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Research Article

Mathematical Safety Assessment Approaches for Thermal Power Plants

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How to use system analysis methods to identify the hazards in the industrialized process, working environment, and production management for complex industrial processes, such as thermal power plants, is one of the challenges in the systems engineering. A mathematical system safety assessment model is proposed for thermal power plants in this paper by integrating fuzzy analytical hierarchy process, set pair analysis, and system functionality analysis. In the basis of those, the key factors influencing the thermal power plant safety are analyzed. The influence factors are determined based on fuzzy analytical hierarchy process. The connection degree among the factors is obtained by set pair analysis. The system safety preponderant function is constructed through system functionality analysis for inherence properties and nonlinear influence. The decision analysis system is developed by using active server page technology, web resource integration, and cross-platform capabilities for applications to the industrialized process. The availability of proposed safety assessment approach is verified by using an actual thermal power plant, which has improved the enforceability and predictability in enterprise safety assessment.

1. Introduction

Prevention and mitigation of accidents for over a century have had great impact on process industries such as power industries and chemical industries [1]. Many scientists have been working on methodologies and technologies to resolve safety problems in process plants that can diagnose primary faults in process systems [2–8]. The methodology research, such as fault tree analysis (FTA) and cause consequence analysis (CCA), of safety assessment for thermal power plants is very important, considering management safety, environment protection, and safety in equipment operation, which can change safety factors from uncontrolled status to controlled status [9]. Experts are still searching for ideal mathematical models for safety assessment that include fuzzy mathematics, cluster analysis, and osculating value method of multiobjective decision. Some pertinent mathematical models of system safety assessments are necessary for analyzing accident causes on process industries.

Preponderant system functions are used to analyze structure effect and cooperation mechanisms [10–12]. These functions have been used for safety assessment of thermal power plants, but there are concerns when constructing the Delphi weight judgment matrix of combined index awkwardly, because it is strenuous processing when the judgment matrix is exceptionally large. There will be problems of a lack of data sources and a defect of high level subjectivity, so it is difficult to compute the influences among the factors in a system accurately. The analytic hierarchy process (AHP) is widely used in systems of thermal power plants and other fields [2]. It has been combined with entropy weighting, artificial neural networks, and other methods and often combined with fuzzy mathematics to create the fuzzy analytical hierarchy process (FAHP) [13–15]. FAHP is replacing AHP in several academic fields including machinery evaluation and risk evaluation, because it better represents the fuzzy features of systems. Otherwise, the set pair analysis (SPA) is used to analyze systematic relations, systematic forecasts, systematic evolutions, and other uncertain problems [16–18].

An integrated mathematical modeling approach for thermal power plant safety assessment is proposed in this paper. The safety status can be obtained by constructing preponderant functions of the system safety, and the nonlinear structural layers will be constructed by FAHP and SPA, respectively. An AHP-based safety assessment decision analysis system (SADAS) will be developed by using ASP.NET technology for identifying the systemic hazard evaluation and real time performance evaluation in the safety engineering.

System structure and cooperation functions utilize index weight to judge the matrix by Delphi method at first and then use AHP to quantitative analysis. But when there are many indexes, relationship judgment matrix of combination factors becomes so very large that it is not easy to be obtained in reality. So, it is difficult to implement.

Every kind of factor, which influencing the safety of thermal power plant, is analyzed by using the perspective of system analysis approaches. According to present situation of safety assessment for power plants, a mathematical model and approach for them are proposed, in which the key factors influencing the power plants safety are considered; on the basis of establishing multihierarchy valuation structure for power plants, A synthetic safety assessment model for power plant was constructed by combining fuzzy analytical hierarchy process (FAHP), set pair analysis (SPA), and system functionality, in which the key factors influencing the power plants safety were considered, and interaction among the factors influencing the power plants safety was analyzed quantitatively; a preponderant function of system safety was constructed by use of the result to solve the problem that the system safety function preponderates over the weight sum of safety functions of subsystems. Based on this, the UML and C#.NET is used to design and develop assessment components. A simulation system for safety assessment platform is developed. The instances show that the systemic question and real time assessment problem in the safety analyses assessment are resolved; maneuverability and wide adoption are improved. The model can integrate immanence relation and nonlinearity influence of factors in power plant, which make safety assessment more reasonably, and it can also offer scientific foundation for decision-making in safety management.

2. Safety Assessment Approaches

2.1. System Functionality. System functionality reflects the emergence of objective systems, and is used to solve linear and nonlinear contribution problems of each subsystem for a complex objective system. The system function can be defined in active scope of the system, optimized as the structure evolves. The holistic behavior at the system is not equal to the algebraic sum of subsystems or parts usually. Various energy and attribute integration functions can emerge from the combined resources (e.g., human beings, materials, equipment, environment, management, software, data, etc.) in a complex industrial system. Assume X describes the system safety of thermal power plants, x describes the important factors in the system, that is, $x = (x_1, x_2 \dots, x_n) \in X$, and W describes the system holistic behavior. The preponderant function of system safety can be defined as a mathematical formula as follows:

$$\begin{aligned} w &= \varphi(x_1, x_2, \dots, x_n) \\ &= \sum_{i=1}^{n} \alpha_i x_i + \sum_{i>j=1}^{n} \alpha_{ij} x_i x_j + \sum_{i>j>k=1}^{n} \alpha_{ijk} x_i x_j x_k \\ &\quad + \cdots + \alpha_{12\cdots n} \prod_{i=1}^{n} x_i, \end{aligned} \tag{1}$$

where the sum of $\alpha_i x_i$ describes the linear contribution to system safety and the high order terms represent the nonlinear contributions to the system safety. The preponderant function of system safety is the emergence of the system mathematical model. This is the system of linear and nonlinear problems and also is the system structure function of cooperation and cooperative function problem.

In the formula (1), the first summation term in the right of equation is described the linear contribution of important factors, and the rest of summation terms means the nonlinear cooperative relationship of the factors. The effect of cooperative relationship is not only associated with their values (x_1, x_2) but also associated with the match appropriateness. That is to say, management injects energy into the system, so-called management energy or other functions, of course. The functional coefficient α describes a corresponding cooperation quantity in the objective system. The factors interact with each other in the system and the effect produced is related to respective activities and mutual cooperation, which is embodied by α. Evaluating security state of the system can be obtained, comparing the preponderant function value of system and the system function optimal value. The W value measures system security value. Observers determine the minimum security value of the system by experience.

