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Design and implementation of a fuzzy expert system for performance assessment of an integrated health, safety, environment (HSE) and ergonomics system: The case of a gas refinery

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The objective of this study is to design a fuzzy expert system for performance assessment of health, safety, environment (HSE) and ergonomics system factors in a gas refinery. This will lead to a robust control system for continuous assessment and improvement of HSE and ergonomics performance. The importance of this study stems from the current lack of formal integrated methodologies for interpreting and evaluating performance data for HSE and ergonomics. Three important reasons to use fuzzy expert systems are (1) reduction of human error, (2) creation of expert knowledge and (3) interpretation of large amount of vague data. To achieve the objective of this study, standard indicators and technical tolerances for assessment of HSE and ergonomics factors are identified. Then, data is collected for all indicators and consequently, for each indicator four conditions are defined as “acceptance”, “low deviation”, “mid deviation” and “high deviation”. A membership function is defined for each fuzzy condition (set) because an indicator cannot be allocated to just one of the above conditions. The expert system uses fuzzy rules, which are structured with Data Engine. Previous studies have introduced HSE expert system whereas this study introduces an integrated HSE and ergonomics expert system through fuzzy logic.

1. Introduction

1.1. HSE and ergonomics

HSE at the operational level will strive to eliminate injuries, adverse health effects and damage to the environment. Effective application of ergonomics in work system design can achieve a balance between worker characteristics and task demands. This can enhance worker productivity, provide improved worker safety (physical and mental) and job satisfaction. Several studies have shown positive effects of applying ergonomic principles to the workplace including machine, job and environmental design [1–6]. Studies in ergonomics have also produced data and guidelines for industrial applications [3,7–9]. However, there is still a low level of acceptance and limited application in industry. The main concern of work system design in context of ergonomics is improvement of machines and tools. Lack of utilization of the ergonomic principles could

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bring inefficiency to the workplace. Moreover, an ergonomically deficient workplace can cause physical and emotional stress, low productivity and poor quality of work conditions [9–11]. It is believed that ergonomic deficiencies in industry are root cause of workplace health hazards, low levels of safety and reduced workers' productivity [12]. Although ergonomics applications have gained significant momentum in developed countries, awareness remains low in developing regions.

By considering health, safety, environment and ergonomics (HSEE), an organization manages its operations in a manner that places safety and health first. It encourages employees to adopt a healthy and safe life-style. It develops and operates its facilities with due concern for the health and safety of its neighbors and collaborates with authorities in the preparation of emergency response plans. It contributes to eco-efficiency by continuously improving energy consumption and reducing waste, emissions and discharges. It designs and develops products to have the minimum adverse effect on the environment throughout their life-cycle. It optimizes the relation between man and machine in a manner that man faces the least fatigues and gets the most efficiency [13,14].

1.2. The integrated HSE and ergonomics

There are close relationship between health, safety, environment and ergonomics factors. Inappropriate design between human and machine could lead to decreased safety. Inappropriate design of system leads to management error. Management error and work environment injurious factors could cause human error and safety issues which consequently would result in environmental risks (Fig. 1).

Unexpected events in technological systems can occur in different areas. Various methods and procedures were presented to deal with unexpected events with major emphasis toward the applications of management systems in recent years. Defining and implementing an isolated system cannot insure safety preservation and promotion. Thus, it is necessary to introduce an appropriate integrated system for continuous monitoring and control of unexpected events [15].

Chen et al. [15] described the development of an interactive computer assisted ergonomics analysis system (EASY) [16]. Their proposed system consists of three components: EIAS for evaluation of tasks by the worker; PWSI to be used by supervisor for further investigation of problem situations and DJAS for manual material handling. The proposed technique was claimed to have a fairly high rate of acceptance by ergonomic experts. Wilson and Corlett [63] described an expert system for ergonomics design of work tasks [17]. Their approach was oriented towards physical aspects of work tasks such as lighting. Their system, ALFIE, operated in the same way as the previous systems; and its output included statements reminiscent of logic theory which were highly unfamiliar to engineers. Fang et al. (1990) provided a collection of articles regarding the use of computers in ergonomics, many of which incorporated AI-based techniques and procedures [18].

