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Development of an intelligent decision support system for air pollution control at coal-fired power plants

Qian Zhou[a], Guo H. Huang[a], Christine W. Chan[b,*]

[a]Environmental Systems Engineering Program, University of Regina, Regina, Sask, Canada S4S 0A2

[b]Software Systems Engineering Program, Faculty of Engineering, University of Regina, Regina, Sask, Canada S4S 0A2

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Abstract

Air pollution from power plants is responsible for some of the most pressing environmental problems today. Much research has been done on pollution control for power plants. Contemporary approaches to pollution control often take advantage of computer technology, but research on use of expert systems for power plant management is scarce. In this study an expert system was developed to assist power plant decision makers in selecting an economical and efficient pollution control system that meets new stringent emission standards. The study will also provide the key design parameters for such a system. A fuzzy relation model and a Gaussian dispersion model were integrated into this expert system. Using the fuzzy relation model, the system can quickly select feasible control methods according to the desired removal efficiency. The system will then identify the most cost effective control strategy according to economic considerations provided by users. To assess and ensure effectiveness of the selected method, ambient air quality is simulated using the Gaussian dispersion model and compared with required standards. The developed system was applied to a case study. The results generated show that the system is able to consider the trade-offs between environmental requirement and economic objective, decrease the possibility of pollutant risk, and help the power plant reduce environmental-related capital and operation costs.

Keywords: Expert decision support system; Environment; Air pollution; Power plants

1. Introduction

An important tool for power plant management is a decision support system that can help select an economically efficient pollutant control scheme which ensures the safety of the environment and the public. In terms of volume and variety of contaminants emitted, few other single pollution sources come close to matching the negative impact from electric power plants. Among power plants, the coal-fired facilities produce the most serious pollution concerns. For instance, the US Environmental Protection Agency (EPA)'s data showed that about 51% of power plant boilers in the US are fueled by coal. They account for emissions of over 93% of nitrogen oxides, over 96% of sulfur dioxide, over 88% of carbon dioxide, and 99% of mercury in the entire electricity industry (Freme and Hong, 1999). These pollutants are extremely harmful to both public health and to the environment. For example, sulfur dioxide (SO_2) is a highly toxic air contaminant. When released into the atmosphere, SO_2 with water, oxygen, and other power plant pollutants, such as nitrogen oxides (NO_x), to form acidic compounds. These acidic compounds return to the earth in the form of acid deposition, which is the major component in acid rain. Sulfate particles contribute to tens of thousands of premature infant deaths each year.

A number of emission control technologies have been made ready for reducing contaminant emission from coal-fired power plants. The decision making process for quickly selecting an appropriate emission control strategy is complicated and difficult. Different power plants have different emission characteristics depending on plant size, coal type, coal mineral matter content, combustion system, boiler type and so on. In addition, present emissions control requirements and laws are complicated and stringent, and emission control equipment represents a significant portion of the combustion equipment costs. Inadequately specified or applied control devices could result in very costly errors.

* Corresponding author. Tel.: +1-306-585-5225; fax: +1-306-585-4855.
E-mail address: christine.chan@uregina.ca (C.W. Chan).

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All of these factors need to be considered before a final decision on emission control strategy can be made. Thus, a dedicate emission control strategy needs to be selected for each power plant. Considering all of these factors simultaneously renders the decision for choosing the most economical control methods a difficult one for many utilities. As yet, there is no automated tool to help analyze and solve the control-method-selection problem. This gap in technology support can cause economic loss to the power plant and other adverse environmental impacts. Consequently, there is need for a new approach that can support decision makers so that the choice on emission control methods can be made accurately, quickly, and cost-effectively. In this study, an expert system for air pollution control called ES-APC was developed to support such a decision-making process.

The overall objective of this study is to develop an expert system that helps managers at a coal-fired power plant select a cost-effective emission control system. The system can generate the following results:

- The plant status, coal composition and selected control system
- Design specifications of the control system(s)
- Controlled and uncontrolled pollutant emissions
- Capital, operation and maintenance (O and M) costs involved

2. Background: pollution control for coal-fired power systems

Coal-fired electricity generating plants are the cornerstones of central power systems. Multitudinous innovative, low-cost environmental compliance technologies and efficiency-boosting innovations are being developed to preserve this economically vital energy foundation. Also, recently introduced and increasingly stringent ambient air standards demand more attention to development of advanced technologies. A brief review of recent innovations is discussed below.

According to the US Department of Energy (DOE), an integrated advanced system includes low emission boiler systems (LEBS), high performance power systems (HIPPS), integrated gasification combined cycles (IGCC), and pressurized fluidized bed combustion (PFBC). These subsystems will be examined through an integrated design approach (Harvey, Soung, & Massood 1999). In addition, three innovation technologies, which were designed to simultaneously reduce emissions of SO_2 and NO_x from existing coal-fired utility boilers, were examined by the Clean Coal Technology (CCT) projects. Among these, SNOX Flue Gas Cleaning consists of NO_x removal by selective catalytic reduction (SCR) and SO_2 removal by oxidation/hydrolysis to make sulfuric acid (H_2SO_4) which can achieve greater than 95% SO_2 emissions reduction and greater than 90% NO_x emissions reduction. Distinguishing features of the SNOX™ technology are high pollutant removal efficiencies and the production of sulfuric acid, which avoids the solid wastes associated with processes using sorbent injection. Another new technology SOX-NOX-Rox Box™ (SNRB™) Flue Gas Cleanup consists of SCR for NO_x control and dry sorbent injection for SO_2 control, which can reach 90% reduction of NO_x emissions, 70% reduction of SO_2 emissions with sodium-based sorbent, and particulate emissions below 0.03 lb/million Btu. A unique feature of the SNRBTM process is that all emissions reduction takes place within a high-temperature baghouse.

Research works concerning how to select among the cost-effective technologies are scarce. Maritta Koch-Weser developed a Fast Track Model to help select cost-effective, environmentally friendly technologies for coal-based power generation in countries grappling with impending power and capital shortages in the face of stricter environmental regulations. This report focused on plants greater than 100 MW_e in India and China. The Fast Track Model was built using four logical steps. This step design provided a tool enabling users to handle the large amounts of information that had to be considered in power plant projects. The best available control technology (BACT) provided instruction and guidance for preparing and evaluating the BACT (Texas Natural Resource Conservation Commission, 2001). There were many research works that concentrated on analyzing and evaluating a variety of control technologies. However, the focus of these studies are limited to evaluating individual control technology, or simply suggesting the concept of best technology selection. There has not been efforts devoted to developing an automated tool that can function as an integrated environmental control system for power plants. We propose that an expert system would be a good technology to fill this need.

Expert systems research has been ongoing for approximately 30 years and now encompasses a broad range of studies and applications, including environmental management. Over the last decade, expert systems have been used in a number of environmental engineering applications. Basri (2000) developed a prototype expert system, called the Leachate Management Advisor (LMA) to assist in the conceptual design of leachate management facilities in a sanitary landfill. The objectives of this system include: (1) establish the expected leachate production and its polluting potential, (2) recommend a policy for leachate containment, and (3) investigate whether lining, leachate collection or treatment is necessary. Kaplan developed a computer model called Integrated Air Pollution Control System (IAPCS) to evaluate pollution control systems for utility boilers (Kaplan, Pickett, Soderberg, & Meyers, 1994). This system illustrates that advanced computer-based controls are an essential component of the increasingly sophisticated environmental control systems being applied today.

Optimizing boiler operation and emissions performance requires embedding artificial intelligence or other advanced computer-based controls into a power plant's digital control system.

A CCT project at Georgia Power Company's 500 MW_e Plant Hammond demonstrated the importance and potential of artificial intelligence systems. The Generic NO_x Control Intelligent System (GNOCIS™) was installed at Plant Hammond and the plant subsequently achieved an efficiency improvement of 0.5%, a reduction in fly ash unburned carbon of 3%, and a NO_x reduction of 15%. GNOCIS™ is the result of a joint development effort by C and PS, EPRI, PowerGen, Radian International, Southern Company, and the UK Department of Trade and Industry. An estimated 35 plants, representing approximately 20,000 MW_e of capacity, have either installed or are in the process of installing GNOCIS™. Ralph Moshage developed Coal-Fired Central Energy Plant Operation Expert System (CEPES) to analyze and recommend solutions to coal-fired boiler operational problems. CEPES performed as an automated diagnostic tool for coal-fired central heating plant equipment. It reduced the demand for human labor freeing skilled personnel for higher priority work, reduced downtime for repair, promoted thermal efficiency, and improved online reliability.

In summary, expert systems for environmental management have been successfully applied to power plant operations. In particular there are some good examples for the application of such systems to coal-fired power plants. However, there has hitherto not been any attempt at developing an automated technology selection tool to support the power plant decision-maker. In this study, the attempt was made and an expert system was developed for the task.

3. Methodology

Successful selection of technology requires that all project-specific environmental, economic, and technical aspects are considered. In the emission control of a power plant, three pollutants including sulfur oxides, nitrogen oxides, and suspended particulate matter (PM) need to be simultaneously considered. To properly combine different control technologies is a complicated task. In order to clarify the procedure of technology selection, this task is decomposed into several sub-tasks:

1. Calculate the degree of pollutant over-standard emission (this assumes a proper emission standard should be established for each power plant);
2. Sort all the main emission control technologies according to their removal efficiencies;
3. Roughly classify the control methods according to the different combinations of control technology, to do this, a criteria table can be set up;
4. Locate the control method for different emission positions using a fuzzy set procedure;
5. Subdivide the control method into different design parameters and cost. For example, ESP will be regarded as one main particulate control device in step 2. However, it will be considered as several different methods in step 5 with different design parameters and costs. Select the most cost-effective control method according to the users' preference;
6. Use the Gaussian dispersion model to calculate the maximum ground concentration of the pollutant after treatment and assess the chosen control method.

These steps are discussed in detail as follows.

3.1. Control technology

The main pollutants emitted from power plants are PM, SO_2, and NO_x. There are a variety of removal technologies that have been employed for controlling these pollutants. In this section, some of the technologies will be inspected and then a comprehensive sorting of the technologies and their removal efficiencies will be presented.

Sulphur oxides (SO_x) are emitted from coal-fired combustion through oxidation of the sulphur contained in the fuel. Flue gas desulphurisation (FDG) control technology is used to remove SO_x either during or after the combustion of fossil fuels. Over the last decade, FGD technology has made considerable progress in terms of efficiency, reliability, and costs—as SO_2 emission regulations have become more stringent all over the world (Takeshita and Soud, 1993). Generally FGD was classified in the following five categories:

- Wet scrubbers;
- Spray dry scrubbers;
- Sorbent injection processes;
- Regenerable processes;
- Combined SO_2/NO_x removal processes.

