 994.0]
2019	[974.3, 1102.8]	[970.4, 1098.4]	[966.5, 1094.0]	[959.9, 1087.5]	[956.0, 1083.2]
2020	[1185.6, 1197.2]	[1180.9, 1192.4]	[1176.2, 1187.7]	[1168.5, 1180.7]	[1163.9, 1176.0]

Table 4-22

The amount of NG consumed from Pipeline C (10^5 m^3/year)

Year	Nodes	
	1	2
2011	[489.2, 490.2]	450.0
2012	[490.7, 492.8]	450.0
2013	[492.1, 495.5]	450.0
2014	[493.7, 498.4]	450.0
2015	[495.3, 501.5]	450.0
2016	[497.0, 504.9]	450.0
2017	[498.7, 723.9]	[450.0, 663.3]
2018	[500.5, 1017.2]	[450.0, 949.9]
2019	[502.4, 1331.3]	[450.0, 1256.8]
2020	[504.4, 1667.8]	[450.0, 1585.6]

Table 4-23

The amount of NG consumed from Pipeline D (10^5 m^3/year)

Year	Nodes				
	1	2	3	4	5
2011	[866.8, 897.0]	[863.3, 894.4]	[859.9, 889.8]	[848.1, 877.7]	[844.7, 874.2]
2012	[909.8, 973.6]	[906.1, 969.7]	[902.5, 965.8]	[890.2, 952.7]	[886.7, 948.9]
2013	[954.5, 1055.6]	[950.7, 1051.3]	[946.9, 1047.1]	[934.1, 1033.1]	[930.3, 1029]
2014	[1001.1, 1143.4]	[997.1, 1138.8]	[993.1, 1134.3]	[979.7, 1119.2]	[975.8, 1114.7]
2015	[1049.6, 1237.5]	[1045.4, 1232.5]	[1041.2, 1227.6]	[1027.2, 1211.4]	[1023.1, 1206.5]
2016	[1100.0, 1338.2]	[1095.6, 1332.8]	[1091.2, 1327.5]	[1076.7, 1310.1]	[1072.4, 1304.9]
2017	[1152.6, 1360.0]	[1148.0, 1354.6]	[1143.4, 1349.1]	[1128.2, 1330.8]	[1123.7, 1325.5]
2018	[1207.3, 1360.0]	[1202.4, 1354.6]	[1197.6, 1349.1]	[1181.8, 1329.9]	[1177.1, 1324.6]
2019	[1264.2, 1360.0]	[1259.1, 1354.6]	[1254.1, 1349.1]	[1237.6, 1328.9]	[1232.6, 1323.6]
2020	[1323.5, 1360.0]	[1318.2, 1354.6]	[1312.9, 1349.1]	[1295.7, 1327.9]	[1290.5, 1322.5]

Table 4-24

The amount of NG consumed from Pipeline E (10^5 m^3/year)

Year	Nodes
	1
2011	450.0
2012	450.0
2013	450.0
2014	450.0
2015	450.0
2016	450.0
2017	[450.0, 557.1]
2018	[450.0, 838.6]
2019	[450.0, 1140.0]
2020	[450.0, 1462.8]

Table 4-25

The amount of NG consumed from Pipeline F (10^5 m^3/year)

Year	Nodes	
	1	2
2011	[839.5, 868.9]	[836.2, 865.4]
2012	[881.3, 943.3]	[877.8, 939.6]
2013	[924.8, 1023.1]	[921.1, 1019]
2014	[970.1, 1108.5]	[966.2, 1104]
2015	[1017.2, 1199.9]	[1013.2, 1195.1]
2016	[1066.3, 1297.9]	[1062.0, 1292.7]
2017	[1117.4, 1360.0]	[1112.9, 1354.6]
2018	[1170.6, 1360.0]	[1165.9, 1354.6]
2019	[1225.9, 1360.0]	[1221.0, 1354.6]
2020	[1283.5, 1360.0]	[1278.4, 1354.6]

Table 4-26

The amount of NG consumed from Pipeline H* (10^5 m^3/year)

Year	Nodes			
	1	2	3	4
2011	0	0	0	0
2012	0	0	0	0
2013	0	0	0	0
2014	0	0	0	0
2015	0	0	0	0
2016	0	0	0	0
2017	1000	995	990	985.1
2018	1000	995	990	985.1
2019	1000	995	990	985.1
2020	1000	995	990	985.1

*Pipeline “H” only exists when the annual increment of gas demand is 7.1%. In the low demand scenario, where the annual increment of gas demand is 4.1%, the expansion is not implemented.

The amount of NG production for Sub-model 2 is shown in Table 4-27. The transportation cost of pipeline I is the lowest among the three upstream pipelines. The results shown in Table 4-28, Table 4-29, and Table 4-30 reflect this trend. As soon as pipeline I is in service, it works under its maximum load.

In addition, the solutions of flow rate and gas consumption for every pipeline section are shown in Table 4-31 to Table 4-41.

4.5.3 Dual-interval variables

As discussed previously, the possibilities of the two sub-models are 33% and 67%. Then, the results of the two sub-models can be further converted to dual-interval format. In Table 4-42 to Table 4-47, the dual-interval solutions of the starting points of all the pipelines are presented.

(7) Pipeline A

For most cases, pipeline A is operating under its maximum load. There are no dual-interval issues for this pipeline. In Case 3, the flow rate of Pipeline A drops to 276343 (10^5 m^3) per year in 2018. In Case 4, the flow rate of Pipeline A drops to 251798 (10^5 m^3) per year in 2018. Therefore, in those two years, the annual NG flow rates are interval formatted as [251798, 300000] and [276343, 300000], respectively. This shows that in order to achieve the most profitable solution, the flow rate of Pipeline A should not drop lower than 251798 (10^5 m^3) and 276343 (10^5 m^3) in 2016 and 2018, respectively. For the other years, it should remain operating at the maximum flow rate.

Table 4-27

NG production for Sub-model 2 (10^5 m^3/year)

Year	Gas Field				Total Production
	1	2	3	4	
2011	250000	[98291, 105107]	40000	40000	[428291, 435107]
2012	250000	[127408, 142082]	40000	40000	[457408, 472082]
2013	250000	[158505, 182201]	40000	40000	[488505, 512201]
2014	250000	[191717, 225730]	40000	40000	[521717, 555730]
2015	250000	[227187, 250000]	40000	[40000, 62958]	[557187, 602958]
2016	250000	250000	40000	[55069, 114234]	[595069, 654234]
2017	250000	250000	40000	[95534, 169906]	[635534, 709906]
2018	250000	250000	40000	[138801, 230312]	[678801, 770312]
2019	250000	250000	40000	[185010, 295851]	[725010, 835851]
2020	250000	250000	[40000, 106962]	[234361, 300000]	[774361, 906962]

Table 4-28

The amount of NG flow through Pipeline A (10^5 m^3/year)