Several companies use the acronym HSE to describe health, safety and environment as one entity [19]. The principal of HSE is now well recognized but there is the conundrum: "How do I select the inherently safer and more environmentally benign design for development when the definition at the concept stage is poor?" Ngai and Cheng [48] outlined an integrated management system (IMS) for HSE. IMS reflects injury prevention values, best practices for successful organizations and supports an integrated approach toward managing HSE [20].

It is therefore realized that health, safety, environment and ergonomics systems require a continual and systematic effort to achieve sustainable success. This paper presents a framework for a comprehensive performance analysis of HSE and ergonomics factors which we refer to from this point on to as HSEE. HSEE is modeled and analyzed by a fuzzy expert system. Furthermore, an integrated model is designed for continuous performance assessment, monitoring, control and improvement of HSE and ergonomics factors. HSEE has the following features and capabilities: First, the fuzzy expert system should be used on a continuous basis in the refinery or other complex systems. Second, it collects data like any other expert system. Third, it is used for assessment of HSEE indicators or factors. Fourth, it is used for monitoring by the operators dedicated to the fuzzy expert system. Hence, an expert system is monitored by human operators (analysts, problem solving team, etc.).

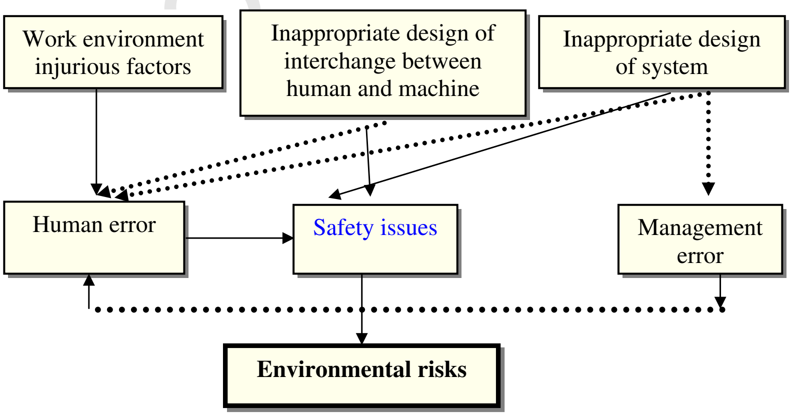

Fig. 1. The relationship between different systems and environmental risks.

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Fifth, it is used for control and improvement of the HSEE factors in the refinery or other complex system by proposing improving methods. A fuzzy expert system is developed to be able to model and assess both quantitative and qualitative indicators. The required data, time period and the collection methods are defined for the HSEE indicators. Related international and national standards were identified to construct a benchmark for the expert system.

2. Problem domain

First, the indicators and standards related to HSEE are defined. Then, data related to these indicators are collected and analyzed by the proposed expert system. Appendix 1 presents the complete list of indicators and their tolerances [21–24]. These indicators are categorized as follows:

Safety factors: An important indicator is accident frequency rate. It is the rate of the occurrence of accidents, often expressed in terms of the number of accidents over a period of time. It is one of the methods used for measuring the effectiveness of loss prevention services.
Environmental factors: One of the most important indicators is water consumption in emergency situation maneuver measured in m^3/day.
Ergonomics factors: The expected response rate of personnel with respect to temperature level in scales of hot, warm, moderately warm, null, moderately cold and cold.
Health factors: Number of unhealthy spirometry to total executed spirometry.
General factors: Formation of regular weekly HSEE committee meetings according to pre-defined criteria.