2.2. Fuzzy Analytical Hierarchy Process. FAHP provides a basis for choosing key factors through calculating their weights for a given objective and ameliorates some disadvantages (such as difficulty in estimation consistency of judgment matrix, distinction that contrasts the judgment matrix with the human thinking) of AHP. FAHP has been used in many domains [2]. Some basic analysis steps of FAHP are summarized as follows [13].

Step 1 (construction of hierarchy). The first step of FAHP is to determine all the important criteria and their relationship in the form of a hierarchy, which is very crucial because the selected criteria can influence the safety assessment. The hierarchy structure can be determined from the target layer through the intermediate layer to the bottom layer.

Step 2 (definition of the new fuzzy comparison matrix). The criterion on the same layer of the hierarchy is compared with each of the criteria from the upper layers. A pairwise comparison is performed by using a triangular fuzzy number that employs 0.1–0.9 scales. The scale ranges from 0.1 for "*absolutely less than*" to 0.5 for "*equal*" to 0.9 for "*absolutely more than*" covering the entire spectrum of the comparison.

A triangular fuzzy number regarding a given value can be denoted by (L, M, U), which represent the minimum value, most-likely value, and maximum value of the fuzzy number, respectively. The reverse judgment is treated as complementary and reversed order of the fuzzy number of the corresponding judgment. For example, suppose that criterion B_1 compared with criterion B_2 is "more important" and denoted by fuzzy number (0.6, 0.75, 0.9) and the reverse judgment B_2 compared with criterion B_1 is "less important" and described by $(1-0.9, 1-0.75, 1-0.6)$, namely, (0.1, 0.25, 0.4). After the upper triangular matrix is completed, the lower triangular matrix is filled with the element of its reverse judgment. The upper level factor A dominates the lower level factors $B_1, B_2 \cdots B_n$. The b_{ij} denotes the relative importance of criterion B_i compared with criterion B_j in the same hierarchy.

Suppose a matrix A of order n; when $b_{ij} = (l_{ij}, m_{ij}, u_{ij})$ and $b_{ji} = (l_{ji}, m_{ji}, u_{ji})$ are elements of matrix A of order N, they possess the following properties:

$$A = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \cdots & \cdots & \cdots & \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix},$$
$$l_{ij} + U_{ji} = 1, \qquad m_{ij} + m_{ji} = 1, \qquad u_{ij} + u_{ji} = 1,$$
$$i \neq j, \quad 1 \leq i, \quad j \leq N, \tag{2}$$
$$l_{ii} = 0.5, \quad m_{ii} = 0.5, \quad u_{ii} = 0.5, \quad 1 \leq i \leq N.$$

The judgment matrix A is triangular fuzzy number complementary judgment matrix.

Step 3 (calculation of local weight of order vector). Triangular fuzzy weight vector q_i is defined in (3), using fuzzy numbers $b_{ij} = (l_{ij}, m_{ij}, u_{ij})$ and $b_{ji} = (l_{ji}, m_{ji}, u_{ji})$ of matrix A. Vector q_i represents the fuzzy relative weight of each factor. The formula to compute relative weight vector q_i of every couple criteria denoted by triangular fuzzy number is given by

$$q_i = \left(\frac{\sum_{j=1}^{n} l_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} u_{ij}}, \frac{\sum_{j=1}^{n} m_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} u_{ij}}, \frac{\sum_{j=1}^{n} u_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} u_{ij}} \right), \quad i, j \in N. \tag{3}$$

There are two relative weight vectors of random element, represented as $q_i = (x_i, y_i, z_i)$ and $q_j = (x_j, y_j, z_j)$, respectively, and the element of possibility degree matrix P_{ij} that represents possibility degree of $q_i \geq q_j$ can be calculated by formula (4). The possibility degree matrix P is still a triangular fuzzy number complementary matrix:

$$P_{ij} = \lambda \max\left\{1 - \max\left\{\frac{y_j - x_i}{y_i - x_i + y_j - x_j}, 0\right\}, 0\right\} + (1-\lambda)\max\left\{1 - \max\left\{\frac{z_j - y_i}{z_i - y_i + z_j - y_j}, 0\right\}, 0\right\}, \quad i, j \in N, \tag{4}$$

where λ specifies the risk attitude of decision-makers. When $\lambda > 0.5$, the decision-maker is optimistic (tolerant of risk); when $\lambda = 0.5$, the decision-maker is neutral to risk; when $\lambda < 0.5$, the decision-maker is pessimistic (averse to risk).

Lastly, the local weight of order vector can be computed by getting a priority vector of possibility degree matrix $P(p_{ij})$. The element of the order vector is given by

$$w_i = \frac{\sum_{j=1}^{n}\left(p_{ij}\right) + (n/2) - 1}{n(n-1)}, \quad i \in N, \tag{5}$$

where w_i is the ith criterion weight, where $w_i > 0$ and $\sum w_i = 1$, $1 \leq i \leq N$.

Step 4 (calculation of general weight of element). The general weight of the criterion regarding the ith subcriterion is denoted by R. This safety evaluation hierarchy is a tree structure, so R can be computed by the following recursion formula:

$$R_i = \begin{cases} 1, & i \in \text{RootNode} \\ w_i \times R_{F(i)}, & i \notin \text{RootNode}, \end{cases} \tag{6}$$

where R_i is the general weight of the ith criterion, $R_{F(i)}$ is the general weight of the father criterion, $F(i)$ is the father criterion of the ith criterion, w_i is the local weight of ith criterion, and i is the node that represents risk factor.

2.3. *Set Pair Analysis.*

Set pair analysis (SPA) is used to analyze systematic relations, systematic forecasts, systematic evolutions, and other uncertain problems [17]. When applied to connection degree and combined with system functionality, it can be a simple way to construct the preponderant function of system safety avoiding subjective quantify.

2.3.1. *Connection Degree.*

A set pair is composed of two sets A and B, namely, $H = (A, B)$. The connection degree is the key to SPA, which describes the differences between A and B. It can be applied to the study of the relationship between certainty and uncertainty in a macroscopic system. Connection degre μ between A and B is denoted as follows:

$$\mu = a + b_i + c_j, \tag{7}$$

where $i, j \in [-1, 1]$ is a stabilization coefficient for a set pair and a, b, and c are the degree of identity, the degree of discrepancy, the degree of opposition, respectively, for the set pair. Moreover, $a, b, c \in [0, 1]$, and $a + b + c = 1$.