The most common post-combustion process to reduce SO_2 emissions is wet scrubbing. With this technology, the sulfur-containing exhaust gases are 'scrubbed' with hydrated lime or limestone in a counter-flow reactor and the sulfate is force-oxidized to gypsum on the scrubber bottom. Wet scrubbers occupy 80% of the market and are used in large utility boilers (Takeshita and Soud, 1993) due to the high SO_2 removal efficiency achieved, the high reliability of the process, and the low operating costs involved. Limestone is generally used as the sorbent because it is available in large amounts in many countries and is cheaper than other sorbents. With the operation of spray dry scrubbers, lime slurry is usually sprayed to remove SO_2 from the flue gas. Spray dry scrubbers have a considerable share in the remaining market. Spray dry scrubbers are generally characterized by requiring lower

Table 1
Typical features of FGD systems

Control device	SO_2 removal (%)
Wet scrubbers	90–95
Spray dry scrubbers	85–95
Sorbent injection	50–70
Combined SO_2/NO_x regenerable	85–95

capital costs but higher operating costs than wet scrubbers, due to the use of more expensive sorbent (lime). Sorbent injection processes can be sub-divided into the categories of simple bubbler, spray chamber, packed tower, and spray tower. In regenerable processes, the spent sorbent is reused after thermal or chemical treatment to produce concentrated SO_2 which is usually converted to elemental sulphur. A number of combined SO_2/NO_x removal processes also have been developed with the aim of replacing conventional FGD/SCR processes. Combined SO_2/NO_x removal processes can be sub-divided into five categories and each of them employs a unique chemical reaction to remove SO_2 and NO_x simultaneously. From the data obtained in IEA, a comparison of typical features of FGD systems is shown in Table 1.

Technologies currently used to control particulate emissions from coal-combustion include:

- Electrostatic precipitation (ESP);
- Fabric filtration (baghouse);
- Wet scrubbing;
- Mechanical/inertial collection (cyclones/multicyclones).

ESP and fabric filters are the most widely used technologies for particulate control in utility coal-fired power generating facilities. The prevalent particulate control technology in industrial plants has been the cyclone but fabric filters are becoming more widely used in these facilities as well. Table 2 shows the achievable collection efficiencies (%, average) with the various particulate control devices, the data presented were supplied by the systems manufacturers and published by IEA (IEA coal research, 1997b).

Table 2
Ranges of collection efficiencies (%) and captured particle size (mm) with currently available particulate control technologies (IEA Coal Research, 1997b)

Control device	Removal efficiency (%)	Particle size range (μm)
ESP	>99.99	0.1–100
Fabric filter (baghouse)	99–99.9999	0.01–100
Wet particulate scrubber	90–99.9	0.5–100
Mechanical collector (cyclones/multicyclone)	75–99	1.0–100

Nitrogen oxides (NO_x) are formed during combustion. They have an important role in acidification, and are implicated in forest damage and human health effects in heavily populated areas through ozone formation. They also play a role in visibility degradation. The first action to control NO_x emissions, also known as primary measures, normally takes the form of combustion modifications. Where the limits on NO_x emissions cannot be met by combustion control, flue gas treatment must be installed. The dominant methods in use are SCR, selective non-catalytic reduction (SNCR) and combined processes for sulfur and nitrogen oxide removal. Consequently, to reduce the emissions of NO_x from fossil-fuel combustion, three principal technologies are available:

- combustion modifications (CM) and low-NO_x design of combustors;
- SNCR;
- SCR.

In the SCR method the NO_x concentration in the flue gas is reduced through injection of ammonia in the presence of a catalyst. Also, NO_x emissions can be controlled through thermal reactions by using appropriate reducing chemicals, which is called SNCR. SNCR is an attractive method because no catalyst is required.

Based on the data described previously, and also on the information from IEA, the domain expert, and the equipment supplier, a list of potential technologies for controlling three pollutants simultaneously was formulated and presented in Table 3. In the table, the control technologies are identified according to the removal efficiency. The remediation strategy represented by the ID number and the description of each method will be stored in the database of the expert system. The situation of single pollutant over standard is excluded because, in that situation, the choice of appropriate control technology is easily identifiable.

3.2. Fuzzy modeling for supporting decision of control strategies

Fuzzy set theory provides the basis for a method to describe uncertainty and vagueness. Since its introduction in 1965, fuzzy set theory has found applications in a wide variety of disciplines (Zimmermann, 1996). Many systems are not amenable to conventional modeling approaches due to the lack of precise or accurate information, strongly nonlinear behavior, high degree of uncertainty, or time varying characteristics. Fuzzy modeling along with other related techniques constitute powerful tools that can effectively reflect these uncertainties. Some basic notions in fuzzy set theory applicable to the domain of selection of control technologies are discussed as follows.

Table 3
Criteria for method selection under different removal efficiencies (for the three pollutants over-standard) (%)

Remediation strategy (ID)	1	2	3	4	5	6	7	8	9	10	11	12
PM	50	99	50	99	50	99	50	50	50	99	99	99
SO_2	70	70	85	85	90	90	70	85	90	70	85	90
NO_x	50	50	50	50	50	50	80	80	80	80	80	80

3.2.1. Membership function

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x)) | x| \in X\} \tag{1}$$

According to Zadeh's definition (Zadeh, 1965), if X is a collection of objects denoted generically by x, then a fuzzy set $\tilde{A}$ in X is a set of ordered pairs where $\mu_{\tilde{A}}(x)$ is called the membership function or grade of membership of x in $\tilde{A}$, which maps X to the membership space [0,1]. The numbers 0 and 1 define the membership of each element of the subset, where 1 means the element belongs to the subset and 0 means the element does not belong to the subset. The closer the membership value of $\mu_{\tilde{A}}(x)$ to 1, the more certain x belongs to $\tilde{A}$. The membership function is a crucial component of a fuzzy set, and operations with fuzzy sets are often defined via their membership functions.

3.2.2. Fuzzy relation

Fuzzy relations are fuzzy subsets of $X \times Y$, that is, mappings from X to Y. They have been extensively studied by Zadeh (1965 and 1971) and Kaufmann and Gupta (1988). Applications of fuzzy relations are widespread. Fuzzy relations in different product spaces can be combined with each other by the operation of 'composition'. Several versions of composition have been suggested which differ in their results and also with respect to their mathematical properties. The max–min and max–* composition has become the best known and the most frequently used one. However, often the so-called max-product or max–average compositions lead to results that are more appealing (Zimmermann, 1986).

Let $X, Y \subseteq R$ be universal sets; then $\tilde{R} = \{(x,y), \mu_{\tilde{R}}(x,y) | (x,y) \subseteq X \times Y\}$ is called a fuzzy relation on $X \times Y$. Let $\tilde{A} = (a_i | i = 1, 2, \ldots, m)$ be an n-dimension fuzzy vector, and $\tilde{R} = (r_{ij} | i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n)$ be an $m \times n$ fuzzy relation matrix. Then, an m-dimension fuzzy vector $\tilde{B}$ can be obtained as follows:

$$\tilde{B} = \tilde{A}\tilde{R} = (b_1, b_2, \ldots b_n) \tag{2}$$

The above process is called fuzzy transformation, where $\tilde{B}$ can be determined by a max-min or max-* composition (Zadeh, 1971) and also max–average composition. The max-min composition is defined as:

$$b_j = \sum_{i=1}^{m} (a_i \cap r_{ij}) = \max\{\min(a_1, r_{1j}),\ \min(a_2, r_{2j}, \ldots, \min(a_m, r_{mj})\}, \quad j = 1, 2, \ldots, n. \tag{3}$$

The max–* composition is defined as:

$$b_j = \bigcup_{i=1}^{m} (a_i r_{ij}) = \max\{(a_1 r_{1j}), (a_2^* r_{2j}), \ldots, (a_m r_{mj})\}, \quad j = 1, 2, \ldots, n \tag{4}$$

The max–average composition is defined as:

$$b_j = \max\{\mathrm{avg}(a_1, r_{1j}), \mathrm{avg}(a_2, r_{2j}), \ldots, \mathrm{avg}(a_m, r_{mj})\} \quad j = 1, 2, \ldots, n. \tag{5}$$

3.2.3. Fuzzy relation analysis for the selection of pollution control technology

When it is known whether the pollutant is over or under standard, the appropriate control technology can be selected. Since the selection of technology for a coal-fired power plant is a complex task, a number of uncertainty factors are assumed. Based on the fuzzy relational models described above, it was hypothesized that input–output variables were related by fuzzy relationships and represented in a relational matrix **R**. The relational matrix **R** represented the control strategy identification problem and contains every possible combination of input–output conditions with one value between zero and one for each condition. The matrix can be represented with a set of rules. Each value represents the degree of truth for each possible relationship. A value of 'one' indicates that the relationship is the strongest, and a value of 'zero' indicates that the relationship is the weakest.

Factors considered in the matrix **R** include the following. One crucial factor to distinguish among different technologies is pollutant removal efficiency, which is typically determined based upon applicable regulatory drivers. Some control technologies, such as ESP, can provide removal efficiencies of over 99%, while other technologies, such as cyclone, have lower efficiencies. The characteristics of the emission stream are also of critical importance in selecting an appropriate control technology. However, if more than one design or type of device can provide the necessary pollution control, then it becomes essential to choose the most cost-effective technology from among the feasible methods. There is no existing standard designed to identify a particular control technology with different emission situations. Numerous uncertain factors are involved, such as plant status and size, coal content, and a large number of technical and economic considerations. These uncertainties will be modeled using the fuzzy set methods as a step in the procedure of technology selection under uncertainty.

There are two objectives that should be achieved when selecting an appropriate method. The first one is that the ambient pollutant concentration should be reduced to the regulated standard point. In other words, the removal efficiency (η) of the chosen technology should cover the over-standard emission amounts. The second one is applicability of the proposed technology. A screening can be done to generate a series of applicable technologies with the desired removal efficiency (η). In this step, taking advantage of fuzzy set theory, an appropriate technology can be quickly identified from a large number of potential ones. The detailed procedure will be discussed below.

A fuzzy set representation can be set up as shown in Table 3. For the different combinations of the three kinds of pollutant removal efficiencies, there are several potential control methods. For example, in case j, the removal efficiency for PM is P_j, for SO_2 is S_j and for NO_x is N_j. In case j, if all the three removal efficiencies equal the desired removal rates, then method j will be chosen, with a membership value of $r_{ij} = 1$. If the combination of the three removal efficiencies is different from the mean value of method j but located within an acceptable range R_j, then the method is still identified as type j, with a particular membership value calculated using fuzzy membership functions.

From Table 3, the fuzzy relations can be initiated by first defining set X for different pollutants and set J for different cases as follows:

$$X = \{SO_2, PM, NO_x\}\ J = \{1, 2, 3, \ldots, n\}$$
$$= \{\text{Case1}, \text{Case2}, \text{Case3}, \ldots, \text{Case}n\}, \quad n = 28. \tag{6}$$

A fuzzy subset of $X \times J$, which is a binary fuzzy relation from X to J, can be characterized with the following membership function:

$$\tilde{R} : X \times J \rightarrow [0, 1] \tag{7}$$

Then, we have a fuzzy relation matrix as follows:

$$\tilde{R} = \{r_{ij} | i = 1, 2, 3;\ j = 1, 2, \ldots, n\} \tag{8}$$

where

$$i = \{1, 2, 3\} = \{SO_2, PM, NO_x\},$$

$$j = \{1, 2, \ldots, n\} = \{\text{case1}, \text{case2}, \ldots, \text{case}n\}.$$

In the above equation r_{ij} is the membership grade of pollutant i in different cases. As for r_{ij}, the standard value (in Table 3) is v_{ijk}. In this study, for the removal efficiency of SO_2, we graded it into four classes, whereas for the removal efficiencies of PM and NO_x, we graded them into three classes as follows:

when $i = 1$ (SO_2), $k = \{1, 2, 3, 4\} = \{0,70,85,90\}$,
when $i = 2$ (PM), $k = \{1, 2, 3\} = \{0,50,99\}$,
when $i = 3$ (NO_x), $k = \{1, 2, 3\} = \{0,50,80\}$.