The proposed fuzzy expert system is rule-based in which the domain knowledge contains the rules (rules are explained in Section 4.3). For each indicator four conditions are defined: acceptance, low deviation, mid deviation and high deviation. It means that each indicator will be in one of these regions. It is clear that when an indicator is in its standard range it will be accepted and otherwise it has deviation. The four levels of deviation for each indicator are identified according to previous studies and the expert advice. This has been based on national and international standards [25–27]. For example, Iranian national standard for average noise level is 85 dB. Furthermore, the four levels have been identified for noise level (say x) as follows: acceptable level ($x \leqslant 76.5$), low deviation level ($76.5 < x \leqslant 85$), mid deviation level ($85 < x \leqslant 93.5$) and high deviation level ($x > 93.5$). Moreover, we have consulted with experts in each area of HSEE about the severity of deviation for each indicator. Furthermore, the levels of deviations are defined according to severity of the deviation [30]. It means that if the indicator is slightly deviated from the acceptable domain, it is identified as low deviation and so on. The four levels are identified to help user to concentrate on improvement of the indicators that are more deviated than others. For example, in a gas refinery the tolerance of safety culture indicator is defined in an interval of 40–100. It means that if the indicator is less than 40, it is deviated. There are three levels of deviation as high deviation level (less than 32), medium deviation level (between 32 and 36) and low deviation level (between 36 and 40). Finally, in order to confront with the indicators that may not be in the standard range, HSEE problem solving team is established. The HSEE team was composed of 12 experts from the refinery. They were given the required trainings by our experts. The problem solving techniques are chosen according to the levels of deviation (Fig. 2).

For example, the Nordic questionnaire was used for assessment of musculoskeletal disorders among the personnel of storage department [28]. The HSEE team used quick exposure checklist (QEC) for more precise assessment and identification of factors related to this issue. Furthermore, dimensional mismatch of working desks was identified as one of the major causes of high rates of musculoskeletal disorders. The proper action included elimination of improper dimensions from anthropometric perspective in the working area.

2.1. Fuzzy expert system

A fuzzy expert system uses fuzzy logic instead of Boolean logic [29]. In other words, a fuzzy expert system is a collection of membership functions and rules that are used to reason about data [30]. Unlike conventional expert systems, which mainly are composed of symbolic reasoning engines, fuzzy expert systems are oriented toward numerical processing [31]. With the definition of the rules and membership functions in hand, we now need to know how to apply this knowledge to specific values of the input variables to compute the values of the output variables. This process is referred to as inferencing. In a fuzzy expert system, the inference process is a combination of four sub-processes: fuzzification, inferencing, composition, and defuzzification [32,33]. The defuzzification sub-process is optional. Fuzzy expert systems are used in several fields including linear and nonlinear control, pattern recognition, financial systems, operations research and data analysis. In fuzzy logic, everything is or is allowed to be a matter of degree [34]. This is the way human thinking is organized. In the real world, almost nothing is black and white.

As mentioned, the proposed expert system is rule-based and uses fuzzy rules. The fuzzy reasoning is explained by an example. Consider safety culture score and unsafe acts indicators. Suppose there are the following Boolean rules:

1. If "safety culture score" is below 50 and "unsafe acts" is above 50 then system identifies "high deviation".
2. If "safety culture score" is below 50 and "unsafe acts" is below 50 then system has "medium deviation".