2.3.2. *The Features of SPA.*

Through the connection degree μ, SPA can be used to analyze and process various uncertain problems such as those caused by fuzzy, stochastic, and incomplete information. The main feature of SPA is that SPA accepts all kinds of uncertainties objectively in the real world and analyzes and processes various uncertain problems as well as the relationship between definitiveness and changefulness through three aspects: identity, discrepancy, and opposition. A method of obtaining the connection degree of safety factors in thermal power plants from routine inspection data is proposed in this paper, which represents the application of SPA in the field of safety assessment.

2.4. Integrated Analysis Approaches. A mathematical integrated safety assessment approach is presented to design and develop a safety assessment decision support system to cope with the increasingly important industrial system safety, combining with the theories of FAHP, SPA, system functionality, and so forth.

2.4.1. System Hierarchy Description for Safety Assessment. The enterprise safety assessment for thermal power plants is the decision-making goal, the hierarchical structure of which is composed of three levels, the target layer A, the criteria layer B, and the subcriteria layer C. The factors affecting the system safety are considered as criteria and the architecture is as shown in Figure 1. As shown in Figure 1, invited experts use the 0.1–0.9 scale for comparisons of every index to get the original triangular fuzzy number judgment matrix, each factor weight vector q denoted by triangular fuzzy number, and possibility degree matrix p.

The hierarchy of the system includes two contexts. The first one is a physical or vertical hierarchy where the subordinate relationship exists between lower layer and upper one, and subcriteria possess a weight to their parent criteria. The second one is a multiple order function hierarchy derived from horizontal interaction among factors where there is an expanded functional structure for the linear energy and nonlinear energy among the criteria in all layers. For example, layer B is composed of four parts, namely, the safety management B1, the equipment safety B2, the labor safety and working environment B3, and metallographic detection B4. The linear hierarchy function of level B originates from the four independent parts, and the nonlinear expanded structure functional derives from interaction among two, three, or all of them. The vertical hierarchy pertains to the research object of FAHP, while the horizontal interaction pertains to system functionality. The analysis process of integrated safety assessment structure is shown in Figure 2.

2.4.2. Calculation of Connection Degrees. Suppose a thermal power plant has been safely inspected m times to n criteria; the matrix $A_{ij} = (d_{ij})_{m\times n}$ can be constructed, whose number of rows and columns is m and n, and whose element d_{ij} denotes the safety state of jth criteria in ith safety inspection. The calculation process to obtain the connection degree for safety assessment criteria is shown as follows.

Step 1 (calculation of correlation coefficient between the factors). d_i is a column vector of the matrix A. The correlation coefficient r between two factors is given by

$$r_{ij} = \left| \frac{\operatorname{cov}\left(d_i, d_j\right)}{\sqrt{V_x}\sqrt{V_y}} \right|, \quad i, j \in N, \tag{8}$$

where x or y indicates the discrete random variable, respectively, while V_x or V_y is the variance of x or y, respectively.

Step 2 (calculate connection degree between the factors). For the two same evaluation factors, the higher the identity degree of the factors is, the more similarly the trend changes, the higher the corresponding department coordination will appear. The identity degree can be described as follows:

$$\begin{aligned} h_{ijk} = {} & \left(d_{(k+1)i} * \zeta_{ki(k+1)} - d_{ki}\right) \\ & * \left(d_{(k+1)j} * \zeta_{kj(k+1)} - d_{kj}\right), \quad i, j, k \in N \\ a_{ij} = {} & \frac{\operatorname{Countif}\left(h_{ijk} > 0\right)}{m-1} \times r_{ij}, \quad i, j \in N, \end{aligned} \tag{9}$$

where a_{ij} is degree of identity between ith and jth factors. "Countif" indicates the number satisfying certain conditions. $\zeta_{ki(k+1)}$ indicates the score percentage of the parent factor of ith difference between kth and $(k+1)$th inspection.

The degree of discrepancy can be computed by

$$b_{ij} = 1 - r_{ij}, \quad i, j \in N. \tag{10}$$

For the two same evaluation factors, the higher the degree of opposition of the factors is, the more the trend reverses, the worse the contradiction of corresponding department coordination will appear. c_{ij} denotes degree of opposition between ith and jth factors, which should satisfy the following:

$$c_{ij} = \frac{\operatorname{Countif}\left(h_{ijk} < 0\right)}{m-1} \times r_{ij}, \quad i, j \in N. \tag{11}$$

From formula (7), the connection degree between ith and jth factors can be given by

$$\mu_{ij} = a_{ij} + b_{ij} i + c_{ij} j. \tag{12}$$

The matrix whose elements are μ_{ij} satisfies the following properties. Firstly, μ_{ij} have symmetry relationship, id est, and a random μ_{ij}, satisfying $\mu_{ij} = \mu_{ji}$. It shows that the connection degree of ith factor and jth factor is equal to the connection degree of jth factor and ith factor. Secondly, the diagonal value in the matrix is constant; namely, $\mu_{ij} = 1$. It shows that the connection degree of two same factors is 1 and degree of discrepancy and opposition is 0.

2.4.3. Calculation of Functional Coefficient α of Factors. The cooperation harmony of departments is revealed by $(a_{ij} - c_{ij})$ with reliability $(a_{ij} + c_{ij})$. Harmony of each department should satisfy $\sum (a_{ij} - c_{ij})(a_{ij} + c_{ij})$. The variance of ith factor's record score is marked as $\operatorname{var}(d_i)$. The functional coefficient α of ith factor is given by

$$\begin{aligned} \alpha_i = {} & \frac{\sum_{j=1}^{n}\left(a_{ij} - c_{ij}\right)\left(a_{ij} + c_{ij}\right) - \operatorname{var}\left(d_i\right)}{\sum_{i=1}^{n}\left(\sum_{j=1}^{n}\left(a_{ij} - c_{ij}\right)\left(a_{ij} + c_{ij}\right) - \operatorname{var}\left(d_i\right)\right)}, \\ & \lambda \in 2n, \quad n, i, j \in N. \end{aligned} \tag{13}$$

2.4.4. Creation of the Preponderant Function of System Safety. Safety assessment consists of linear and nonlinear components, and the functional coefficient relates not only to factor's independent safety state but also to connection degrees. The linear part can be quantified by means of weighted averages