Year	Nodes				
	1	2	3	4	5
2011	300000	298800	[296131, 296154]	[294947, 294970]	[293767, 293790]
2012	300000	298800	[296006, 296056]	[294822, 294872]	[293643, 293692]
2013	300000	298800	[295870, 295951]	[294687, 294767]	[293508, 293588]
2014	300000	298800	[295723, 295838]	[294540, 294655]	[293362, 293476]
2015	300000	298800	[295563, 295718]	[294381, 294535]	[293203, 293357]
2016	[251798, 300000]	[250791, 298800]	[247573, 295590]	[246582, 294407]	[245596, 293230]
2017	300000	298800	[295201, 295453]	[294020, 294271]	[292844, 293094]
2018	[276343, 300000]	[275237, 298800]	[271838, 294997]	[270750, 293817]	[269667, 292641]
2019	300000	298800	[294775, 295150]	[293596, 293969]	[292421, 292793]
2020	300000	298800	[294534, 294983]	[293356, 293803]	[292183, 292628]

Table 4-29

The amount of NG flow through Pipeline B (10^5 m^3/year)

Year	Nodes				
	1	2	3	4	5
2011	[128291, 135107]	[127778, 134566]	[127266, 134028]	[126362, 133090]	[125857, 132558]
2012	[157408, 172082]	[156778, 171394]	[156151, 170708]	[155104, 169590]	[154484, 168912]
2013	[188505, 212201]	[187751, 211352]	[187000, 210507]	[185801, 209192]	[185058, 208355]
2014	[221717, 255730]	[220830, 254707]	[219946, 253688]	[218585, 252160]	[217711, 251152]
2015	[257187, 302958]	[256158, 301747]	[255133, 300540]	[253599, 298781]	[252584, 297586]
2016	[52435, 295069]	[52225, 293888]	[52017, 292713]	[51205, 290993]	[51000, 289829]
2017	[59906, 335534]	[59667, 334192]	[59428, 332855]	[58536, 330937]	[58301, 329613]
2018	[52458, 120312]	[52248, 119830]	[52039, 119351]	[51205, 118163]	[51000, 117690]
2019	[75010, 185851]	[74709, 185108]	[74411, 184367]	[73444, 182859]	[73150, 182127]
2020	[124361, 256962]	[123863, 255934]	[123368, 254910]	[122160, 253054]	[121671, 252042]

Table 4-30

The amount of NG flow through Pipeline I (10^5 m^3/year)

Year	Nodes				
	1	2	3	4	5
2011	0	0	0	0	0
2012	0	0	0	0	0
2013	0	0	0	0	0
2014	0	0	0	0	0
2015	0	0	0	0	0
2016	[0, 350000]	[0, 348600]	[0, 347206]	[0, 345817]	[0, 344434]
2017	[0, 350000]	[0, 348600]	[0, 347206]	[0, 345817]	[0, 344434]
2018	350000	348600	347206	345817	344434
2019	350000	348600	347206	345817	344434
2020	350000	348600	347206	345817	344434

Table 4-31

The amount of NG flow through Pipeline C (10^5 m^3/year)

Year	Nodes	
	1	2
2011	[49015, 49071]	45000
2012	[49257, 49379]	45000
2013	[49515, 49712]	45000
2014	[49791, 50074]	45000
2015	[50086, 50467]	45000
2016	[50401, 76259]	[45000, 70113]
2017	[64354, 111703]	[58481, 104745]
2018	[91900, 150160]	[85395, 142320]
2019	[121319, 191885]	[114140, 183090]
2020	[152738, 237157]	[144839, 227324]

Table 4-32

The amount of NG flow through Pipeline D (10^5 m^3/year)

Year	Nodes				
	1	2	3	4	5
2011	[223492, 227771]	[222598, 226860]	[221708, 225953]	[218685, 222879]	[217810, 221988]
2012	[241774, 250988]	[240807, 249984]	[239844, 248984]	[236603, 245633]	[235656, 244651]
2013	[261299, 276177]	[260254, 275072]	[259213, 273972]	[255739, 270321]	[254716, 269240]
2014	[282152, 303507]	[281023, 302293]	[279899, 301084]	[276177, 297108]	[275073, 295920]
2015	[304422, 333161]	[303205, 331828]	[301992, 330501]	[298005, 326172]	[296813, 324867]
2016	[328207, 340000]	[326894, 338640]	[325587, 337285]	[321317, 332673]	[320031, 331343]
2017	340000	338640	337285	[332396, 332396]	[331066, 331066]
2018	340000	338640	337285	[332095, 332095]	[330767, 330767]
2019	340000	338640	337285	[331769, 331769]	[330442, 330442]
2020	340000	338640	337285	[331414, 331414]	[330089, 330089]

Table 4-33

The amount of NG flow through Pipeline E (10^5 m^3/year)

Year	Nodes 1
2011	45000
2012	45000
2013	45000
2014	45000
2015	45000
2016	[45000, 59429]
2017	[48006, 93439]
2018	[74437, 130341]
2019	[102666, 170379]
2020	[132814, 213820]

Table 4-34

The amount of NG flow through Pipeline F (10^5 m^3/year)

Year	Nodes	
	1	2
2011	[216489, 220650]	[215623, 219767]
2012	[234264, 243222]	[233327, 242249]
2013	[253248, 267713]	[252235, 266642]
2014	[273522, 294286]	[272428, 293109]
2015	[295176, 323118]	[293995, 321825]
2016	[318301, 340000]	[317028, 338640]
2017	340000	338640
2018	340000	338640
2019	340000	338640
2020	340000	338640

Table 4-35

The amount of NG consumed from Pipeline A (10^5 m^3/year)

Year	Nodes				
	1	2	3	4	5
2011	1200.0	1195.2	[1184.5, 1184.6]	[1179.8, 1179.9]	[1175.1, 1175.2]
2012	1200.0	1195.2	[1184.0, 1184.2]	[1179.3, 1179.5]	[1174.6, 1174.8]
2013	1200.0	1195.2	[1183.5, 1183.8]	[1178.7, 1179.1]	[1174.0, 1174.4]
2014	1200.0	1195.2	[1182.9, 1183.4]	[1178.2, 1178.6]	[1173.4, 1173.9]
2015	1200.0	1195.2	[1182.3, 1182.9]	[1177.5, 1178.1]	[1172.8, 1173.4]
2016	[1007.2, 1200.0]	[1003.2, 1195.2]	[990.3, 1182.4]	[986.3, 1177.6]	[982.4, 1172.9]
2017	1200.0	1195.2	[1180.8, 1181.8]	[1176.1, 1177.1]	[1171.4, 1172.4]
2018	[1105.4, 1200.0]	[1100.9, 1195.2]	[1087.4, 1180.0]	[1083.0, 1175.3]	[1078.7, 1170.6]
2019	1200.0	1195.2	[1179.1, 1180.6]	[1174.4, 1175.9]	[1169.7, 1171.2]
2020	1200.0	1195.2	[1178.1, 1179.9]	[1173.4, 1175.2]	[1168.7, 1170.5]