When there are three pollutants under consideration, the desired removal efficiencies can be presented as follows:

$$\eta = \{\eta_i | i = 1, 2, 3\} \tag{9}$$

Therefore, the membership grade of fuzzy relation between given η_i and case j can be calculated as follows.

When ($i = 1$ and $k = 2, 3$) or ($i = 2$ and $k = 2$) or ($i = 3$ and $k = 2$), then:

$$\begin{array}{ll} \text{when } v_{ijk} \geq \eta_i \geq v_{ijk-1} & r_{ij} = (\eta_i - v_{ijk-1})/(v_{ijk} - v_{ijk-1}) \\ \text{when } v_{ijk-1} \geq \eta_i \text{ or } \eta_i \geq v_{ijk} & 0 \\ \text{when } \eta_i = v_{ijk} & 1 \end{array} \tag{10}$$

When (i=1,2,3, and k=1), then:

$$\begin{array}{ll} \text{when } v_{ijk+1} \geq \eta_i \geq v_{ijk} & r_{ij} = (v_{ijk-1} - \eta_i)/(v_{ijk+1} - v_{ijk}) \\ \text{when } v_{ijk} \geq \eta_i & 1 \\ \text{when } \eta_i = v_{ijk+1} & 0 \end{array} \tag{11}$$

When (i=1 and k=4) or (i=2 and k=3) or (i=3, k=3), then:

$$\begin{array}{ll} \text{when } v_{ijk} \geq \eta \geq v_{ijk-1} & r_{ij} = (\eta_i - v_{ijk-1}) \\ \text{when } v_{ijk} \leq \eta_i & 1 \\ \text{when } \eta_i < v_{ijk-1} & 0 \end{array} \tag{12}$$

Fig. 1 shows the membership function of method j corresponding to SO_2 removal efficiency. From the above analysis, a case combining three different pollutant control methods can be considered as a three-array fuzzy relation.

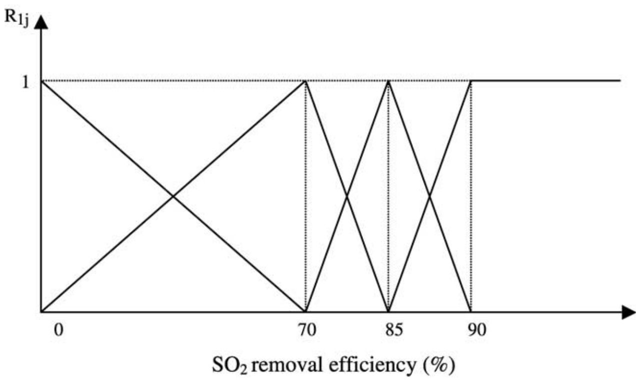

Fig. 1. Membership function of method j corresponding to SO_2 removal efficiency.

Let S, P, N be the universal sets, where $S, P, N \subseteq \tilde{R}$, then:

$$\tilde{R} = \{((S,P,N), \mu_{\tilde{R}}(s,p,n)) | (s,p,n) \subseteq S \times P \times N\} \quad (13)$$

where:

$$\tilde{S} = \{\mu_{1j} | j = 1,2,\ldots,28\},$$
$$\tilde{P} = \{\mu_{2j} | j = 1,2,\ldots,28\}, \quad (14)$$
$$\tilde{N} = \{\mu_{3j} | j = 1,2,\ldots,28\}$$

For this application, $\tilde{D}$ is defined as the membership functions of three pollutants belonging to 28 cases, respectively, where $\tilde{D} = \tilde{S} \times \tilde{P} \times \tilde{N} = \{d_1, d_2, \ldots, d_n\}$, $n = 28$. Then the fuzzy relation d_j, which represents the membership grade for case j to be selected, can be obtained by using the max–min, max–* or max–average composition. In this study, the max–average composition was employed because it better reflects the study conditions. The details are given as follows:

$$\begin{aligned} d_j &= \sum(\mu_{1j} \cap \mu_{2j} \cap \mu_{3j}) \\ &= \max\{\mathrm{avg}(\mu_{11}, \mu_{21}, \mu_{31}), \mathrm{avg}(\mu_{12}, \mu_{22}, \mu_{32}), \ldots, \\ &\quad \mathrm{avg}(\mu_{1n}, \mu_{2n}, \mu_{3n})\}, \quad n = 28. \end{aligned} \quad (15)$$

3.3. Pollutant emission standard

Actions to reduce pollutant emission are most often responses to the introduction of legislative and regulatory requirements. The emission standards for coal combustion vary from country to country. In general, the limits of particulate, SO_2 and NO_x emissions from fuel burning sources have tended to become more stringent. For example, when the Clean Air Act Amendments (Hermine, 1991) were passed, coal-fired utilities faced new emission standards for SO_2 and NO_x in two phases; the more stringent regulations took effect in 2000.

Standards to control particulate emissions from coal-combustion were first introduced early in the last century in Japan, USA and Western Europe. Over the subsequent decades, they became progressively more stringent and more widespread. Currently, over 30 countries have formulated standards for particulate emissions from coal-fired plants. The standards vary according to plant status and country. The ranges of limits for various sizes of boilers in some countries are listed in Table 4.

Recently, significant developments in NO_x control legislation have taken place, both nationally and internationally. Limits on NO_x emissions may take various forms but most countries have chosen to set standards for the concentration of NO_x emitted in flue gas. The way in which emission standards for NO_x are set varies among countries. More than 10 countries now have regulations setting national limits on NO_x emissions from coal combustion.

Table 4
Range of current national emission standards for particulate (mg/m^3) (McConville, 1997; IEA Coal Research, 1997a)

Country	New plants (mg/m^3)	Existing plants (mg/m^3)
Australia	90–280	–
Austria	50–280	50–280
Bulgaria	75–250	115–250
Canada	145	–
Croatia	50–105	200–215
Denmark	55	55–165
EC	50–100	–
Germany	50–150	50–150
Greece	50	50–150
India	150–350	150–350
Italy	50	50
Japan	50–300	50–300
New Zealand	105	105
Republic of Korea	50–100	50–100
Slovenia	50	125–150
Spain	50–100	200–750
Sweden	35	35
Switzerland	55–160	55–160
USA	37–123	37–123

Pressure to reduce SO_2 emissions resulting from the combustion of fossil fuels has led to the introduction of guidelines and regulations on a regional and national basis in many countries. Regulations became progressively more stringent and have resulted in large reductions in SO_2 emissions in some countries. Environmental legislation limiting SO_2 emissions has been adopted in many countries and is expressed in a number of different units. In most cases these are limits on the mass of pollutant emitted per unit of heat input based on gross or net heat value, or per volume of flue gas. In order to compare such standards, measurements were calculated at 6% O_2, 273 K and 101.3 kPa on dry flue gas.

3.4. Economic evaluation of control technologies

After identifying applicable technologies which can satisfy the emission standard regulations, the second step in selecting cost-effective control methods involves consideration of economic attribution. Generally, capital costs and operation/maintenance (O and M) costs reflect whether or not a technology is economically feasible. Another factor that needs to be taken into account is the space requirement of the technology. In this study, the capital and O and M costs for all the applicable technologies will be examined and compared. In some cases, space limitation will also be considered in making a decision. The related data such as coal content and boiler type are inserted into the method database as considerations in the economic evaluation. All the data came from the experimental works or equipment suppliers, published by the IEA and EPRI.

Electrostatic precipitators (ESP) and fabric filter are the most attractive technologies for particulate control in utility coal-fired power generating facilities when the power plant is facing the more stringent emission standard. Hence, research often focused on the improvement of these two kinds of technologies. Consequently, more details will be included on these two technologies. Original equipment manufacturers (OEMs) supplied pricing and key features of the control devices. Some design variables can significantly impact the cost of a particulate control device. For example, flue gas volumetric flow rate will greatly affect the capital cost of ESP. Therefore, the method database needs to include the design parameters as well as other factors relevant in the economic evaluation of the technologies. For example, each record of Baghouse (Reverse-gas baghouse) in the method database includes the important design parameters such as the length of the bag and the bag material as well as the A/C ratio which is needed in the method demonstration.

There are many innovations about reducing SO_2 emissions from coal utilization. These include fluidized bed combustion (FBC) and IGCC power generation. However, as a mature technology, FGD still occupied the major part of the market for SO_2 control. For each system, they can be divided in terms of parameter design and system performance. For example, wet scrubbers include a variety of FGD processes using lime/limestone, dual alkali, sodium-based sorbent, seawater, ammonia and so on. Even for wet limestone scrubbers, these can be generally classified into four types in terms of whether prescrubber and/or oxidation vessels exist or not. In this study, all the typical FGD systems were inspected with respect to capital costs, levelised cost and power consumption when it is necessary. The detailed information were inserted in the method database of the expert system.

Technologies currently employed in coal combustion of NO_x emission control are generally categorized into combustion measures and flue gas treatment. In addition, the main alternatives for low NO_x combustion are applicable to different conditions, particularly the type of fuel and combustion. The flue gas treatment was mainly known as the SCR, SNCR and combined SO_x/NO_x processes. A breakdown of the levelised costs of SNCR and SCR has been given in Table 5. Few processes are in operation using simultaneous desulphurisation and denitrification of the flue gases. The cost data of those processes were included in the method database.

Thus, to evaluate whether a control technology is suitable for a power plant, the decision-maker needs to consider the technology's efficiency, economic factors, coal type, and plant size. The important design parameters can significantly affect the removal efficiency and control cost. Hence, the method database includes the control methods as well as information on plant size, plant status, boiler type, coal type, sulfur content, and description of the methods' key design parameters. Except for the efficiency and cost data, all the factors are included in the database. The structure and some of the records of the method database are shown in Fig. 2. The approach of the expert system is to scan all the feasible control methods stored in the method database and calculate the cost for each one according to the user's preference, and then select the most cost effective control strategy.

Table 5
A breakdown of the levelised costs of SNCR and SCR (Cochran et al., 1993)

	SNCR	SCR
1997 Total capital costs, 1000	12,820	35,390
1997 Total levelised costs ($/kWh)	27.9	76.9
Fixed charge on capital ($1000/yr):		
1997 O and M costs, ($1000/yr)	1010	2800
Power consumption	1180	1090
Maintenance	380	3610
Reagent consumption	2000	520
Loss of fly ash sale	2010	0
Fly ash landfill	600	0
Force outage rate increase	4400	1100
Total	10,570	6320
1997 total levelised costs ($1000/yr)	11,580	9120
1997 total levelised costs (mills/kWh)	4.4	3.5

3.5. Gaussian model for simulating ambient pollutant concentrations

It is necessary to calculate the ambient concentrations of the pollutant emitted from a power plant after the treatment because they are the bases for assessing environmental impacts and risks from the plant. Various dispersion models have been devised for the prediction of atmospheric pollution, including over 100 types of models for different applications (Leung, 1995). Selection of a proper model is essential because an exaggerated prediction can lead to unnecessary control measures. Conversely, a model that under-predicts ambient pollutant concentrations may result in expensive retrofit control measures. The model that is most frequently used as the basis for air pollution calculations is the Gaussian plume model, which is also incorporated into ES-APC. (Fig. 3) The details are provided in Appendix A.