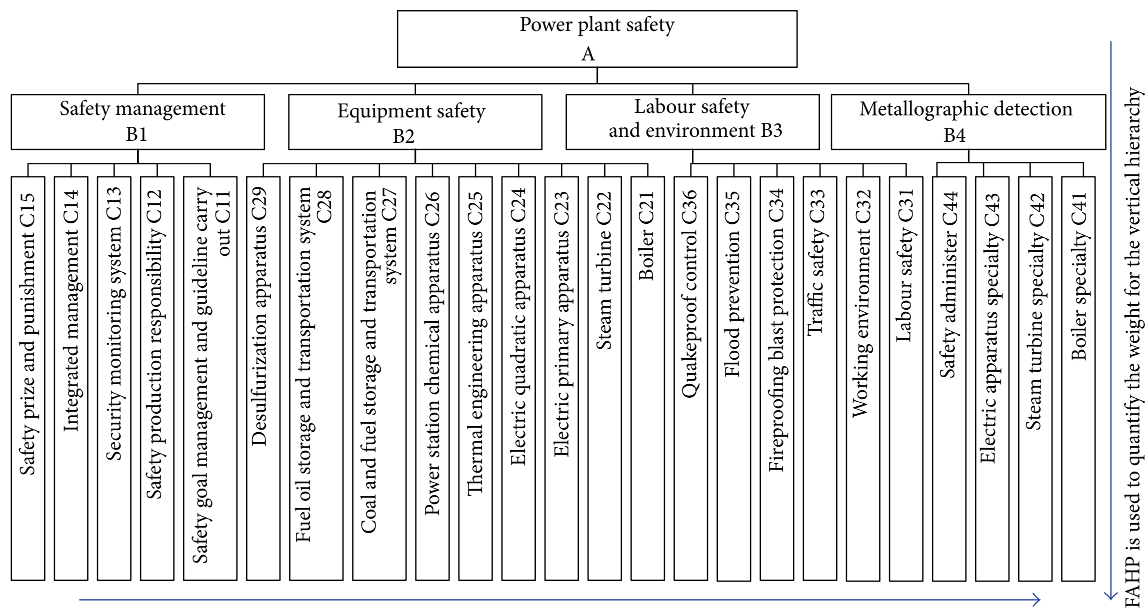

Figure 1: The architecture of safety assessment for thermal power plants.

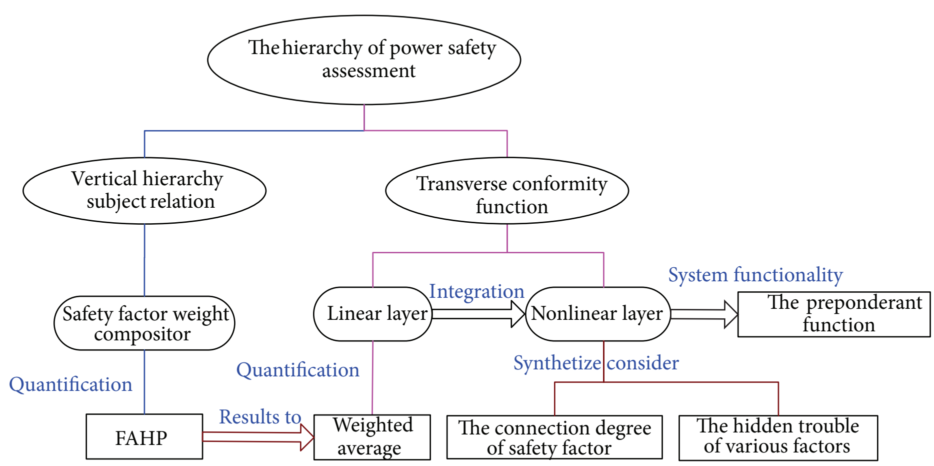

Figure 2: The process of the integrated safety assessment.

from FAHP. The fluctuating range of a factor's score reveals its safety state which is denoted by their variance. Formula (14) is the mathematical model for the safety assessment of thermal power plants based on FAHP, SPA, and system functionality:

$$\begin{aligned} F(x) &= f_1 + f_2 + \cdots + f_n \\ &= R_i \sum_{i=1}^{n} x_i + \alpha_i \alpha_j \sum_{i>j=1}^{n} x_i x_j + \alpha_i \alpha_j \alpha_k \sum_{i>j>k=1}^{n} x_i x_j x_k \\ &\quad + \cdots + \prod_{i=1}^{n} \alpha_i \prod_{i=1}^{n} x_i. \end{aligned} \tag{14}$$

2.5. Decision Analysis System. Once introduced into the area of safety assessment for thermal power plants, decision support is the kind of system that combines information technology and decision theories in management science. The internet technology-based decision support system is a very good technical solution to safety assessment, which can help appraisers of thermal power plants make objective, scientific, and speedy decisions. However, decision support systems have made few inroads in practice because the safety assessment process for thermal power plants is a very complicated project that involves knowledge of many fields, so there is a problem as to how to combine expert judgments and mathematical models, transfer expert experiences into a language which computer can identify, manage these expert knowledge scientifically and orderly, and make inferences based on offered knowledge.

We will construct a special safety assessment website using a browser/server model to synchronously integrate different expert safety assessments for thermal power plants. This method of constructing SADAS is based on FAHP, SPA, system functionality, and information technology for thermal power plants and is used to improve the level of safety management. Knowledge and date capturing from safety assessments are completed by knowledge transformation, that is to say, collecting former assessment data, expert experience, and evaluations standard of safety assessment of thermal power plants; identifying the relationships among knowledge points in the complex information; determining the relationships among standards; and transforming the formal knowledge according to production rule and hierarchical network. The concept of knowledge restructuring is very important to restructure the knowledge of knowledge base and form new information when new relationship is clarified during the process of inference.

3. System Design and Implementation

The web-based SADAS is used to provide a platform for evaluation experts to build a multiple criteria evaluation index system and for administrators to get decision-making advice so that the policy maker can make an easy decision. In this study, we construct a system architecture made up of five functional parts: (1) user management module (UMM), (2) system evaluative model (SEM), (3) matrix parameter identification (MPI), (4) report module (RM), and (5) help module (HM), as shown in Figure 3.

The end users are classified into database administrators, whose responsibility is keeping the system working normally, avoiding database breakdown, and servicing the database system; the evaluation experts who establish and modify the evaluation system architecture and evaluation index system; and the enterprise users who are to make daily rectification decisions on the enterprise safety in UMM functional part. All users can access SADAS functions within their authorization.