Table 4-36

The amount of NG consumed from Pipeline B (10^5 m^3/year)

Year	Nodes				
	1	2	3	4	5
2011	[513.2, 540.4]	[511.1, 538.3]	[509.1, 536.1]	[505.4, 532.4]	[503.4, 530.2]
2012	[629.6, 688.3]	[627.1, 685.6]	[624.6, 682.8]	[620.4, 678.4]	[617.9, 675.6]
2013	[754.0, 848.8]	[751.0, 845.4]	[748.0, 842.0]	[743.2, 836.8]	[740.2, 833.4]
2014	[886.9, 1022.9]	[883.3, 1018.8]	[879.8, 1014.8]	[874.3, 1008.6]	[870.8, 1004.6]
2015	[1028.7, 1211.8]	[1024.6, 1207.0]	[1020.5, 1202.2]	[1014.4, 1195.1]	[1010.3, 1190.3]
2016	[209.7, 1180.3]	[208.9, 1175.6]	[208.1, 1170.9]	[204.8, 1164.0]	[204.0, 1159.3]
2017	[239.6, 1342.1]	[238.7, 1336.8]	[237.7, 1331.4]	[234.1, 1323.7]	[233.2, 1318.5]
2018	[209.8, 481.2]	[209.0, 479.3]	[208.2, 477.4]	[204.8, 472.7]	[204.0, 470.8]
2019	[300.0, 743.4]	[298.8, 740.4]	[297.6, 737.5]	[293.8, 731.4]	[292.6, 728.5]
2020	[497.4, 1027.8]	[495.5, 1023.7]	[493.5, 1019.6]	[488.6, 1012.2]	[486.7, 1008.2]

Table 4-37

The amount of NG consumed from Pipeline C (10^5 m^3/year)

Year	Nodes	
	1	2
2011	[490.1, 490.7]	450.0
2012	[492.6, 493.8]	450.0
2013	[495.2, 497.1]	450.0
2014	[497.9, 500.7]	450.0
2015	[500.9, 504.7]	450.0
2016	[504.0, 762.6]	[450.0, 701.1]
2017	[643.5, 1117.0]	[584.8, 1047.4]
2018	[919.0, 1501.6]	[854.0, 1423.2]
2019	[1213.2, 1918.9]	[1141.4, 1830.9]
2020	[1527.4, 2371.6]	[1448.4, 2273.2]

Table 4-38

The amount of NG consumed from Pipeline D (10^5 m^3/year)

Year	Nodes				
	1	2	3	4	5
2011	[894, 911.1]	[890.4, 907.4]	[886.8, 903.8]	[874.7, 891.5]	[871.2, 888.0]
2012	[967.1, 1004.0]	[963.2, 999.9]	[959.4, 995.9]	[946.4, 982.5]	[942.6, 978.6]
2013	[1045.2, 1104.7]	[1041.0, 1100.3]	[1036.9, 1095.9]	[1023.0, 1081.3]	[1018.9, 1077.0]
2014	[1128.6, 1214.0]	[1124.1, 1209.2]	[1119.6, 1204.3]	[1104.7, 1188.4]	[1100.3, 1183.7]
2015	[1217.7, 1332.6]	[1212.8, 1327.3]	[1208.0, 1322.0]	[1192.0, 1304.7]	[1187.3, 1299.5]
2016	[1312.8, 1360.0]	[1307.6, 1354.6]	[1302.3, 1349.1]	[1285.3, 1330.7]	[1280.1, 1325.4]
2017	1360.0	1354.6	1349.0	[1329.6, 1331.1]	[1324.3, 1325.7]
2018	1360.0	1354.6	1349.0	[1328.4, 1330.2]	[1323.1, 1324.9]
2019	1360.0	1354.6	1349.0	[1327.1, 1329.3]	[1321.8, 1324.0]
2020	1360.0	1354.6	1349.0	[1325.7, 1328.3]	[1320.4, 1323.0]

Table 4-39

The amount of NG consumed from Pipeline E (10^5 m^3/year)

Year	Nodes
	1
2011	450.0
2012	450.0
2013	450.0
2014	450.0
2015	450.0
2016	[450.0, 594.3]
2017	[480.1, 934.4]
2018	[744.4, 1303.4]
2019	[1026.7, 1703.8]
2020	[1328.1, 2138.2]

Table 4-40

The amount of NG consumed from Pipeline F (10^5 m^3/year)

Year	Nodes	
	1	2
2011	[866.0, 882.6]	[862.5, 879.1]
2012	[937.1, 972.9]	[933.3, 969.0]
2013	[1013.0, 1070.9]	[1008.9, 1066.6]
2014	[1094.1, 1177.1]	[1089.7, 1172.4]
2015	[1180.7, 1292.5]	[1176.0, 1287.3]
2016	[1273.2, 1360.0]	[1268.1, 1354.6]
2017	1360.0	1354.6.0
2018	1360.0	1354.6.0
2019	1360.0	1354.6.0
2020	1360.0	1354.6.0

Table 4-41

The amount of NG consumed from Pipeline I (10^5 m^3/year)

Year	Nodes				
	1	2	3	4	5
2011	0	0	0	0	0
2012	0	0	0	0	0
2013	0	0	0	0	0
2014	0	0	0	0	0
2015	0	0	0	0	0
2016	[0, 1400.0]	[0, 1394.4]	[0, 1388.8]	[0, 1383.3]	[0, 1377.7]
2017	[0, 1400.0]	[0, 1394.4]	[0, 1388.8]	[0, 1383.3]	[0, 1377.7]
2018	1400.0	1394.4	1388.8	1383.3	1377.7
2019	1400.0	1394.4	1388.8	1383.3	1377.7
2020	1400.0	1394.4	1388.8	1383.3	1377.7

Table 4-42

The amount of NG flow through Pipeline A (10^5 m^3/year)

Year	Nodes
	1
2011	300000
2012	300000
2013	300000
2014	300000
2015	300000
2016	[251798, 300000]
2017	300000
2018	[276343, 300000]
2019	300000
2020	300000

Table 4-43

The amount of NG flow through Pipeline B (10^5 m^3/year)

Year	Nodes
	1
2011	[(117466, 128291), (129494, 135107)]
2012	[(134578, 157408), (159981, 172082)]
2013	[(152391, 188505), (192632, 212201)]
2014	[(170935, 221717), (227602, 255730)]
2015	[(190240, 257187), (265055, 302958)]
2016	[(52435, 210336), (295069, 305167)]
2017	[(59906, 148153), (231255, 335534)]
2018	[(52458, 120312), (194224, 253033)]
2019	[(75010, 185851), (243567, 275703)]
2020	[(124361, 256962), (296412, 299303)]

Table 4-44

The amount of NG flow through Pipeline C (10^5 m^3/year)