4. Development of ES-APC

Selecting the most cost-effective emission control strategy is the most difficult and costly technical problem for coal-fired-plant operators. ES-APC is a decision support system that aims to recommend a feasible scheme that can satisfy the environmental regulations as well as the minimum cost requirements for the plant. Confronted with the problem, a decision maker often would select

metho	name	scale_lo	plant sta	boiler	efficier	efficienc	efficienc	capital_c	o&m_cost	method description
82	combustion modif	210	retrofit	Tanger	0	0	45	36	0	Natural gas reburning
83	combustion modif	100	retrofit	Tanger	0	0	45	45	0	Natural gas reburning
84	combustion modif	300	retrofit	Wall	0	0	60	14	1246	Natural gas rebNatural gas
85	combustion modif	300	retrofit	Wall	0	0	60	16	1822	Natural gas reburning
86	combustion modif	300	retrofit	Wall	0	0	60	18	2396	Natural gas reburning
87	combustion modif	500	retrofit	all	0	0	60	30	280	Natural gas reburning
88	combustion modif	500	retrofit	all	0	0	60	30	0	Natural gas reburning
89	combustion modif	500	retrofit	all	0	0	60	30	0	Natural gas reburning
90	combustion modif	500	retrofit	all	0	0	60	30	0	Natural gas reburning
91	combustion modif	500	retrofit	all	0	0	85	40	550	Natural gas reburing + sele
92	combustion modif	500	retrofit	all	0	0	70	50	270	Natural gas reburning + low
93	combustion modif	110	retrofit	cyclon	0	0	49	67	110	Reburing using pulverised
94	combustion modif	605	retrofit	cyclon	0	0	53	43	420	Reburing using pulverised
95	Flue gas treatmer	200	retrofit	Wall	0	0	80	148	1650	
96	Flue gas treatmer	200	retrofit	Tanger	0	0	80	148	2640	
97	Flue gas treatmer	200	retrofit	Wall	0	0	80	148	2640	combined with combustion
98	Flue gas treatmer	200	retrofit	Tanger	0	0	80	148	3520	combined with combustion
99	Flue gas treatmer	250	new	All	0	0	80	70	0	
100	Flue gas treatmer	250	retrofit	All	0	0	80	200	0	
101	Flue gas treatmer	460	new	Wall	0	0	47	70	0	5 ppmv NH3 slip with Com
102	Flue gas treatmer	460	new	Wall	0	0	47	77	0	2 ppmv NH3 slip with Com
103	Flue gas treatmer	100	retrofit	Wall	0	0	80	122	2358	5 year catalyst life
104	Flue gas treatmer	300	retrofit	Wall	0	0	80	88	1803	5 year catalyst life
105	Flue gas treatmer	500	retrofit	Wall	0	0	80	80	1681	5 year catalyst life

Fig. 2. The structure and partial records of the method database.

an approach that is most familiar or most easily available to him/her. Unfortunately that scheme may not be the most appropriate or the most cost effective one. Hence, ES-APC addressed a gap in the literature and helps to support the decision maker by first analyzing a large amount of information and data from various sources and then recommending a reasonable method.

ES-APC consists of three basic components, including the knowledge base, the inference engine, and the user interface. The knowledge base contains facts, definitions, heuristics and computational procedures applicable to the problem domain or subject area to which the expert system is applied. The inference engine processes the knowledge base during the reasoning processes (Han and Kim 1989), and uses an interpreter to decide how to apply the rules to infer new facts and conclusions (Waterman, 1986). The user interface is the means by which the user communicates with the system. It supports the user inputting the data required by the expert system and enables the system to provide answers to the system user. The basic structure of the expert system ES-APC is shown in Fig. 4. Details on the system development process and the system will be presented as follows.

4.1. Knowledge acquisition

The process of knowledge acquisition aims to build the knowledge base. Knowledge acquisition has been recognized as one of the more problematic stages of expert system design. This critical phase involves gathering knowledge from the sources of expertise and representing that knowledge (Greenwell, 1988). The two main sources used were: (1) knowledge from the domain experts; and (2) knowledge from prior research and publications such as articles and books.

To acquire knowledge from experts, interviews were conducted. The experience of domain experts is crucial in the development of this expert system. The selection of technology for a coal-fired power plant is a complicated and site-specific task because it involves the evaluation and optimization of a large number of technical and economic considerations. The particular situation in each power plant is important because the control strategy for a new power plant will differ from that of an existing plant. The domain experts had much

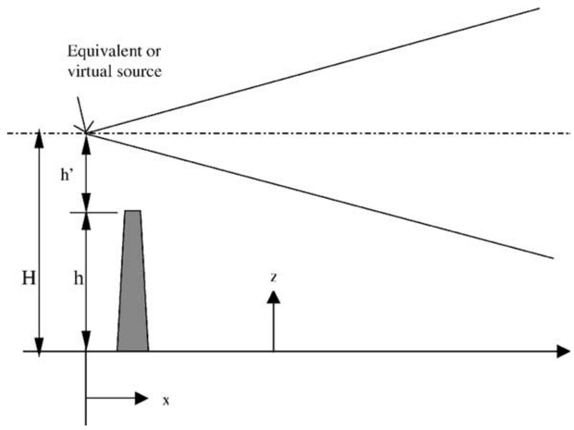

Fig. 3. A dispersion model with virtual source at an effective stack height H.

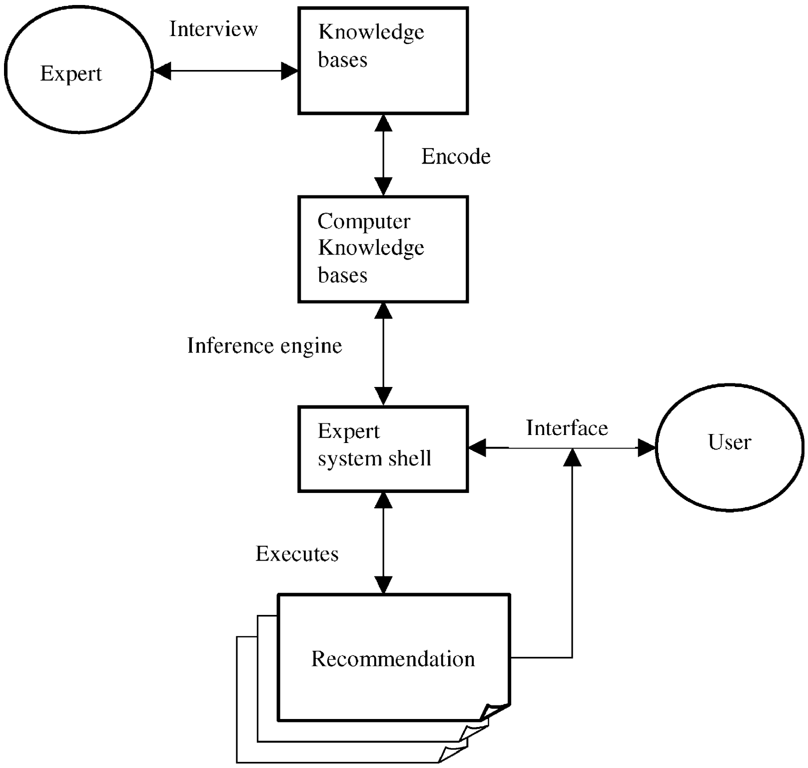

Fig. 4. Basic structure of expert system.

experience and knowledge on air pollution control and management, and their comments and suggestions on various cases were incorporated in the system.

The second source of knowledge was publications. The parameters and data on the technologies used in this work are mainly from the following published sources:

International Energy Agency (IEA) coal research. IEA coal research is a collaborative project established in 1975 involving member countries of the IEA. It contributes to promoting a wider understanding of the key issues concerning coal, with special emphasis on clean coal technologies and security of supply. The database of emission standards and the technology removal efficiency table were taken from IEA.

Electric Power Research Institute (EPRI). EPRI is recognized as a world leader in creating technology and marketing solutions for the energy industry and for the benefit of the public. The main objective of EPRI is to help solve today's toughest energy problems and to develop strategic vision and planning for science and technology.

4.2. Knowledge analysis

The domain knowledge acquired was analysed using the Inferential Modeling Technique (Chan 1992, 1995). The IMT is a domain independent, top-down technique that can be used in conjunction with bottom-up techniques such as protocol analysis for analysing elicited expertise in a domain. With the technique, the knowledge engineer can decompose the main task into several subtasks. This decomposition process will continue until each subtask can be tackled easily. In this system, the main task is to identify the appropriate emission control method for a given coal-fired power plant. The method selection will depend on parameters such as power plant location, the emission over-standard degree and technology cost evaluation etc. Then the subtasks will be related to these parameters during the decision processes. Thus the main task structure is shown in Fig. 5.

Decision trees can be used to express both the main task and the subtasks. The main decision trees corresponding to the decision processes for determining the emission level and technology evaluation are shown in Figs. 6 and 7, respectively. Each leaf of the decision trees represents an action to be performed by the expert system.

4.3. Inference engine

The inference engine is responsible for the reasoning process. The knowledge base consists of encoded knowledge on the domain of expertise, which can be in the form of production rules. These rules occur in sequences and are expressed in the form of: if ⟨conditions⟩ then ⟨actions⟩, where if the *conditions* are true then the *actions* are executed. Two methods of inference often used are forward and backward chaining. Forward chaining uses facts as they become available to satisfy conditions in rules. When

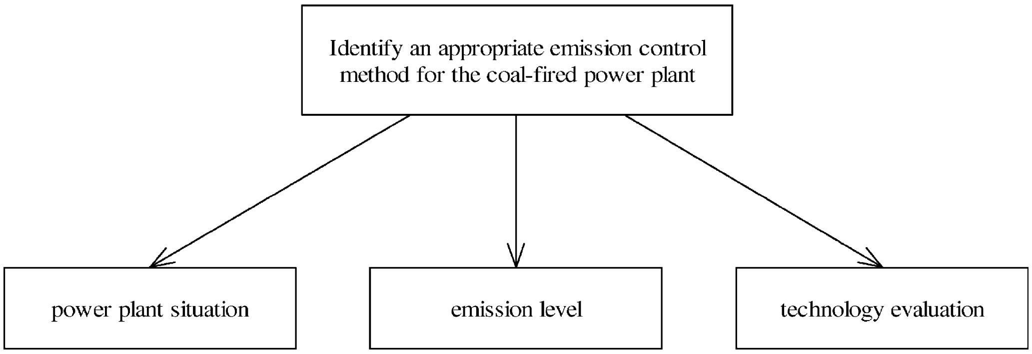

Fig. 5. Structure of main task.

the conditions are satisfied, the actions in the consequent are executed. In other words, the objective of forward chaining is to move the problem state forward from its initial state to one satisfying the goal. Backward chaining is the reverse. It starts with goals (or actions), and queries the user about information that may satisfy the conditions contained in the rules. In this study, we infer the cost-effective control method based on the user's input information. Therefore the inference engine in ES-APC operates by forward chaining.