The AHP and system functionality module (SFM) will be embodied in SEM functional part. AHP is a multiple criteria decision-making tool that has found applications in almost all the fields related to decision making [2]. SFM can be accessed from the system, optimized through structure evolvement. The unitary function behavior of the system is not equal to the algebraic sum of all parts [21]. The module is used to avoid too many judgment matrixes. In addition, SFM can be considered as an interface (connection tool) to obtain effective data through mining the thermal power plant safety assessment information system which is introduced in another paper [22]. MPI can automatically process and calculate the judgment matrix by using AHP and SFM; whether the calculation results satisfy the condition or not is called consistency in AHP. The matrix and result will be stored in the database for enterprise user query. The RM module provides graphic or character-based results to help managers make decisions according to the decisions of experts; HM module supplies the users who first access the system with the results of AHP and SFM.

The data flow diagram, shown in Figure 4, describes the data through the flow of information through the system and the system implementation. When the user inputs an accepted name and password, he will log into the system and do some operations according to the user identity; the data flows into the data dictionary along with the user's operation. The data flows in the process of transforming the input to output based on the figure mode of data transmission and processing. A complex system is decomposed step by step according to the hierarchical structure of the system, reflecting the main function of the new system, that is, input-output of the external environment, internal processing of the system, data communication, data storage, and so on. An arrow is used to denote the data flow direction. An entity relationship diagram (ERD) is a visual diagram based on the cognition that objective realities in the world are composed of entity of fundamental objects and the relations of such objects. ERD is used to construct a database in the global design process, which includes authenticity, simplicity, avoidance redundancy, and aptitude. The design technology of ERD is an important foundation for database design and database application development, and ERD of the web-based decision analysis system is designed according to the principles mentioned here, as shown in Figure 5. When ERD is complete, the data dictionary can be defined expediently. In the paper, there are six data dictionaries to store data from web pages or other information, the effect and structure of which will be described here.

The function of user information is to store basic user information in the four columns of the table so that users can browse through database information according to their permissions. The table of evaluation established by evaluation experts is designed to store the index system of decision-making project and the table structure is meant especially to provide universality of the decision-making object. The factor of the judgment matrix is stored into the table named judgment matrix. An example of table structure can be seen in Figure 6. The data of judgment matrix is stored into the table of judgment matrix through an eigenvalue approach to the pairwise comparisons, and the judgment matrix information table can store nine rank matrixes; but if the length of field name is modified, the table can store another nine rank matrixes. It is difficult to use Oracle9i to store hierarchical relational tree, because it is relational database. Here, the hierarchical relational tree is decomposed into various father-son relationships which, in turn, can be integrated to form a whole model structure of AHP through combination of the judgment matrix table and judgment matrix information table to achieve the desired function. The weight of judgment matrix is stored in the table of weight information. Assessment result table is used to store the result of decision-making using evaluation expert reports.

Remote decision support of safety assessment is developed by adopting concepts described in this paper. The system effectively separates the inference engine and knowledge base and mainly concentrates on the design of the whole

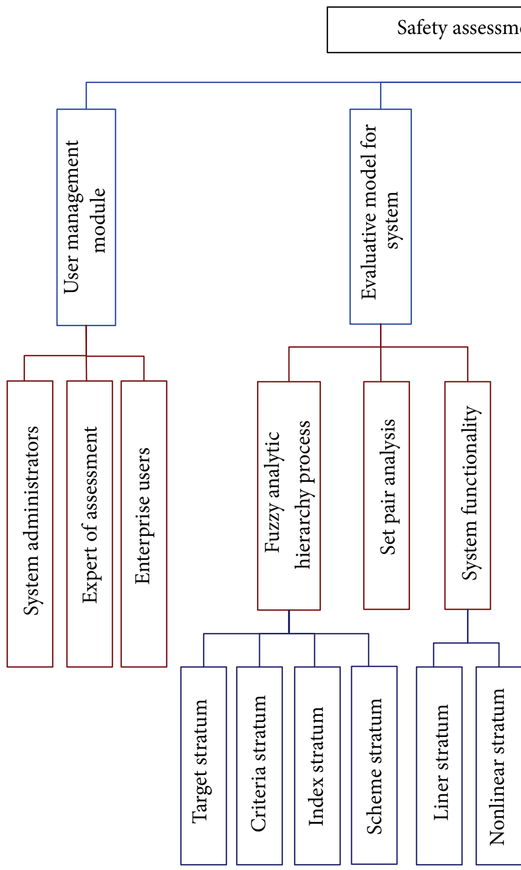

Figure 3: The system architecture of SADAS.

system. The dynamic web page techniques ASP and .NET technology are used to develop B/S structure and IIS6.0 is utilized to design an open inference engine. Production rule-based knowledge is constructed in the form of database which is developed according to expert experience and standard manual of safety assessment. The data table is constructed from the former eight tables.

All of HTML and ASP is put into the package to format the enforceability file with the profession installation program making which can be set up at the platform of windows. In addition, data dictionary can be established through a file in the package. The original data are input into SADAS after SADAS is deployed into the web server, and the user will be able to browse and use the system to carry out safety assessments. Figure 6 shows the input interface to the judgment matrix, and the data that are input via the interface is obtained by using the network on the basis of the subject offer experience of the experts. Figure 7 shows the result of the judgment matrix by using FAHP and combining it with information and computer technology.

Figure 8 shows the system functionality for the safety assessment of thermal power plants based on FAHP and SPA. The data from the safety assessment manage information system has been deployed into the several power plants since 2007 for inputting the x_i to obtain the result about $F(x)$ and it can be measured by using FAHP method as dimensionless variable. The assessment value of the thermal power plant safety can be acquired through calculating $F(x)$ and the safety degree of the thermal power plant can be confirmed by comparing the optimal safety status (the experts set the values) obtained through calculating x in formula (17). The safety assessment model is issued only in the criteria level here while the other levels can also be disposed in the same way.

As the key report function of the system, the function of SADAS is to enable the enterprise user to make decisions. In order to accelerate the development progress, we chose ASP and JS to generate reports on the basis of the weight of judgment matrix from FAHP. Moreover, the calculation result which is very small must be amplified to generate the figure report that can be queried expediently in the web pages. Figure 9 shows the result of the safety assessment of thermal power plant obtained by using the technology described here.

The evaluation index system established by SADAS for an actual thermal power plant that is used in daily work and the effectiveness of SADAS will be validated in the future.