Year	Nodes
	1
2011	[(48925, 49015), (49025, 49071)]
2012	[(49067, 49257), (49278, 49379)]
2013	[(49215, 49515), (49549, 49712)]
2014	[(49369, 49791), (49840, 50074)]
2015	[(49530, 50086), (50152, 50467)]
2016	[(49697, 50401), (50485, 76259)]
2017	[(49871, 64354), (72387, 111703)]
2018	[(50052, 91900), (101718, 150160)]
2019	[(50240, 121319), (133132, 191885)]
2020	[(50436, 152738), (166776, 237157)]

Table 4-45

The amount of NG flow through Pipeline D (10^5 m^3/year)

Year	Nodes
	1
2011	[(216695, 223492), (224247, 227771)]
2012	[(227439, 241774), (243389, 250988)]
2013	[(238624, 261299), (263890, 276177)]
2014	[(250267, 282152), (285847, 303507)]
2015	[(262388, 304422), (309363, 333161)]
2016	[(275006, 328207), (334548, 340000)]
2017	[288141, 340000]
2018	[301814, 340000]
2019	[316048, 340000]
2020	[330866, 340000]

Table 4-46

The amount of NG flow through Pipeline E (10^5 m^3/year)

Year	Nodes
	1
2011	45000
2012	45000
2013	45000
2014	45000
2015	45000
2016	[45000, 59429]
2017	[(45000, 48006), (55713.2, 93440)]
2018	[(45000, 74437), (83858, 130341)]
2019	[(45000, 102666), (114001, 170379)]
2020	[(45000, 132814), (146284, 213820)]

Table 4-47

The amount of NG flow through Pipeline F (10^5 m^3/year)

Year	Nodes
	1
2011	[(209880, 216489), (217223, 220650)]
2012	[(220327, 234264), (235834, 243222)]
2013	[(231201, 253248), (255767, 267713)]
2014	[(242522, 273522), (277115, 294286)]
2015	[(254307, 295176), (299979, 323118)]
2016	[(266574, 318301), (324466, 340000)]
2017	[279345, 340000]
2018	[292640, 340000]
2019	[306479, 340000]
2020	[320886, 340000]

(8) Pipeline B

From 2011 to 2015, the flow rate of Pipeline B increases with the NG demand. According to the different possibilities of each scenario, a possibility distribution figure can be developed. In Figure 4-4, the possibility distribution of the flow rate in 2011 is demonstrated. In 2011, the total NG production is [(417466, 428291), (429494, 435107)] (10^5m^3/year). As mentioned previously, Pipeline A is operating at maximum load due to its lower transportation cost. Thus, the flow rate of Pipeline B is [(117466, 128291), (129494, 135107)] (10^5m^3/year).

Consider the two scenarios provided earlier in Ch.4, for 67% of possibility, the flow rate of Pipeline B is between [128291, 135107] (10^5m^3/year). For the other 33% of possibility, the flow rate is between [117466, 129494] (10^5m^3/year). Referring to Figure 4-4, the two intervals are integrated into dual-interval format by their degree of possibility. Based on the two possible scenarios, the flow rate at the starting point of Pipeline B will definitely (100%) include [128291, 129494] (10^5m^3/year). For 67% of possibility, the flow rate can meet 135107 (10^5m^3/year), and it can be as low as 117466 (10^5m^3/year) with 33% of possibility. Therefore, it can be expected that the flow rate will be between [128291, 135107] (10^5m^3/year) for most possibilities (greater than 67%).

Similar observations can be made for 2011 to 2015. In 2006, due to the expansion of Pipeline I, the possibility distribution changes to another shape, as shown in Figure 4-5. In this case, the flow rate should be controlled between [52435, 295069] (10^5m^3/year) for most possibilities (over 67%).

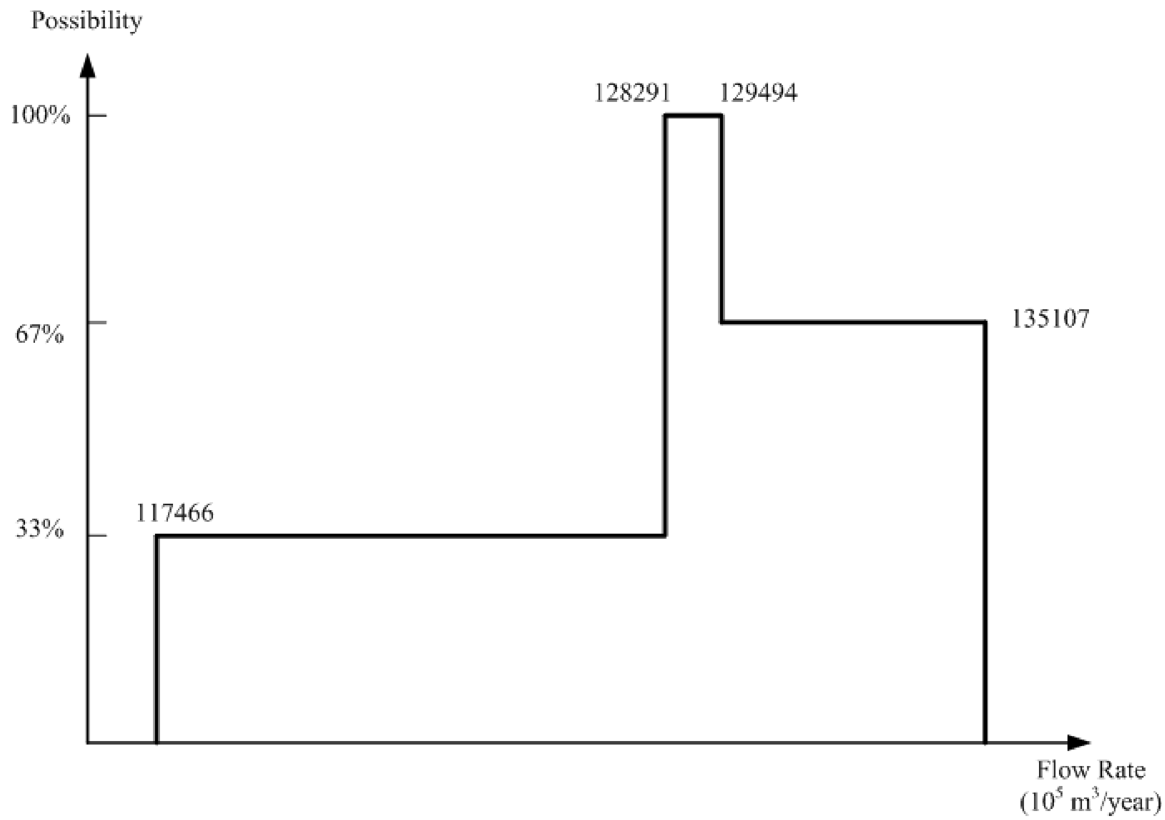

Figure 4-4 Possibility distribution for the flow rate of Pipeline B in 2011

The possibility distributions for 2018 to 2020 are quite different from those of previous years. In 2018, when gas demand increases by [6.8%, 8.5%], expansion of Pipeline I is conducted. As a result, the flow rate of Pipeline B drops sharply due to its higher transportation cost. On the other hand, when gas demand increases by only 4.1%, it is not necessary to perform any expansion. Thus, the flow rate of Pipeline B still maintains high at 253033 (10^5m^3/year). If the gas demand increases by 7.1%, the model decides to construct Pipeline H in 2017. In 2018, the flow rate of Pipeline B is 194224 (10^5m^3/year), still higher than it is in the high-demand scenario. As a result, the possibility distribution is much more complex, as presented in Figure 4-6.