5. Implementation of ES-APC

ES-APC was implemented in Visual Java++ (VJ++), which is a graphical object-oriented development toolkit using the Java language. VJ++ has three distinguishing characteristics which renders it suitable for developing an expert system. First, the software can operate on different platforms with little modification. That is, with minor modification, this expert system can run in Windows or Windows NT, as well as Unix. Second, the database can convert to other database systems such as Oracle and MS SQL server. Since the system is relatively small, the MS Access database was used in ES-APC. Finally, VJ++ supports a user-friendly interface that is easy to operate even for persons unfamiliar with the expert system and the computer. This section describes first the structural framework of the ES-APC and each component of the system. Then some display screens from the system will be presented.

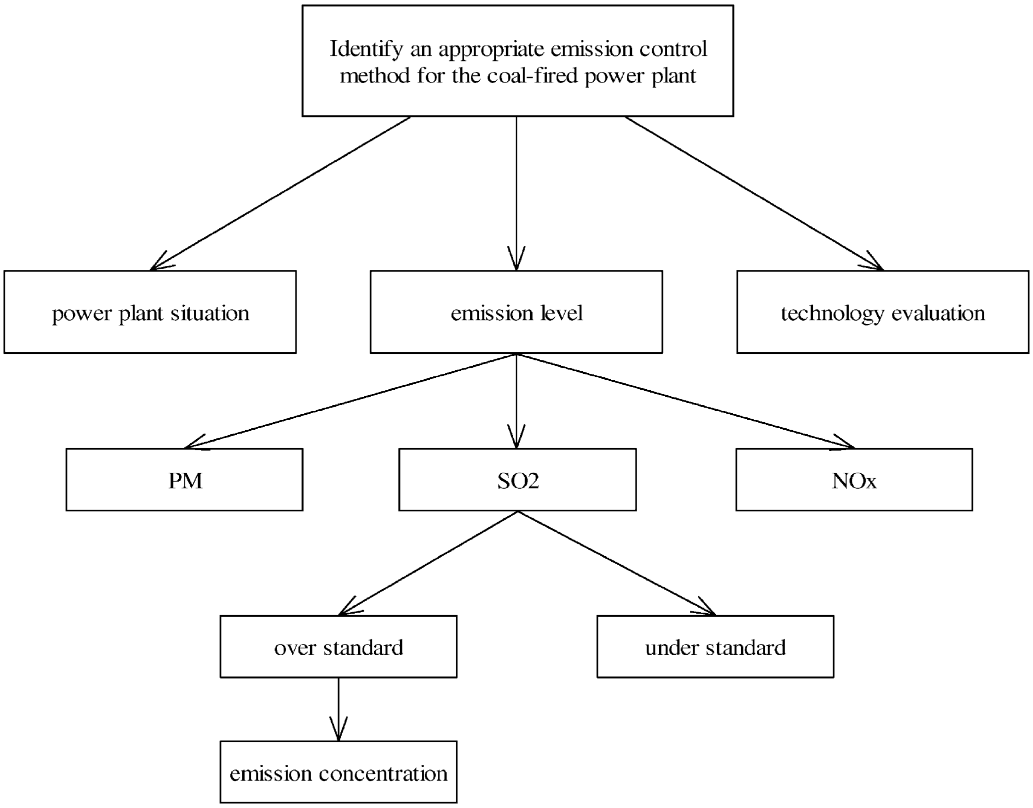

Fig. 6. Decision trees for determining the emission level.

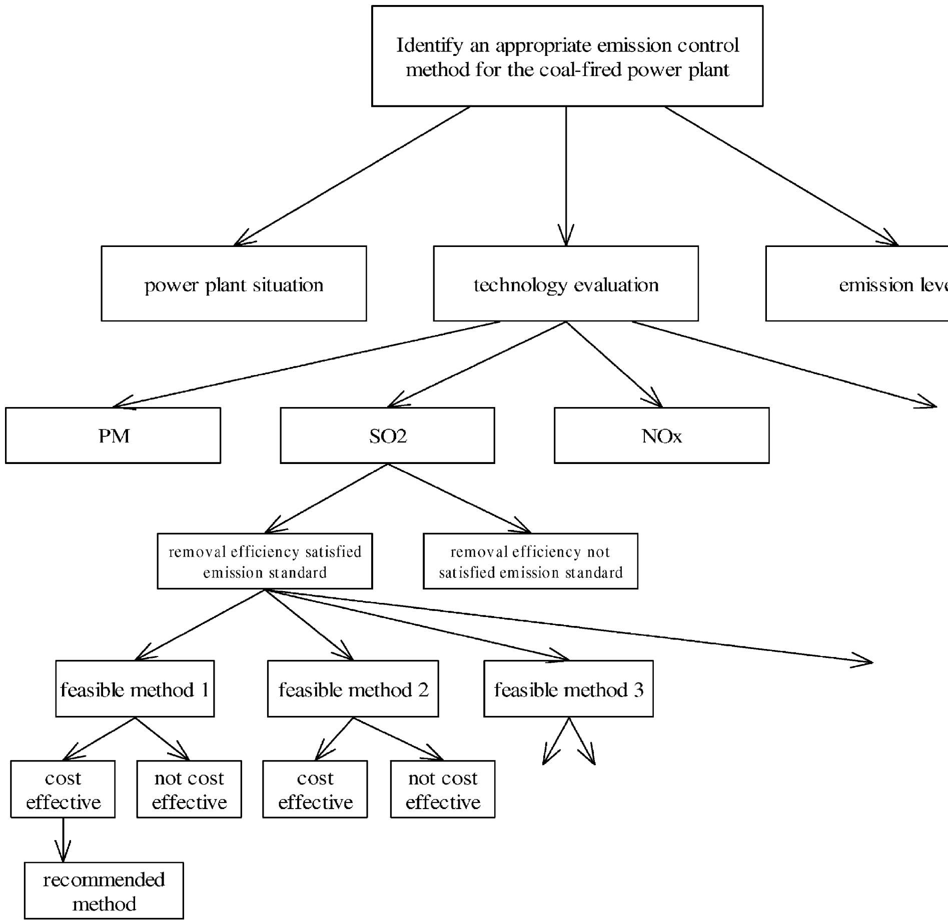

Fig. 7. Decision tree for determining control method.

5.1. Structural framework of ES-APC

ES-APC consists of seven modules as shown in Fig. 8. These modules include (1) the Graphical User Interface (GUI), (2) data input/output (I/O) module, (3) Gaussian dispersion module, (4) standard validation module, (5) fuzzy set module, (6) economic evaluation module and (7) database maintenance module. Except for the GUI, each module is composed of several process components. Each module is described as follows.

The main functional components of some of the modules are shown in Fig. 9.

(1) GUI

The GUI of the expert system supports the functions of: data input and output, Gaussian module, standard validation, database maintenance, economic evaluation, and final reporting. The GUI was built with the Java language and includes menu, push-button, and drop-list which facilitate user operations.

(2) Data Input/Output Module

The different input and output data for ES-APC are:

- Plant data required includes the location and size of the plant, which affect the selection of emission standards and final result. For instance, a power plant located in Canada will have different emission standards from one located in the USA.
- The Gaussian dispersion model requires input data on flue gas flow rate, temperature, wind speed and stack height, etc. This module uses a Gaussian model to calculate maximum pollutant concentrations according to user specifications. For example, users can choose either a full meteorology or a single stability class of meteorology; also they can choose the simple elevated or flat terrain option.
- *Coal content input*. The content of ash and sulfur in a particular kind of coal will affect the selection of the control technology.
- *User preference input*. This system offers users two options about the technology's economic evaluation: (1) capital cost, and (2) operation and maintenance cost (or levelised cost). The system will derive the weight for each option according to the user's preference and then select the most economical method.
- *Mid-term report output*. Based on the users' inputs, the system can generate the pollutant concentration that will be compared to the emission standard. The mid-term report informs the user on whether the pollutant concentration is over-standard as well as on the degree of over standard for each pollutant.

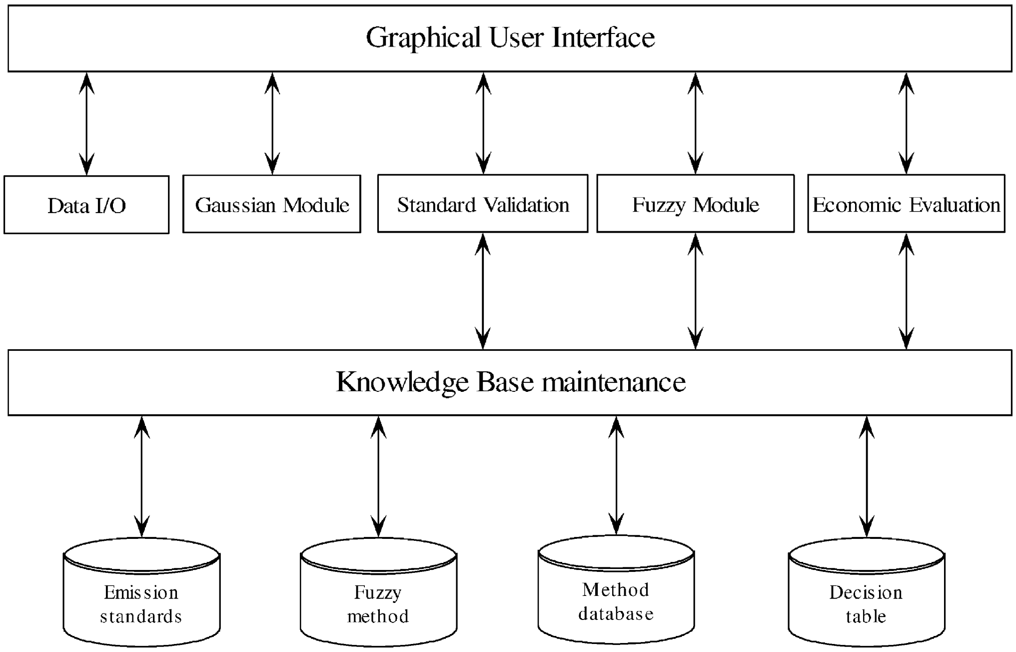

Fig. 8. Structural framework of the ES-APC.

- *Final report output*. The final report informs users about pollutant concentration after treatment. A detailed description of the chosen control method as well as the key design parameters are included in the final report output.
- *Input data validation*. This module will examine the user inputs and display a dialog box to inform users when the input data are invalid. For example, if a user is supposed to input a number for the stack height and the user inputs an alphabet descriptor instead, the system displays an error message.