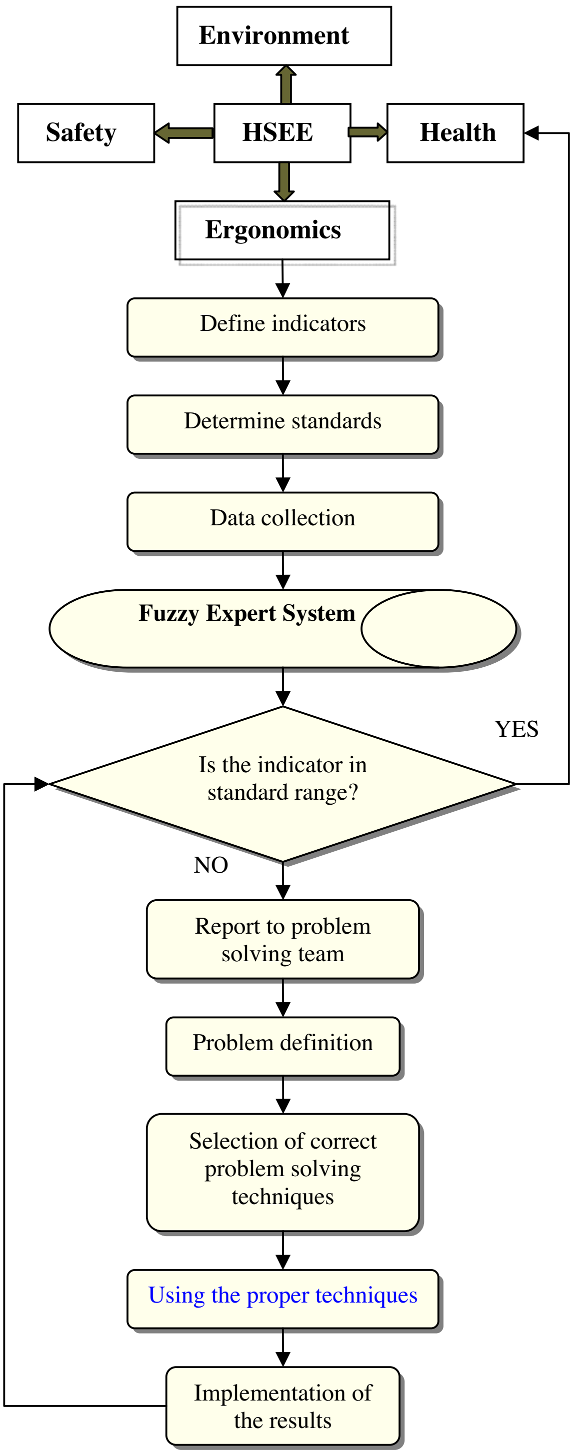

Fig. 2. Health, safety, environment and ergonomics (HSEE) assessment by the fuzzy expert system.

3. If "safety culture score" is above 50 and "unsafe acts" is above 50 then system identifies "low deviation".
4. If "safety culture score" is above 50 and "unsafe acts" is below 50 then system identifies "acceptance".

Now consider the following two situations:

- "safety culture score" = 51 and "unsafe acts" = 49;

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- “safety culture score” = 49 and “unsafe acts” = 51.

As seen these two cases are close to each other, but according to the rules the first case is accepted and the second one has high deviation. Therefore, utilization of Boolean rules is not useful and we have to apply fuzzy rules. Fuzzy expert system eliminates the preceding problem and provides meaningful outputs.

3. Shortcomings of the manual analysis

Q6 According to Chin et al. [16], there is hardly any development of analysis tools for supporting the organizational performance assessment [35]. They also found that a number of organizations such as gas refineries do not have sufficient expertise and knowledge to carry out their own self-assessment process. The purpose of this study is to fill this gap by developing a formal methodology for performance analysis, a methodology that could lead to identification of the cause(s) of the problems uncovered.

Performance analysis is not a common practice in businesses today and the expertise in this area seems to come from experience rather than formal education. Most managers simply ignore performance analysis because of the limited staff availability and the time delay involved. Valuable information is therefore lost about opportunities for enhancing operational performance. For analysis of the gas refinery we first must analyze the four factors. There should be an expert or performance analyst for each of the HSEE factors. Therefore, there seems to be a major problem in integration of the HSEE factors. There are other common problems as follows:

- inaccessibility of the integrated system to the performance analysts;
- the problem of consulting with four performance analyst simultaneously;
- tiredness, fatigue and other obstacles for the performance analysis;
- complexity and large amount of data.

4. The proposed tool

The problem described above could be overcome by developing an expert system to substitute or supplement the performance analysts. The knowledge possessed by the analysts and managers can be incorporated into the expert system. The required knowledge could include what to look for, where to find supporting data, how to interpret trends and outliers, how to put together an accurate portrayal of productivity performance, how to diagnose the problem areas, and how to choose an appropriate set of solutions. At the touch of a button on a personal computer, the managers or executives can have an instantaneous assessment that would otherwise require a team of HSE and ergonomics specialists.