4. Safety Assessment for the Thermal Power Plants

The enterprise safety assessment for thermal power plants is the decision-making goal, the hierarchical structure of which is composed of three levels, the target level A, the criteria level B, and the subcriteria level C. Hazards will be analyzed quantitatively and qualitatively to confirm the probability of

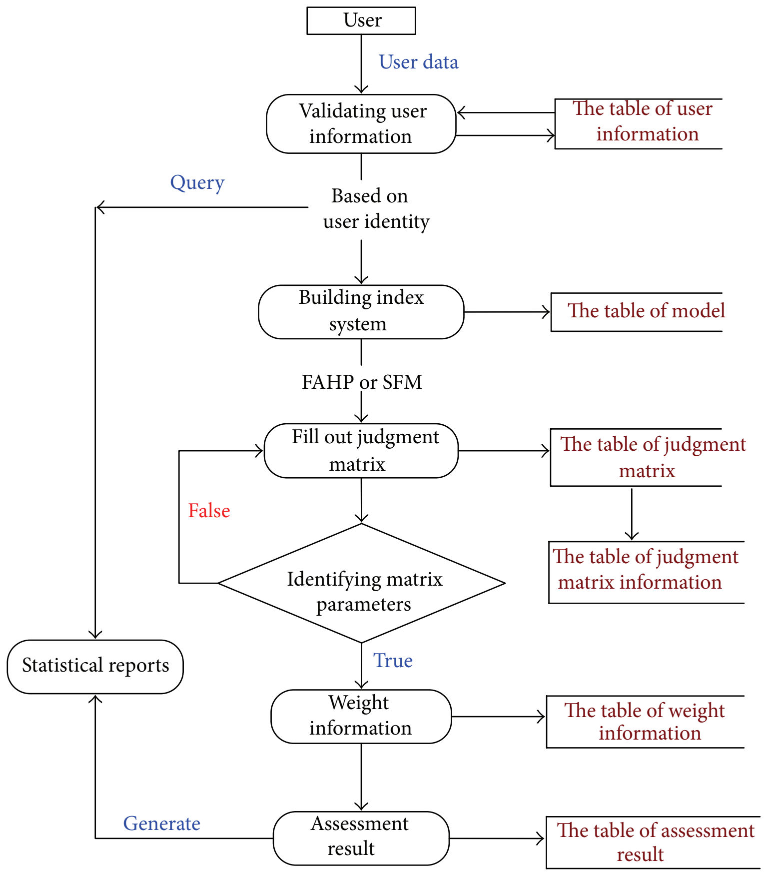

Figure 4: The flow chart about FAHP.

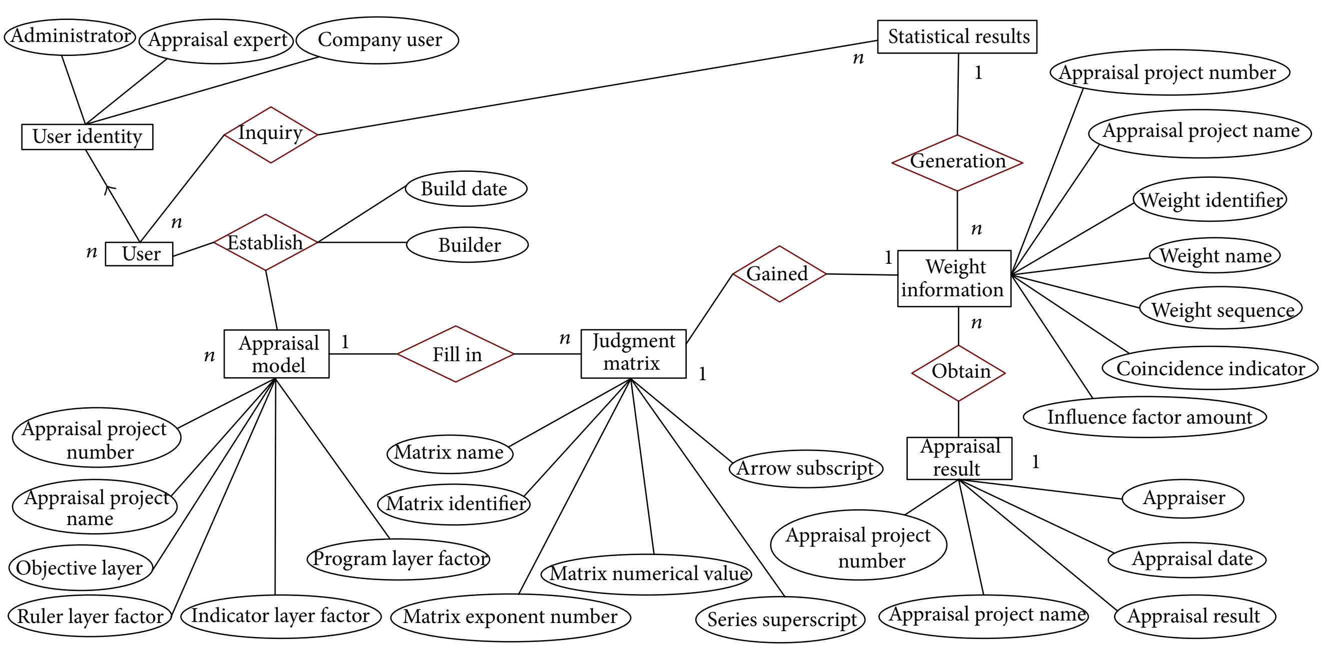

Figure 5: The entity relationship diagram for SADAS.

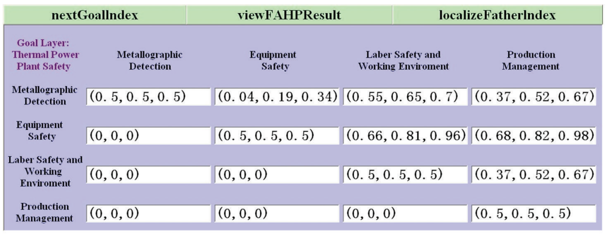

Figure 6: A part of input interface for the judgment matrix.