(3) Gaussian dispersion model module

In this module, the system will calculate the maximum ground concentrations of pollutants after treatment using a Gaussian dispersion model. To enhance the likelihood that the result would approximate the real situation, the system provides the user with several options:

- *Urban/Rural option*. This choice is based upon land use or population density.
- *Meteorology*. A full meteorology analysis will examine all stability classes and wind speeds. Users can also specify a single stability class or a single stability class with wind speed.
- *Simple elevated or flat terrain option*. Simple elevated terrain is where terrain heights exceed stack base but are below stack height; simple flat terrain is where terrain heights are assumed not to exceed stack base elevation.

(4) Standard validation

Standard validation is conducted in two steps:

- Select the proper emission standard for each plant according to the input data about plant location, size and status. According to the IEA, emission regulations depend on the plant status and size and also vary from country to country. Usually a new and large plant will face more stringent regulations. Based on input data on the plant, the system scans the emission standard database and selects the appropriate standard for the plant;
- After the most cost-effective control strategy was selected for the plant, the Gaussian model can be used to generate the maximum ground concentration, which is compared to the ambient air quality standard to ensure the selected control method can satisfy the governmental regulation. The comparison result is shown in the final report.

(5) Fuzzy set module

This module consists of a set of criteria for the control strategy under different concentrations for each pollutant; the criteria are presented in Table 3. The set of criteria helps to determine the proper control strategy according to pollutant concentrations.

(6) Economic evaluation module

Two evaluation steps are involved in this module: First, based on the criteria in the fuzzy set model, the system eliminates technologies with removal efficiencies that could not satisfy the emission regulation. Then, for each individual plant, all the remaining technologies will be displayed with the associated cost data. The cost data include (1) capital cost, (2) operating and (3) maintenance cost, space requirement, as well as key design parameters. Secondly, the system sets weights for the three different

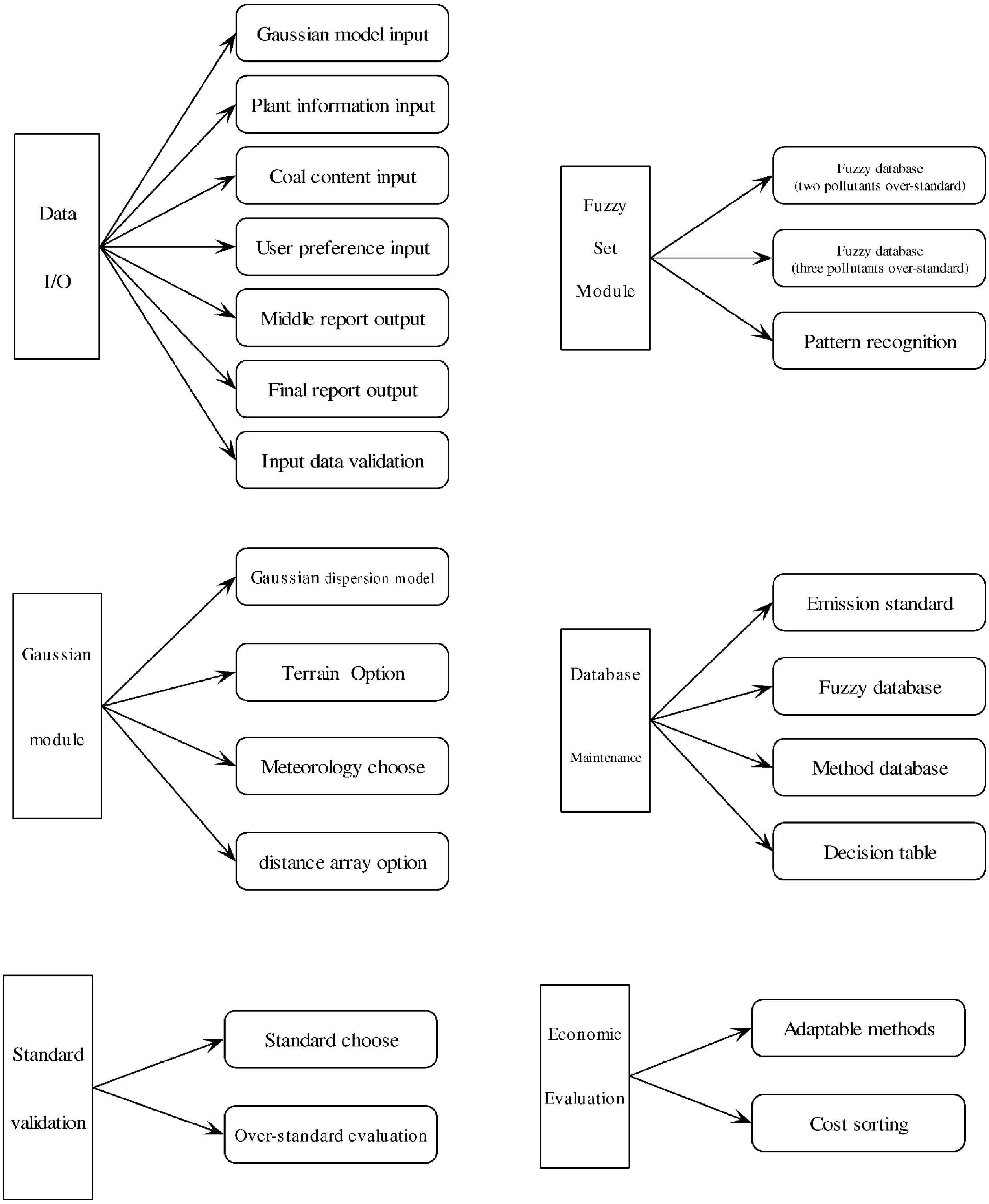

Fig. 9. Main functional components of the modules.

costs based on user preferences and calculate the costs of all feasible technologies. Then ES-APC selects the most cost-effective method for the plant.

(7) Database maintenance module

This is an important module for two reasons: (1) Since there are five databases included in this expert system, it is important to have a special module to maintain them. (2) Enhancements made to the database can help to maintain the expert system. In the future, it is inevitable that new technologies will become available while some old technologies will become obsolete. Faced with this situation, the system can easily add the new technologies and remove the obsolete technologies. In addition, some incomplete databases can be completed in the future. For instance, the SO_2 emission standard database includes the standards for only five counties. If more data on standards of other countries can be included, the expert system will have more comprehensive application. Fig. 10 shows the maintenance module for the database of pollution control methods.

5.2. Operation of the ES-APC

The processing logic of ES-APC is represented as shown in Fig. 11. A brief user manual is presented as follows. To Start ‘Expert System for Air Pollution Control’, double click the ‘ES_APC’ icon. ES-APC is a MDI (Multiple Document Interface) program. This system supports two ways to approach system functions such as system design and data maintenance: (1) by clicking quick-buttons in the tool bar; (2) by selecting menu items to execute system functions. The main steps for system operation include:

- *Input design data in main system*. To design an air pollution control system using ES-APC, users first input data on pollutant concentration, power plant size, location, status, the type and content of coal, stack height, and wind speed. The data input screen is shown in Fig. 12. The input data on this screen enables the system to choose the correct emission standard and select the appropriate emission control strategy for each plant. Specifically, the data on pollutant concentration, power plant size, and location can help the system to determine the emission standard to be used.
- *Display stack air information*. After all the data input required by the system are entered, the user can press the ‘Next’ button and the stack air information report screen will appear. This system output screen provides users with information about which pollutant is over-standard and indicates the pollution degrees in percentages. The system uses two colors to distinguish whether the pollutant is under standard or over standard. If the number is displayed in green, the emission is under standard; if the number is displayed in red, the emission exceeds the standard. To help the user understand the system, this report will also include the emission standard and the concentration for each pollutant. The degree to which the pollutant was over standard was considered as the desired removal efficiency of the control technology.
- *Display fuzzy analysis results*. The system output interface displays the result of fuzzy analysis and selected method to the user. This interface also enables users to select the priority among considerations of capital cost, operation and maintenance costs, which will affect the final decision. The capital cost, operation and

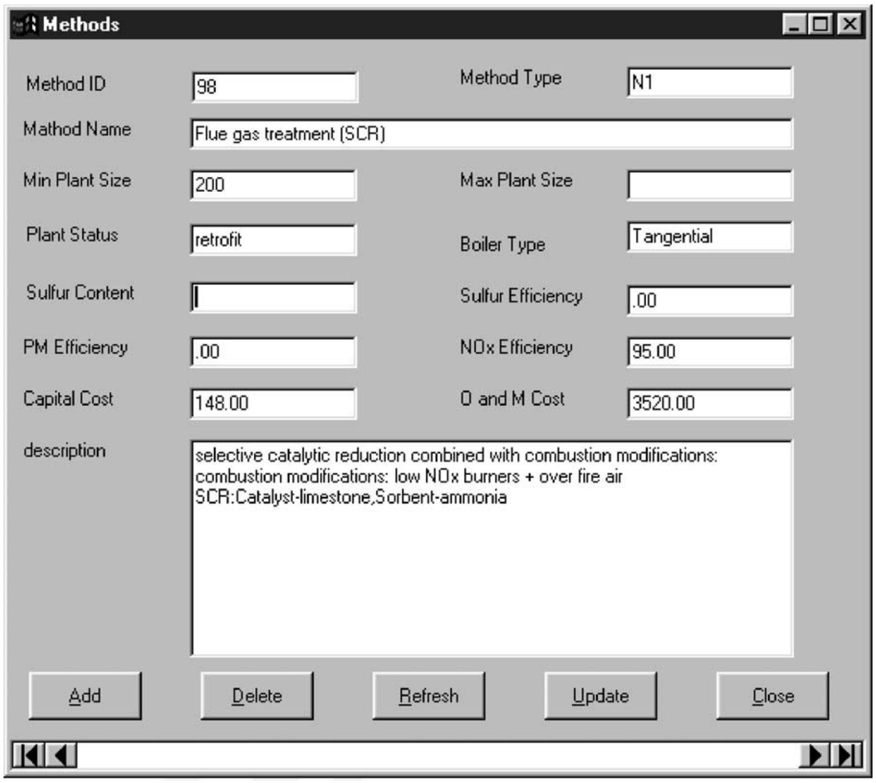

Fig. 10. Database maintenance module for pollution control methods.