Since there is no overlap between the two scenarios, Figure 4-6 shows the possibility of each scenario. It is a difficult task to choose between the two possible solutions. In the real world, it requires decision makers to compromise and balance many factors that could influence system profit and system reliability. In the model, it is assumed that the high-demand scenario is most likely to happen. Thus, when managing the SNLPS, [52458, 120312] (10^5m^3/year) is a more reliable solution.

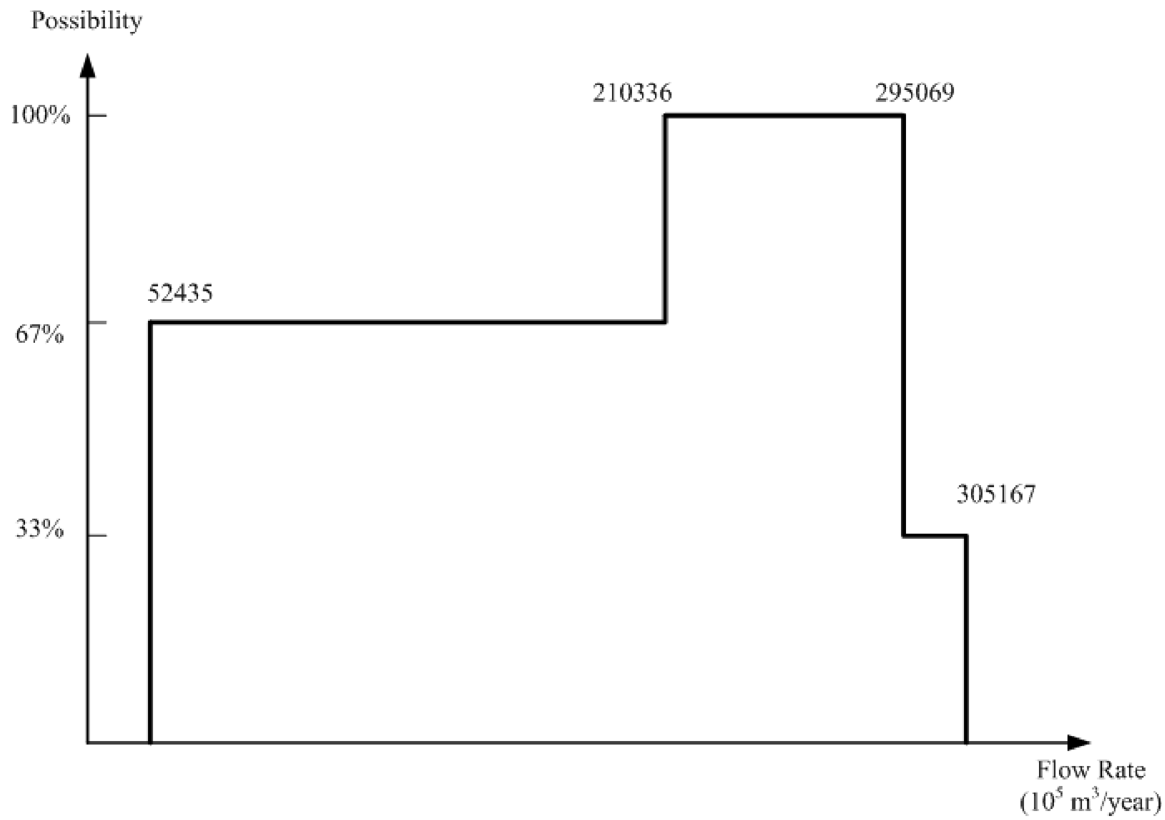

Figure 4-5 Possibility distribution for the flow rate of Pipeline B in 2016

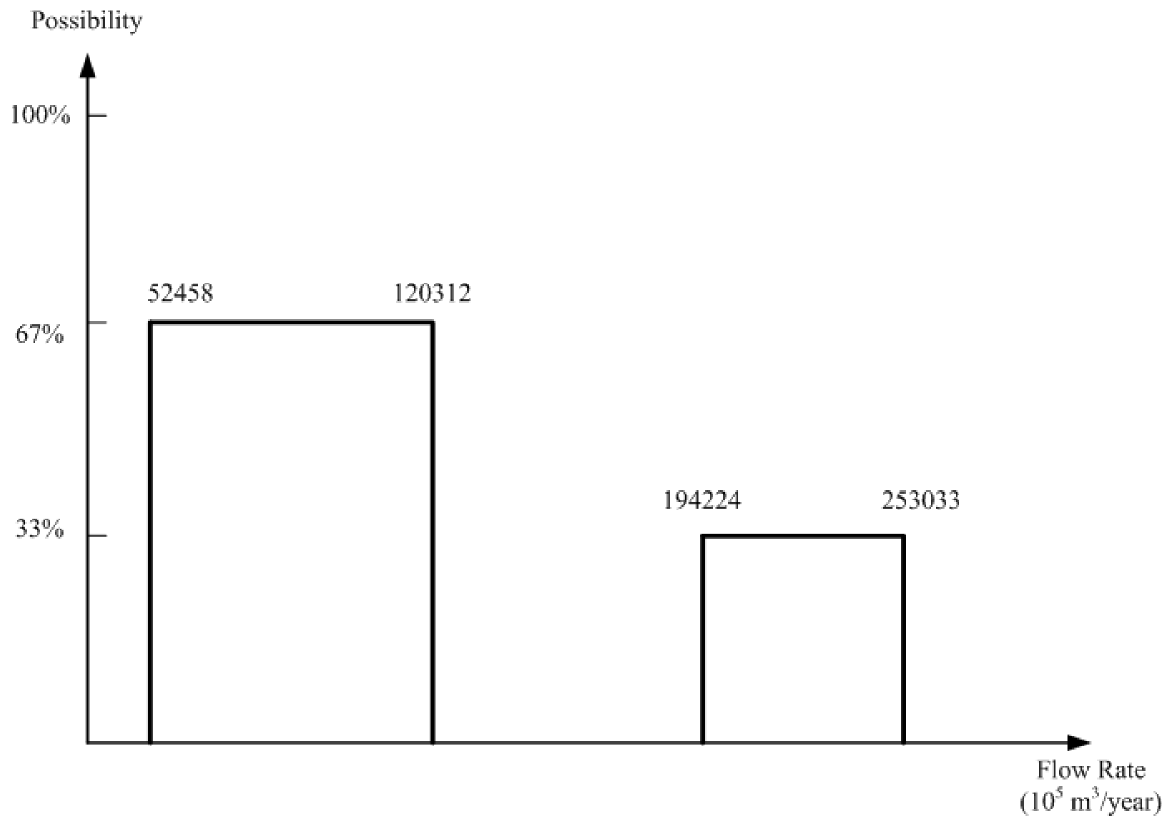

Figure 4-6 Possibility distribution for the flow rate of Pipeline B in 2018

(9) NG Production

Table 4-48 presents the dual-interval solution of total NG production. From 2011 to 2020, the possibility of total NG production retains the same distribution. Figure 4-7 shows the possibility distribution of total NG production in 2011. When decision makers are planning the NG production in 2011, the solution must include [428291, 429494] (10^5m^3/year). For 67% of possibility, the NG production can be increased to 435107 (10^5m^3/year). However, the extra 5613 (10^5m^3year) of NG may exceed the demand in the case of 33% of possibility. In this case, planning NG production should consider [428291, 435107] (10^5m^3/year) because this range can reflect the most possibilities.