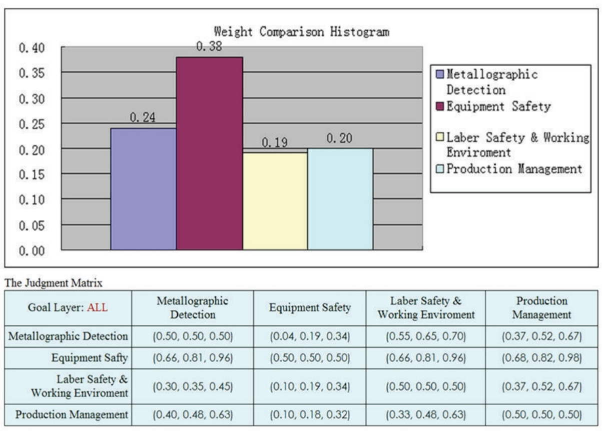

Figure 7: The interface of FAHP result.

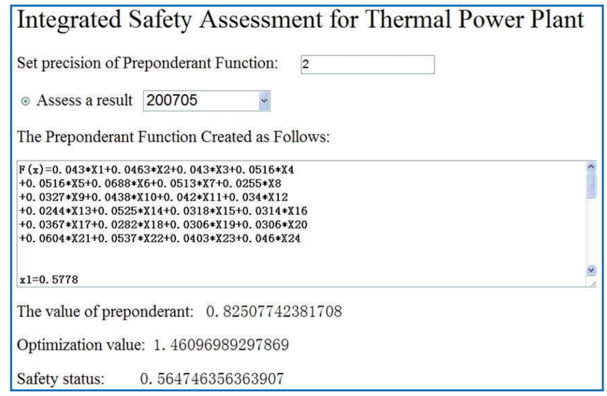

Figure 8: The interface of creating preponderant function of system safety.

risk and work out the necessary measures to attain the lowest accident rate and superior safety investment performance. The factors affecting safety analysis and the architecture are shown in Figure 1.

Once the hierarchy is established, expert knowledge is elicited through interviews and questionnaires whose results will be used to generate the weighting factors for the upper level; triangular fuzzy values in 0.1–0.9 scales are used to obtain the upper triangular values of judgment matrix. The corresponding lower triangular matrix represents negative judgment. An example of the matrix A established on 0.1–0.9 scales is shown as follows:

$$A_{4\times 4} = \begin{bmatrix} (0.50, 0.50, 0.50) & (0.04, 0.19, 0.34) & (0.55, 0.65, 0.70) & (0.37, 0.52, 0.67) \\ (0.66, 0.81, 0.96) & (0.50, 0.50, 0.50) & (0.66, 0.51, 0.96) & (0.68, 0.82, 0.98) \\ (0.30, 0.35, 0.45) & (0.04, 0.19, 0.34) & (0.50, 0.50, 0.50) & (0.37, 0.52, 0.67) \\ (0.33, 0.48, 0.63) & (0.02, 0.18, 0.32) & (0.33, 0.48, 0.63) & (0.50, 0.50, 0.50) \end{bmatrix}. \quad (15)$$

The relative weight vector Q for every set pair denoted a by triangular fuzzy number is given as Q_1 : $(0.1513, 0.2325, 0.3480)$, Q_2 : $(0.2591, 0.3675, 0.5354)$, Q_3 : $(0.1254, 0.1950, 0.3087)$, and Q_4 : $(0.1223, 0.2050, 0.3276)$. The possibility degree matrix P, the weight vector W, and the general weight vector R are calculated from formulas (3)–(6), which are given as follows:

$$P = \begin{bmatrix} 0.5 & 0 & 0.69 & 0.64 \\ 1 & 0.5 & 1 & 1 \\ 0.31 & 0 & 0.5 & 0.46 \\ 0.36 & 0 & 0.54 & 0.5 \end{bmatrix},$$
$$W = [0.2355, 0.3750, 0.2004],$$
$$R = [0.2355, 0.3750, 0.1891, 0.2004]. \quad (16)$$

Next, the weight sequence about the subcriteria level C relative to the upper criteria level B can be calculated similarly and the impact factors about thermal power plant safety can be analyzed from the calculated results. The ranking sequence for thermal power plant safety is shown in Table 1.

The 5-time scoring rates for all the criteria come from routine inspection (the score is a 0-1 scale) and the functional coefficient α can be calculated by using (8)–(13) as shown in Tables 2 and 3.

The preponderant function of system safety on the basis of the criteria in B level can be expressed as

$$\begin{aligned} F_B(X) = {} & 0.292x_1 + 0.208x_2 + 0.125x_3 + 0.375x_4 \\ & + 0.148x_1x_2 + 0.039x_1x_3 + 0.046x_1x_4 + 0.042x_2x_3 \\ & + 0.049x_2x_4 + 0.013x_3x_4 + 0.016x_1x_2x_3 \\ & + 0.018x_1x_2x_4 + 0.005x_1x_3x_4 + 0.005x_2x_3x_4. \end{aligned} \quad (17)$$

The preponderant function of system safety for the other layers can also be obtained in the same way. The assessment

Table 1: Local and general weight of index in B and C layer.

C	$R_{B1} = 0.2355$	$R_{B2} = 0.3750$	$R_{B3} = 0.1891$	$R_{B4} = 0.2004$	R	Ranking order
W_{C11}	0.1825	—	—	—	0.0430	11
W_{C12}	0.1968	—	—	—	0.0463	8
W_{C13}	0.1825	—	—	—	0.0430	12
W_{C14}	0.2191	—	—	—	0.0516	5
W_{C15}	0.2191	—	—	—	0.0516	6
W_{C21}	—	0.1834	—	—	0.0688	1
W_{C22}	—	0.1368	—	—	0.0513	7
W_{C23}	—	0.0679	—	—	0.0255	23
W_{C24}	—	0.0872	—	—	0.0327	17
W_{C25}	—	0.1169	—	—	0.0438	10
W_{C26}	—	0.1121	—	—	0.0420	13
W_{C27}	—	0.0906	—	—	0.0340	16
W_{C28}	—	0.0651	—	—	0.0244	24
W_{C29}	—	0.1401	—	—	0.0525	4
W_{C31}	—	—	0.1680	—	0.0318	18
W_{C32}	—	—	0.1659	—	0.0314	19
W_{C33}	—	—	0.1939	—	0.0367	15
W_{C34}	—	—	0.1492	—	0.0282	22
W_{C35}	—	—	0.1616	—	0.0306	20
W_{C36}	—	—	0.1616	—	0.0306	21
W_{C41}	—	—	—	0.3015	0.0604	2
W_{C42}	—	—	—	0.2681	0.0537	3
W_{C43}	—	—	—	0.2010	0.0403	14
W_{C44}	—	—	—	0.2294	0.0460	9

value for thermal power plant safety can be acquired through calculating the $F(x)$ in which x_i would be assigned by factors safety status value and the unitary safety status of the thermal power plant can be assessed by comparing the optimal safety status value of $F(x)$ in which x_i would be assigned by 1 (generally 1 for 0.1–0.9 scale). In practical application, the x_1–x_4 of the formula (17) are assigned and calculated and were compared with the best security state (i.e., security experts set value) to determine the safety level of thermal power plant. Table 4 displays an example result for the thermal power plant safety.