Such expert system can encourage managers to monitor problems very closely and take corrective actions immediately – steps the manager might not otherwise take. The expert system that recommends solutions for a given set of problems can have up-to-date knowledge of new improvement techniques. The day-to-day decisions of managers can therefore become even more effective and beneficial because of real-time analysis and feedback from the system.

Why should we utilize expert systems (ES) technology? The application of expert systems to various problem domains in business has grown steadily since their introduction [36]. Expert system technology has proven to benefit decision-making process in businesses and accounting management of corporations [37–40]. There have been several articles listing and categorizing its numerous applications in business and decision-making [41–45]. Most applications are developed in production/operations management area with lowest number of applications in the human resources area [45]. Are there any ES applications in the area of performance evaluation? Human resource applications include performance appraisal of employees, but not of organizations. There is an ES application for performance measurement of advanced manufacturing technology projects [46]. There was also an expert system for “productivity measurement” using the total productivity model. Performance evaluation or productivity analysis would also fall in the area of auditing and internal control assessment. Several applications exist in auditing and internal control assessment [47–49], but none of them are specifically dedicated for performance evaluation. Performance evaluation requires applications for interpretation and diagnosis. One of the recent ES applications in the area of interpretation includes detection and interpretation of sleep apneas [50], and there are several applications in the area of diagnosis. They include defects diagnostic system for tire production and service [51], fault diagnosis of electrical machines and drives [52], instrument diagnosis on the Internet [53], nuclear power plant accident diagnosis [54], Web-based tele-diagnosis in aquaculture [55], Web-based expert system for fish disease diagnosis [62], diagnosis of anorexia [56], diagnostic expert system for honeybee pests [57], expert system for monitoring and diagnosis of anaerobic wastewater treatment plants [58], and diagnosis system for digital mammograms [59]. These are just a few of the recent applications in the area of diagnosis. It is obvious from the above examples that the applications are in a wide variety of industries. Many other ES applications may even be integrated into mainstream applications losing their own identity as expert systems. There are several potential benefits in utilizing expert systems. These include improved decision-making, more consistent decision-making, reduced design or decision-making cycle time, improved training, operational cost savings, better use of expert’s time, improved product or service levels, and rare or dispersed knowledge captured [60]. Benefits of an expert system approach to productivity analysis include cost

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reductions due to the reduced need for manpower, faster analysis of pressing productivity problems, and more consistent appraisals and interpretation of productivity performance. Perhaps the most significant benefit is the likely increase in management inquiry into productivity performance and the resulting impact on the firm's short- and long-range competitiveness. However, despite these advantages, no expert system for productivity analysis is currently available in complex systems such as gas refineries.

4.1. Fuzzy expert system

The structure of the rule-based fuzzy expert system for performance evaluation of HSEE is shown in Fig. 3. HSEE expert system is unique because HSE is integrated with ergonomics factors and it utilizes fuzzy logic to obtain more precise solutions for the users. HSEE fuzzy-expert system is composed of the following features:

- rule base (definition of linguistic variables, phrases and rules);
- fuzzification (input variables processor);
- inference engine (analysis and assessment);
- defuzzification (output variables processor);
- working memory (knowledge base).

4.2. Data fuzzification

Fuzzy logic is a discipline that has been successful in automated reasoning of expert systems. Uncertainty, vagueness, ambiguity, and impreciseness are some of problems found in relationships between inputs and outputs of real world systems, and these can be tackled effectively by utilization of fuzzy logics. Fuzzification is a process in which the input data, precise or imprecise is converted into linguistic formation, which is easily perceptible by the human minds [61]. Expert system then uses these fuzzified data to give answers to imprecise and vague questions. It also describes the real level of those answers [62]. Therefore, all indicators of the proposed HSEE expert system are linguistic variables. Fuzzy sets for one of the ergonomics indicators are shown in Fig. 4.