(10) Total Profit

Table 4-49 shows the total profit in the dual-interval format. The possibility distribution of the total profit is shown in Figure 4-8. From the figure, the range of total profit will include [1050494, 1074180] (10^5 CNY). For 67% of possibility, the total profit can reach 1101092 (10^5 CNY). Meanwhile, the total profit can be as low as 970268 (10^5 CNY) at 33% of possibility. For most cases, the decision makers can expect the total profit to be within [1050494, 1101092] (10^5 CNY).

Table 4-48

Total NG production (10^5 m^3/year)

Year	Total NG Production
2011	[(417466, 428291), (429494, 435107)]
2012	[(434578, 457408), (459981, 472082)]
2013	[(452391, 488505), (492632, 512201)]
2014	[(470935, 521717), (527602, 555730)]
2015	[(490240, 557187), (565055, 602958)]
2016	[(510336, 595069), (605167, 654234)]
2017	[(531255, 635534), (648153, 709906)]
2018	[(553033, 678801), (694224, 770312)]
2019	[(575703, 725010), (743567, 835851)]
2020	[(599303, 774361), (796412, 906962)]

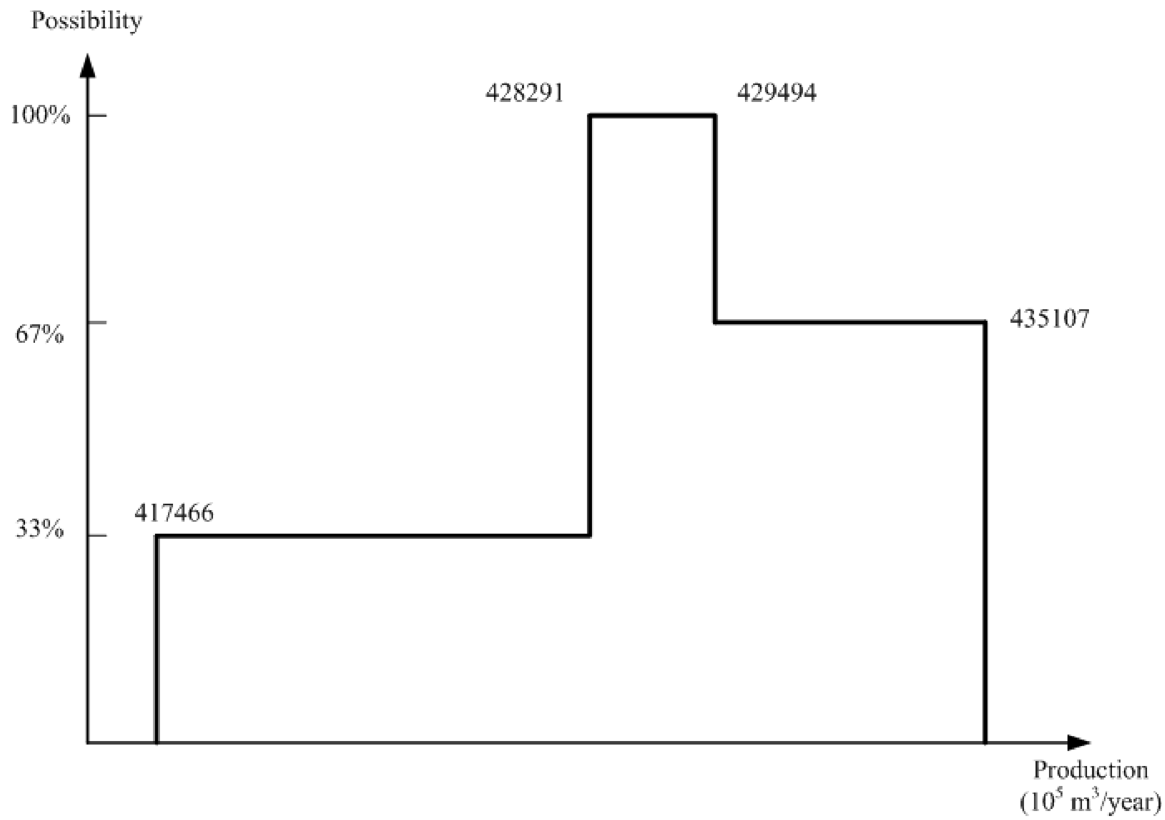

Figure 4-7 Possibility distribution for total NG production in 2011

Table 4-49

Total profit (10^5 CNY)

Total Profit
Gas Demand Increase
[(4.1, 6.8), (7.1, 8.5)]%
[(970268, 1050494), (1074180, 1101092)]