The sequence of factors sorted by general weight is B2 > B1 > B4 > B3 and the key factors are *equipment safety* and *metallographic detection*, where B3 has the most hidden dangers in the B level that cause at least functional coefficient in level B and B2 is crucial since its expanded function is the strongest. The first three in order of arrangement by increasing α in level C are C11 > C23 > C13, which should be emphasized because they have the strongest expanded tendency. It indicates that strict management and surveillance are effective ways to ensure safety in production. The *electric primary apparatus* and *electric quadratic apparatus* are the first two in order of increasing by α in B2, indicating that there is strong dependence of other equipment on them.

5. Conclusions

It is practicable to establish the preponderant function for system safety using FAHP, system functionality, and SPA, which avoid problems of data sources because all the data come from the routine work of safety assessment experts. In addition, this provides a reference value for enterprise

Table 2: Rate of scoring and functional coefficient of index in B layer.

	Rate of scoring (%)						
A	1st	2nd	3rd	4th	5th	α	Sequence
B1	55.39	87.04	91.83	70.72	83.74	0.3722	2
B2	62.86	89.96	93.22	64.37	80.77	0.3985	1
B3	47.67	88.79	93.97	68.10	70.77	0.1053	4
B4	45.38	86.50	94.59	73.48	86.50	0.1240	3

Table 3: Recording score and horizontal functional coefficient of index in C layer.

	Rate of scoring (%)						
	1st	2nd	3rd	4th	5th	α	Sequence
C11	57.78	83.33	88.89	96.67	70.00	0.1022	1
C12	51.00	86.71	94.14	79.14	65.71	0.0120	20
C13	67.50	88.00	91.00	93.00	78.00	0.1002	3
C14	58.33	86.67	83.33	84.71	90.59	0.0318	14
C15	58.00	91.00	85.00	85.00	75.00	0.0102	21
C21	60.33	88.33	91.08	77.42	68.00	0.0536	8
C22	57.08	89.91	92.30	73.53	71.68	−0.0159	24
C23	67.23	91.58	92.87	70.68	69.13	0.1012	2
C24	66.22	92.13	95.43	91.74	82.99	0.0840	4
C25	64.53	89.16	95.42	99.91	78.53	0.0138	19
C26	63.21	89.78	90.95	83.22	77.34	0.0484	9
C27	61.76	90.98	93.53	49.06	64.53	0.0236	16
C28	64.33	86.00	96.00	71.67	71.67	0.0142	18
C29	61.67	96.46	86.01	90.50	76.00	0.0652	6
C31	35.16	88.39	91.13	74.68	65.97	0.0474	10
C32	68.33	91.11	94.44	51.67	75.00	0.0658	5
C33	73.64	89.09	100.00	81.82	70.91	0.0460	11
C34	23.33	80.00	96.67	62.00	57.33	0.0071	22
C35	92.00	100.00	100.00	84.00	84.00	0.0455	12
C36	100.00	100.00	100.00	80.00	80.00	0.0571	7
C41	59.61	87.30	90.01	76.53	77.16	0.0317	15
C42	54.96	86.90	89.17	70.94	79.239	0.0156	17
C43	59.09	80.00	80.81	60.72	69.71	0.0327	13
C44	59.71	86.20	91.80	70.00	82.50	0.0066	23

Table 4: The safety assessment result for the thermal power plants.

	1st	2nd	3rd	4th	5th	Optimal value
$F(x)$ basis of B	0.6321	1.1700	1.2628	0.8741	1.0721	1.3822
Safety status	0.4573	0.8465	0.9136	0.6324	0.7756	1
$F(x)$ basis of C	0.8619	1.3447	1.4168	1.1921	1.0858	1.5907
Safety status	0.5418	0.8454	0.8907	0.7494	0.6826	1

safety; however, it could lead to a great deal of calculations. Therefore, the development of a computer system is useful to facilitate the safety assessment process, which will in turn promote rationalization of safety assessment. Besides, with the web-based decision support system developed here to implement FAHP and SPA, the evaluation index system can be easily established and decision-making advice can be obtained through the steps involved in the FAHP methodology as realized by the ASP.NET technology. Furthermore, the system can be updated and expanded to face the developments, for some interfaces reserved in the system are available to integrate other data acquisition systems and the advice

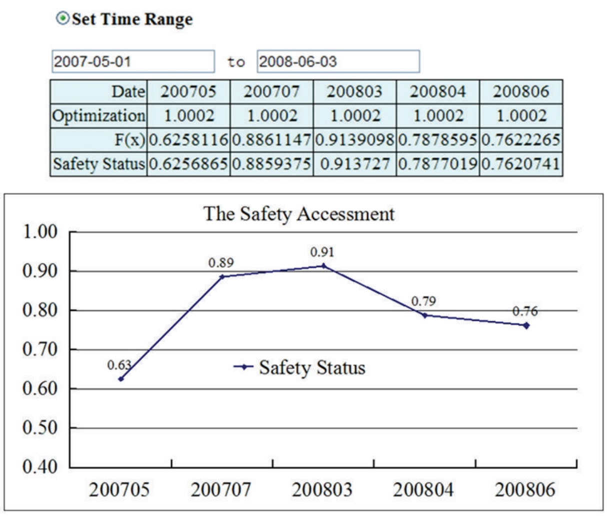

Figure 9: The interface of creating preponderant function of system safety.

obtained will guide the management to cope with emergent events and reduce life and property loss. It is not only a promising methodology to help resolve industrial safety problem, but also a great help to lay the foundation for the next study of safety assessment and decision-making. Finally, it has values for the design and development of web-based decision analysis system corresponding to the methodology and technology presented in this paper.

In the future, we want to integrate the safety assessment management information system which has been deployed into several power plants combining with the data mining or neural network technology to obtain a more ideal safety assessment result to guide safety management activities. The real time results for this system need to be improved.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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