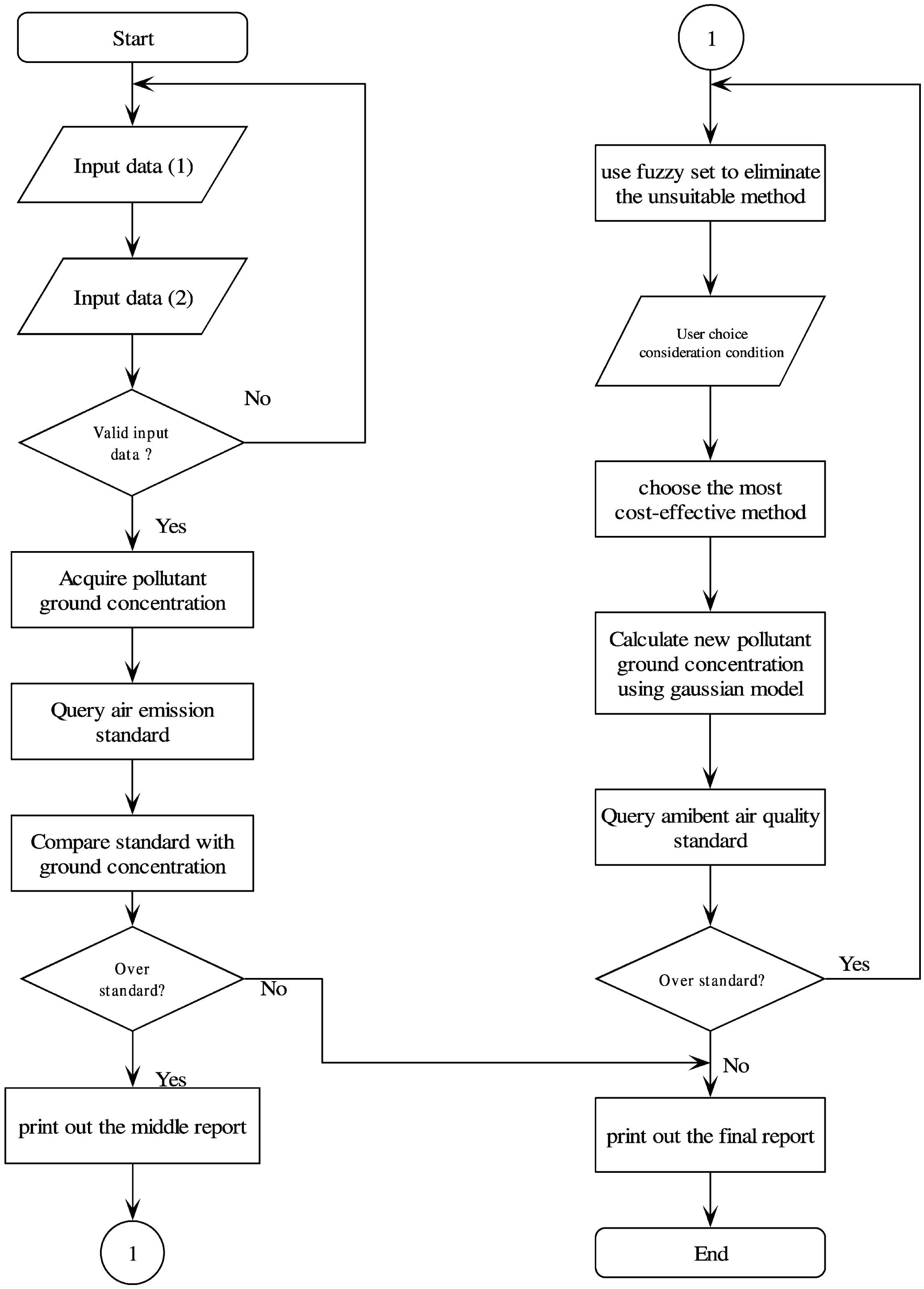

Fig. 11. System process flow chart.

maintainance cost or levelised cost are the main factors to account for different economical evaluations even for the same technology. Based on user specifications on the ranked priorities, the system can recommend the most cost-effective method for the plant. This interface is shown in Fig. 13.

- *Display method report*. The method report interface informs users which control method is suitable for the plant while satisfying environmental requirements. As well, detailed information on the selected method is also displayed. For example, if the ESP was chosen as the control technology for PM, the value of the selected air-pollution control technology will be given in the method description. The removal efficiency of the selected method as well as the total capital, operating and maintenance costs are also given in this report. Fig. 14 shows a sample method report.

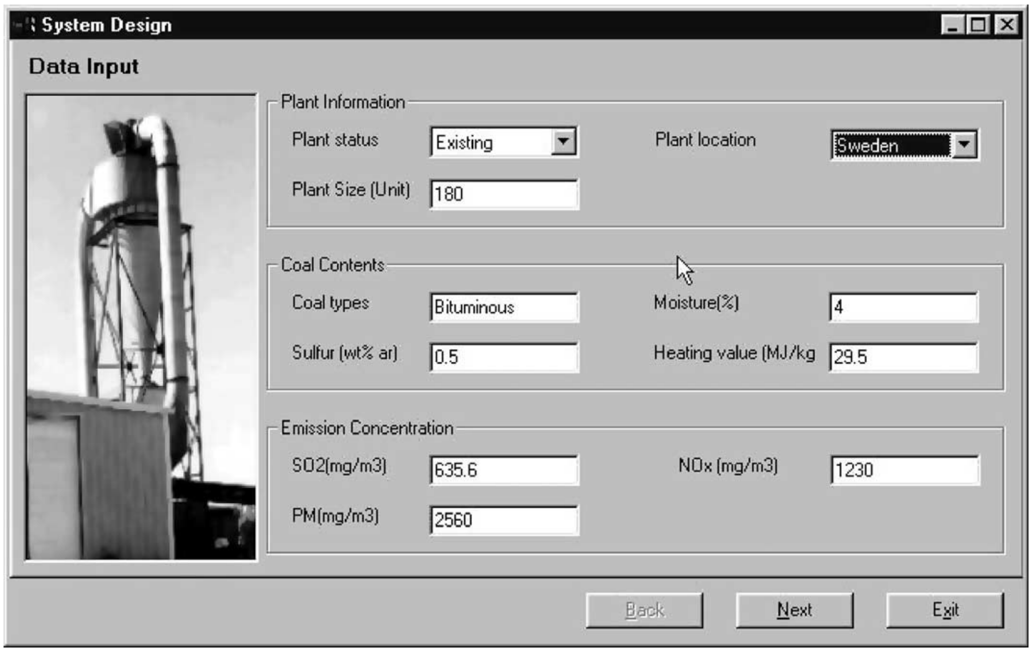

Fig. 12. Screen for input of power plant data.

- *Display Gaussian model report*. This is one of two input screens of the system. It queries the user for data for the Gaussian model, which includes the stack height, inside diameter, temperature, ambient air temperature and pollutant emission rate. The user also needs to specify the options on meteorology and urban/rural selection. The Gaussian model interface is depicted in Fig. 15, and the Gaussian dispersion model calculates the maximum ground concentration. The expert system then compares the results generated with the ambient air quality standard. The final comparison results are displayed to the user in a screen similar to the stack air information interface.

5.3. Application of ES-APC to a power plant in Sweden

The data of a power plant in Sweden are used to illustrate how ES-APC selects a control method for a coal-fired power plant. Table 6 presents detailed information about this plant, which are taken from the IEA coal research CoalPower 3

Fig. 13. Fuzzy analysis interface.

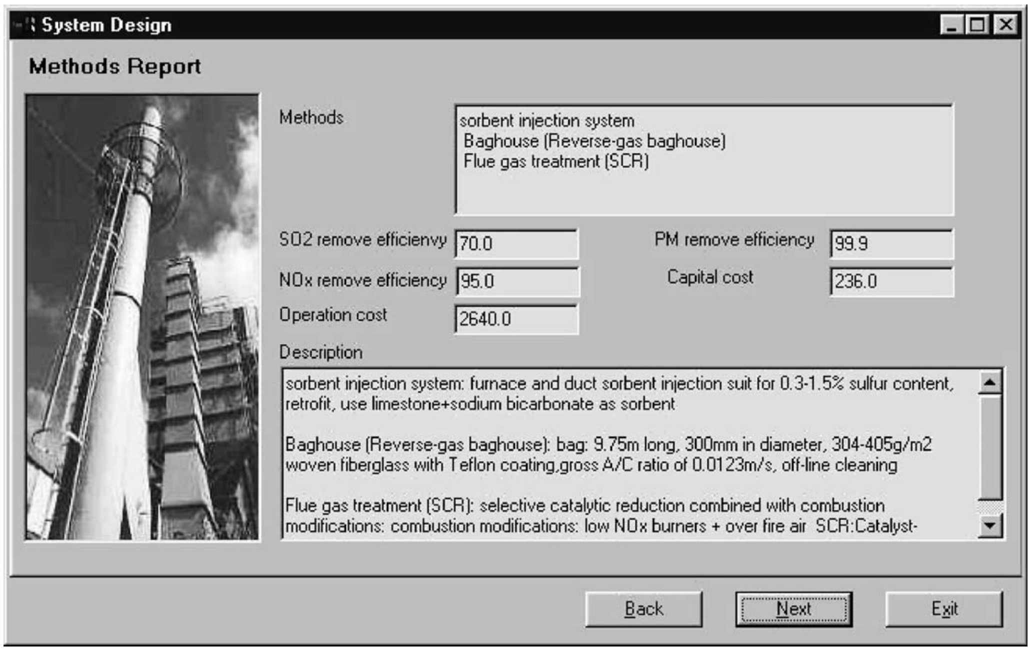

Fig. 14. Method interface.

database (IEA Coal Research—The Clean Coal Centre, 2001). The detailed unit information is shown in Table 7. The regional emission standard for Sweden is shown in Table 8.

From the above input data and emission standards, stack information before treatment can be obtained as shown in Table 9. With the fuzzy set model, the system identifies a control strategy for the power plant under a relatively low emission level for SO_2 and relatively high ones for NO_x and PM. Then the user can assign weights to the economic consideration of capital cost, operating and maintenance (O and M) costs. For example, if the user specified 0.3 for capital cost and 0.7 for O and M cost, then the system would display the selected method and its description in the method report screen. There are several parts in the method report, and the detailed information on

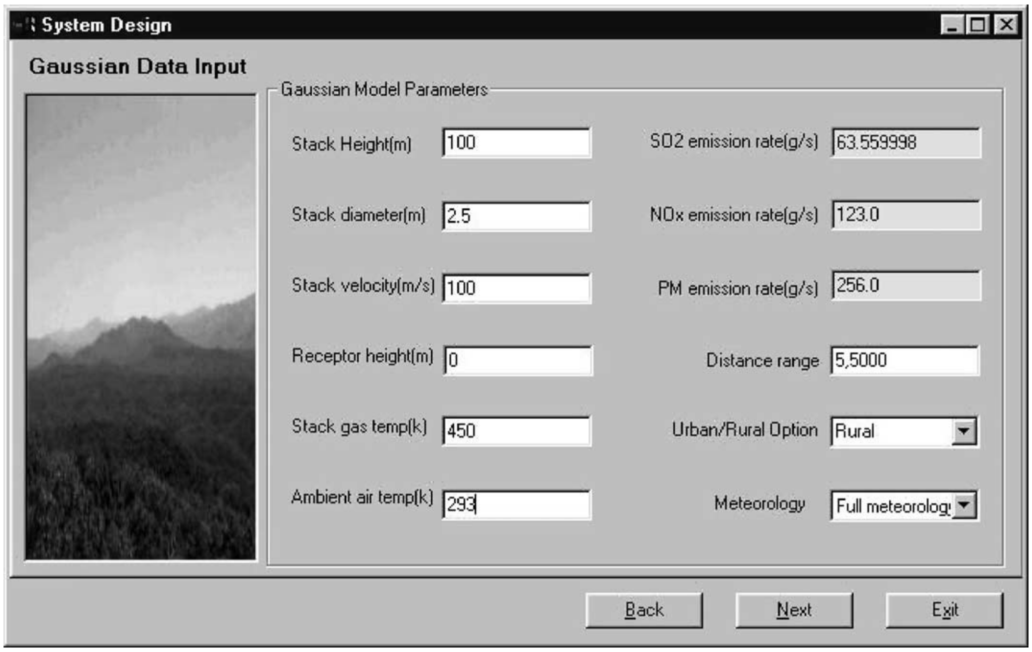

Fig. 15. Gaussian model interface.