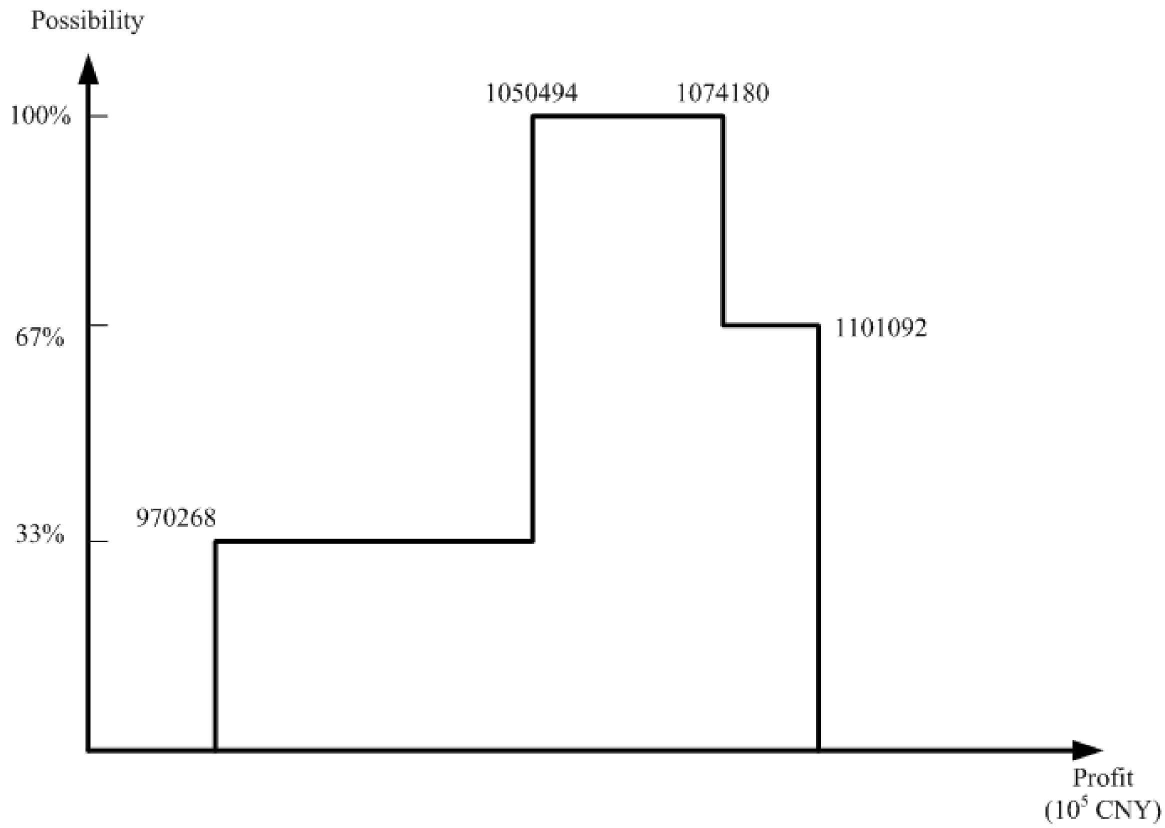

Figure 4-8 Possibility distribution for total profit

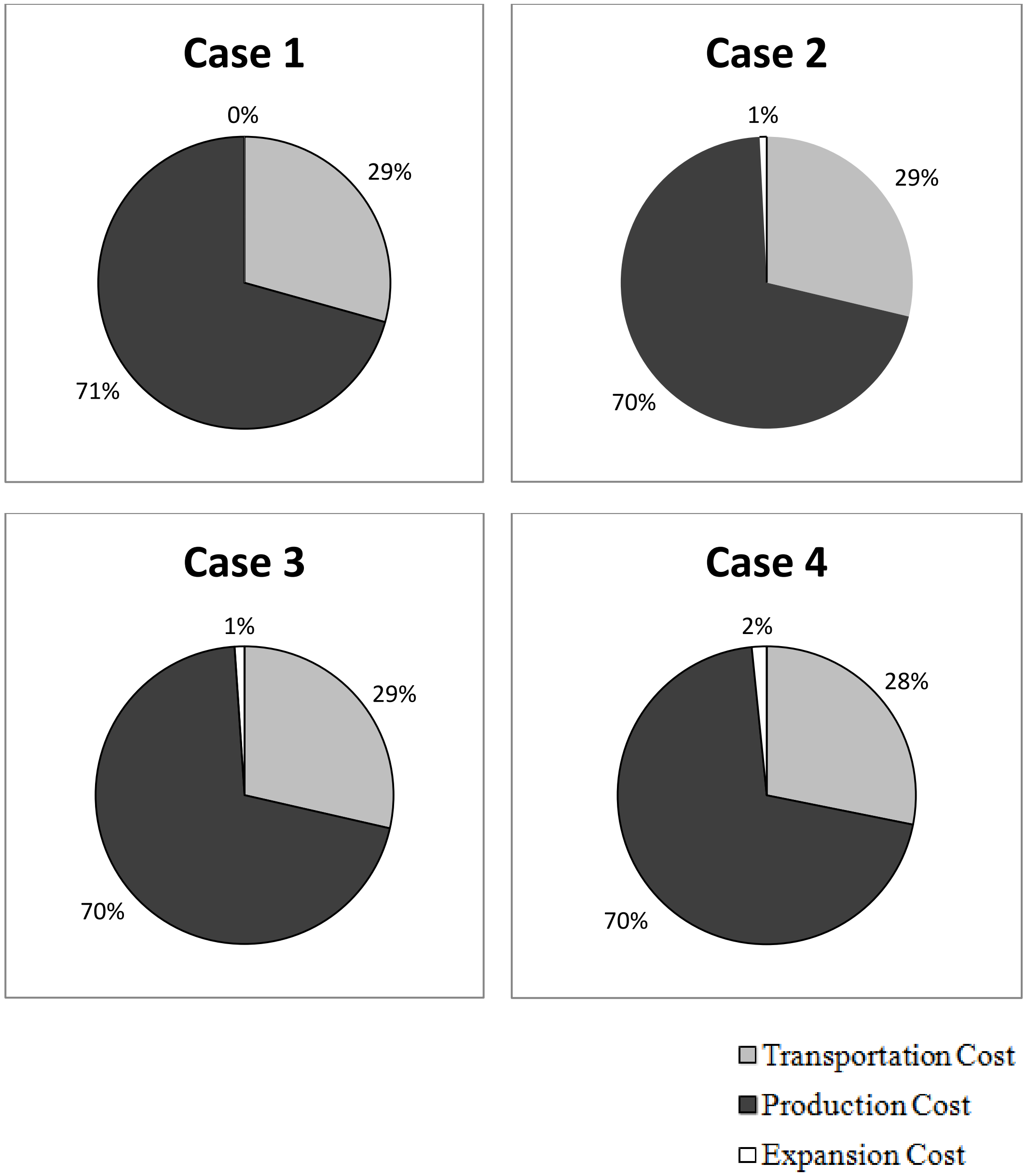

Figure 4-9 Cost analysis for different cases

Table 4-50

Cost and profit of SNLPS from 2011 to 2020 (10^5 CNY)

Case	Transportation Cost	Production Cost	Expansion Cost	Gross Profit	Total Cost	Net Profit	Rate of Return	Net Rate of Return (%)
1	1537438	3700395	0	6208100	5237833	970268	18.52%	18.52
2	1802432	4424091	50000	7350704	6276524	1074180	17.11%	18.05
3	1765665	4344849	66000	7227008	6176514	1050494	17.01%	18.27
4	1931188	4815857	110000	7958136	6857045	1101092	16.06%	17.95

(11) Expansion

According to Table 4-15 and Table 4-30, Pipelines H and I are selected in Sub-model 1 and Sub-model 2, respectively. In Sub-model 1, the DIPSPM determines that Pipeline H should be in service in 2017 when increase of NG demand is 7.1% per year (Case 2). In Sub-model 2, the model decides to select Pipeline I for both cases. The expansions will occur in 2016 for Case 4 and 2018 for Case 3.