Table 6
Power plant information

Ownership	Vaesteraas Stads Kraftvaermeverk AB, Sweden
Number of unit	4
Unit breakdown (MW_e)	2 × 40, 1 × 180, 1 × 250
Capacity (Mw_e)	510
Status	In operation
Coal types	Bituminous
Heating value (MJ/kg)	29.5
Sulfur (wt% ar)	0.5
Ash (wt% ar)	7
Moisture (%)	4

the report is shown in Table 10. Then, the Gaussian dispersion model in the system calculates the pollutant maximum ground concentration. The after treatment pollutant concentration is then compared with the ambient air quality standard to verify that the selected method reduces the power plant emissions to a satisfactory level. The Gaussian model data input and results are shown in Table 11.

6. Conclusions

ES-APC is a rule-based expert decision support system that assists decision-makers in coal power plants select cost-effective pollution control systems. In the process of system development, a variety of methodologies and tools were employed and integrated. First, knowledge acquisition using the Inferential Modeling Technique was conducted with the domain experts. Second, fuzzy set theory was adopted to represent the uncertain factors that affect the selection decisions. Third, the Gaussian model was used for accurately simulating ground concentrations.

A key characteristic of ES-APC is that it provides users with a flexible control strategy given complex and uncertain specifications. The system's recommendation of control methods is based on user preferences. The over hundred control methods stored in the method database belong to 10 groups of principal control technologies with different key design parameters. The costs and removal efficiencies of these techniques also vary dramatically. Hence the selection process can be complex. The result from the case study indicates that the developed system

Table 7
Detailed unit information

Plant status	Vaesteraas Sweden unit 1	Vaesteraas Sweden unit 2	Vaesteraas Sweden unit 4
Unit status	In operation	In operation	in operation
Unit Capacity (MWe)	40	40	180
Steam temperature (°C)	540	540	540
Boiler information	Pulverized coal (PC); front wall fired; dry bottom	Pulverized coal (PC); front wall fired; dry bottom	Pulverized coal (PC); tangentially fired; dry bottom
Sulfur dioxide emitted (mg/m^3)	635.6	953.3	635.6
NO_x emitted (mg/m^3)	1640	1640	1230
PM emitted (mg/m^3)	2230	2230	2560
Flue gas temperature (°C)	150	150	150

Table 8
Power plant emission standard in Sweden

Plant status	PM (mg/m^3)	SO_2 (mg/m^3)	NO_X (mg/m^3)
Existing combustion plants, all size	35	270	135–270
New combustion plants, plant size < 500 MWt	35	270	135
New combustion plants, plant size > 500 MWt	35	160	80

Table 9
Stack information for power plant

Pollutant	Emission standard (mg/m^3)	Current emission (mg/m^3)	Desired removal efficiency (%)
SO_2	270	635.6	58
PM	35	2560	99
NO_x	135	1230	89

Table 10
Pollution control methods for the power plant

Method	FGD (sorbent injection system), Flue gas treatment (SCR), and Baghouse (Reverse-gas baghouse)		
Removal efficiency (%)	SO_2	NO_x	PM
	70.0	95.0	99.0
Cost	Capital cost ($/kWe)	O and M cost ($/t of pollutant removed)	
	2640	236	
Description of method	FGD (sorbent injection system): retrofit, use limestone + sodium bicarbonate as sorbent Baghouse (Reverse-gas baghouse): bag = 9.75 m long, 300 mm in diameter, 304-405 g/m^2 woven fiberglass with Teflon coating, gross A/C ratio of 0.0123 m/s, off-line cleaning SCR: selective catalytic reduction combined with combustion modifications, combustion modifications (low NO_x burners + over fire air), use: catalyst—limestone, sorbent—ammonia		

Table 11
Inputs for Gaussian model

Inputs for Gaussian model			
Stack height (m)	100		
Stack diameter (m)	2.0		
Stack velocity (m/s)	100		
Stack gas temperature (K)	540		
Ambient air temperature (K)	273		
SO_2 emission rate (mg/m^3)	63.56		
NO_x emission rate (mg/m^3)	123		
PM emission rate (mg/m^3)	256		
Distance range (m)	5, 5000		
Urban/rural option	Urban		
Meteorology option	Full meteorology		
Ambient air quality (after treatment)			
Pollutant	Standard (μg/m^3)	Concentration (μg/m^3)	Over-standard
SO_2	365	24.09	No
PM	150	7.769	No
NO_x	100	0.3234	No

can help power plant managers reduce costs of pollution control and risks of environmental damage by selecting an appropriate control technology.

In this study, the cost of different control methods were evaluated based on user preferences. While economic evaluation of different control methods is important, there are considerable problems involved in comparing costs. This is true not only for plant by plant comparisons for similar sources, but also for data from suppliers and operators of various control technologies. To handle the complex data involved in this selection task, ES-APC adopts the fuzzy set theory. In the future, a multi-objective programming model can be adopted for economic evaluation. ES-APC can be easily extended in the future by updating the standard database and the control-method database in order to enhance completeness of the knowledge base.

Currently, ES-APC only considers three pollutants. In the future, a broader range of pollutants can be addressed. For example, a growing concern involves the serious effects of mercury-emission hazards from coal-fired power plants. Thus, control technologies for mercury reduction would be an important consideration in future studies. Furthermore, while this study reports on development of a model-based expert system for supporting decisions of air pollution control selection, the presented approach for developing an expert decision support system can also be applied to areas of water pollution control and solid waste management.

Appendix A. Gaussian model for simulating ambient pollutant concentrations

A.1. The Gaussian model

For the point source such as a stack, the general appearance of the plume might be represented by the schematic shown in Fig. 3. For a point source at an elevation H above the ground, the basic Gaussian dispersion equation for the physical situation shown in Fig. 2 was specified as follows (Kenneth Wark, 1981):

$$C = \frac{Q}{2\pi\mu\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2} + \frac{(z-H)^2}{\sigma_z^2}\right)\right] \quad \text{(A1)}$$

where

C, concentration (g/m^3);
Q, emission rate (g/s)
μ, stack height wind speed (m/s)
σ_y, lateral dispersion parameter (m)
σ_z, vertical dispersion parameter (m)
h_e, plume centerline height (m)
H, mixing height (m)

This equation was based on assumptions of steady state, negligible mass diffusion in the x-direction, a constant wind speed μ at all positions, and constant mass diffusivities in the respective coordinate directions.

A.2. The modified Gaussian model in ES-APC

In this study, the modified Gaussian model is used to simulate the maximum ground concentration of each pollutant. The modified Gaussian equation and the data used to estimate some parameters in this section are based on the SCREEN3 model (USEPA, 1995). With this modified Gaussian model, users are provided with various options including the most plausible conditions. For example, this model examines all the following options: simple elevated or flat terrain option, rural or urban option, choice of meteorology, automated distance array option, discrete distance option.

For a steady-state Gaussian plume, the hourly concentration at downwind distance x (m) and crosswind distance y (m) is given in following equation (Touma, 1995):

$$\chi = \frac{QKVD}{2\pi u_s\sigma_y\sigma_z}\exp\left[-0.5\left(\frac{y}{\sigma_y}\right)^2\right] \quad \text{(A2)}$$

where:

χ, concentration (μg/m^3)
Q, pollutant emission rate (mass per unit time)
K, a scaling coefficient to convert calculated concentrations to desired units (default value of 1×10^6 for Q in g/s and concentration in μg/m^3)
V, vertical term
D, decay term
σ_y, σ_z, standard deviation of lateral and vertical concentration distribution (m)
u_s, mean wind speed (m/s) at release height

The equation for calculating Vertical Term (V), Decay Term (D), wind speed (u_s) and dispersion parameters (σ_y *and* σ_z) will be discussed as follows:

A.2.1. Wind speed (u_s)

The wind power law (Touma, 1995) was used to adjust the observed wind speed, u_{ref}, from a reference measurement height, z_{ref}, to the stack or release height, h_s.

$$u_s = u_{ref}\left(\frac{h_s}{Z_{ref}}\right)^p \quad \text{(A3)}$$

where p is the wind profile exponent. The user may provide values of p as a function of stability category and wind speed class.

A.2.2. The dispersion parameters $\sigma_{y,z}$

Equations that approximately fit the Pasquill–Gifford curves (Turner, 1970) are used to calculate σ_y and σ_z (in m) for the rural mode. The equations used to calculate σ_y are of the form:

$$\sigma_y = 465.11628(x)\tan(\mathrm{TH}) \quad \text{(A4)}$$

$$TH = 0.017453293[c - \mathrm{d}\,\mathrm{Ln}(x)] \quad \text{(A5)}$$

The equation used to calculate σ_z is of the form:

$$\sigma_z = ax^b \quad \text{(A6)}$$

where coefficients a, b, c and d were determined by Briggs as reported by Gifford (1976) and represent a best fit to urban vertical diffusion data reported by McElroy and Pooler (1968).

A.2.3. Vertical term (V)

The Vertical term (V), accounts for the vertical distribution of the Gaussian plume. It includes the effects of source elevation, receptor elevation, plume rise, limited mixing in the vertical, the gravitational settling and dry deposition of particulates. In general, the effects on ambient concentrations of gravitational settling and dry deposition can be neglected for gaseous pollutants and small particulates, which were less than about 0.1 μm in diameter. The Vertical Term without deposition effects is then given by:

$$V = \frac{\sqrt{2\pi}\sigma_z}{Z_i} \quad \text{(A7)}$$

where Z_i, mixing height (m); and at downwind distances, the σ_z/z_i ratio is greater than or equal to 1.6.

A.2.4. The decay term (D)

The decay term in Eq. (A2) is a simple method of accounting for pollutant removal by physical or chemical processes. It is specified as:

$$D = \begin{cases} \exp\left(-\psi \dfrac{x}{u_s}\right) & \text{for } \psi > 0 \\ = 1 & \text{for } \psi = 0 \end{cases} \tag{A8}$$

where

ψ, the decay coefficient (s^{-1}) (a value of zero means decay is not considered)
x, downwind distance (m)

For example, if $T_{1/2}$ is the pollutant half-life in seconds, the user can obtain ψ from the relationship as follows:

$$\psi = \frac{0.693}{T_{1/2}} \tag{A9}$$

The default value for ψ is zero. That is, decay is not considered in the model calculations unless ψ is specified. However, a decay half-life of 4 h ($\psi = 0.0000481\ s^{-1}$) is automatically assigned for SO_2 when modeled in the urban mode (Touma, J.S. 1995).

The above analysis demonstrates that this modified Gaussian model is an an adequate tool to estimate the pollutant concentration; it provides the user with diverse options and simulates a complex situation that is akin to reality. This model was integrated into the expert system to assess the effectiveness of the chosen method.

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