Referring to Table 4-13, Table 4-14, and Table 4-15, in Sub-model 1, the pipeline system is working at nearly its maximum flow rate. As a result, there is no room for any increase of NG demand. In addition, considering the higher possibility of Sub-model 2, Pipeline I is more reliable than Pipeline H.

4.5.4 Cost analysis

From the solution of the model, the transportation cost, production cost, and expansion cost can be calculated. The transportation cost and production cost are proportional to the amount of NG transmitted/recovered. Therefore, it is not necessary to analyze the cost for every single year because the demand of NG is increasing for the entire modeling horizon. In this section, the cost analysis is focused on the entire modeling horizon.

In Table 4-50, all the costs and profits of SNLPS for the modeling horizon are calculated and listed. It can be observed that the majority of the cost is the production cost. In the model, the NG selling price is approximately 1.25-1.3 (CNY/m^3), and, it costs about 0.75-0.8 CNY to produce one cubic metre of NG. Therefore, the production cost can be estimated to be the greatest part of cost. In Figure 4-9, percentages of the three types of cost are compared. For the four cases, the production cost remains 70% and, therefore, verifies the previous estimation. According to Figure 4-9, the transportation cost is another major cost. From Case 1 to Case 4, the percentage of transportation cost stays at 28% to 29%. The amount of expansion cost is around 1%-2%. Compared with the other types of cost, the expansion cost is insignificant to the system profit.

From Figure 4-9 and Table 4-50, another finding is that the ratio of net profit and total cost decreases while the demand increases. In this way, selling more NG will lead to a lower rate of return (ROR). One of the reasons that for this issue is that the expansion cost has negative impacts on the ROR. However, the expansion cost is a temporary cost, since it will only exist in the following ten years after the expansion. Thus, in a long-term view, the reduction of ROR due to expansions is not important.

Therefore, in Table 4-50, a net rate of return (NROR) is calculated. For Cases 2 to 4, the expansion cost is added to the net profit. Then, the NROR can be calculated by using the new net profit divided by the transportation cost and the production cost. However, the same trend still exists from Cases 1 to 4. Table 4-3, Table 4-12, and Table 4-27 reveal the reason for this problem. In Case 1, most of the NG is recovered from the No.1 and No.2 gas fields. Table 4-3 shows that the production costs of these two gas fields are 0.75 (CNY/m^3), which is lower than the production cost of the No.3 and No.4 gas fields. As the demand increases, more gas is recovered from the No.3 and No.4 gas fields, and, therefore, this causes the increase in average production cost. Thus, the NROR decreases when more gas is produced.

In reality, decision makers can respond to this issue. If the overall cost increases, then they can either work on reducing costs or they can increase the gas price. This model reveals that the production cost is significant to the NROR. Thus, decision makers should pay attention to this cost to achieve better profits.

4.6 Summary

In this study, a dual-interval NG pipeline system planning model (DIPSPM) was developed. The model was applied to a case study of the SNLPS. In the case study, the model generated a pipeline operation guideline and an expansion strategy. In the solution, the most possible range of every decision variable is also provided. Decision makers can make further decisions based on the possibility distributions.

Compared to the previous method, the DIPSPM can reflect dual uncertainties of NG demand for the whole modeling horizon. The solution includes not only ranges of the decision variables, but also offers possibility distribution information. Noteworthy improvement is achieved compared to interval energy systems models. Meanwhile, the improvement does not require significant increase of work load. The data collection process is still much easier than with stochastic or fuzzy programming methods.

NG pipeline networks are highly complicated engineering systems. Although the DIPSPM can partially reflect this complexity, the model is still a simplified version of a real pipeline system. Therefore, some recommendations are made for future improvements:

- In the model, the values of various costs and gas selling prices are constant. In the future, change of different types of costs can be included.
- The future version of the model could incorporate a floating gas price that depends on the overall cost in order to determine the most profitable selling price.
- Since the modeling period is ten years, problems such as pipeline corrosion and facility aging are not included. If a longer modeling period is necessary, the model should be modified to reflect such issues.
- For the entire modeling horizon, there are 18 customers. In the future, it can include development of new customers.
- More details of pipeline systems could be included in the future. For example, the operation of compressors and pump stations.
- In reality, there are storage facilities to reduce stress in NG supply during peak seasons. The model can be modified to reflect NG supply for every month. New variables and constraints need to be developed to reflect storage facilities. Then, the model can be used to direct the pipeline systems' operations to reduce the peak effect.

Chapter 5

Conclusions

This research is an attempt to introduce dual-interval linear programming (DILP) method to energy systems studies. In the first part of the research, a dual-interval energy systems planning model (DIESPM) was developed. In the second part, a dual-interval NG pipeline systems planning model (DIPSPM) was developed and applied to the “Se Ning Lan” NG pipeline systems (SNLPS) in China.

The DIESPM was developed through integrating dual-interval programming and mixed integer programming techniques within energy systems planning. The model can deal with not only uncertainties expressed in dual-interval format, but also dynamics of facility expansion. By adjusting parameters, the model is capable of optimizing energy systems under various scenarios. With the support of the energy management plan given by the model, decision makers can compromise among different alternatives and make the choice to support energy systems management with the aim of achieving minimal system cost.

The DIPSPM is demonstrated with a case study of SNLPS, which is the most important pipeline system in north-western China. The model incorporates gas production, pipeline transmission, future expansions, and customer distribution. To reflect the uncertain demand from 2011 to 2020, two scenarios from different research institutes were selected. In the solution, the model provides a comprehensive pipeline management plan for decision makers. The management plan was determined under the greatest amount of possibilities. However, decision makers still need to compromise between reliability of NG supply and system cost.

The solutions of the DIESPM and the DIPSPM prove that a dual-interval energy systems planning model can reflect the complexity in energy systems modeling. The DILP method significantly simplifies the data collection process. No possibility distribution information for each collected interval is necessary. However, after the interval numbers are converted to a dual-interval number, the possibility distribution information of the DILP number can be acquired. Therefore, in energy systems studies, more reliable solutions can be obtained through constructing energy models under dual-interval uncertainties.

In the future, the DILP method can be widely applied to research of energy systems. In the DIPSPM, due to the lack of information, only two scenarios were included. The dual-interval variables in DIPSPM are formulated by two intervals with designated possibilities. Then, the model provides the greatest number of possible solutions for the SNLPS. If more information is available, several scenarios with specified possibilities can be used to formulate dual-interval variables. In this case, the possibility distributions will be more specific, and the reliability of the solution will be improved.

When information is limited, only a few scenarios are available to formulate dual-interval variables. In such cases, each scenario will have a different possibility based on the information reliability and credibility. On the other hand, if large amounts of information are available during data collection, identical possibilities can be assigned to every scenario. Therefore, this overcomes the difficulties in ranking possibilities for every scenario.

To conclude, a DILP energy systems model can reflect the complexity in energy systems. Robust solutions can be obtained even when the data are limited. However, solution reliability can be improved if more information is available. In addition, the data collection process of a DILP energy systems model is much simpler and easier than the data collection processes in previous studies.

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