The input data to a fuzzy system are usually real numbers. The real numbers must be translated to fuzzy sets through various available techniques. The most typical fuzzy set membership function has the graph of a triangle. The fuzzy set membership function of our model is also a triangle. This approach translates the point $(x_1^*, \ldots, x_n^*)$ in set A to a fuzzy set A' as shown in Eq. (1). For example, the fuzzy membership function for one of the indicators is shown in Fig. 5:

$$\mu_{A'}(x) = \begin{cases} 1 - \frac{|x_1 - x_1^*|}{b_1}, \ldots, 1 - \frac{|x_n - x_n^*|}{b_n}, & |x_i - x_i^*| \leqslant b_i \\ 0, & \text{else} \end{cases} \tag{1}$$

4.3. Data defuzzification

Defuzzification is the process of producing a quantifiable result in fuzzy logic [63]. There are five methods for defuzzification as follows [64]:

- centroid average (CA),
- center of gravity (CG),

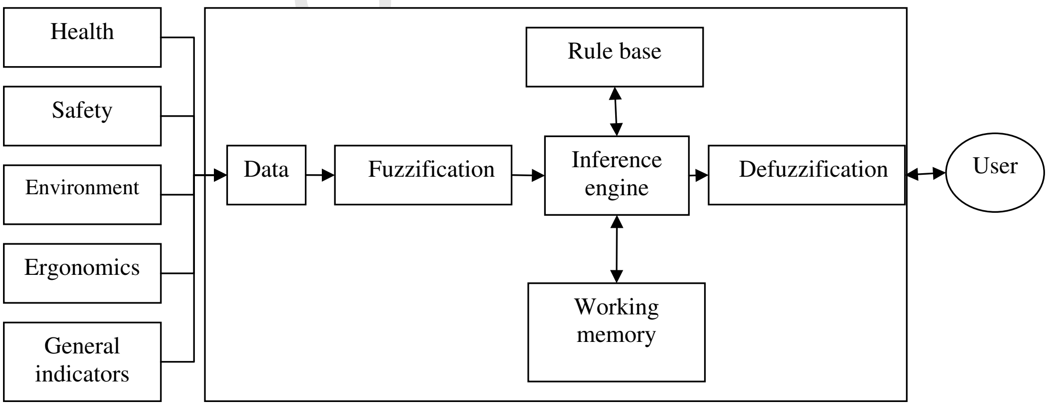

Fig. 3. Rule-based fuzzy expert system for performance evaluation of HSEE.

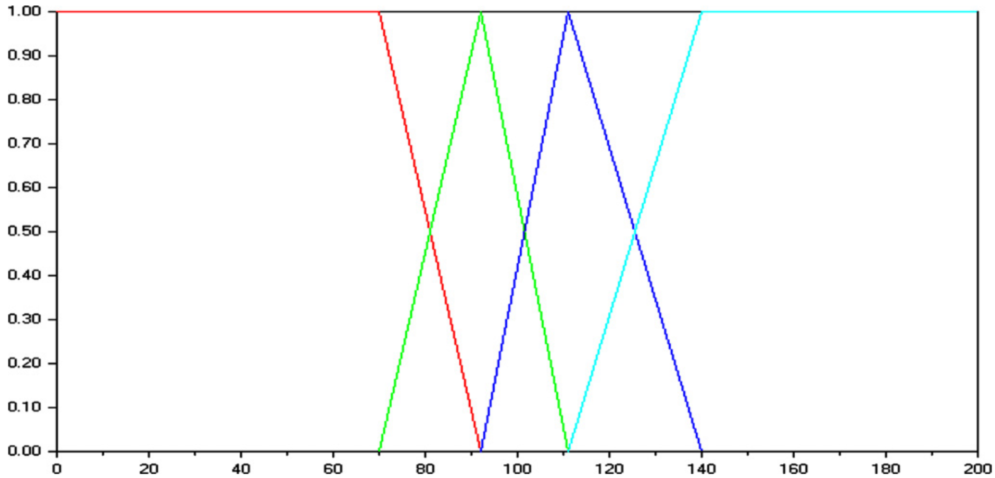

Fig. 4. The fuzzy sets for "confronting with noise level (ergonomics indicator)".

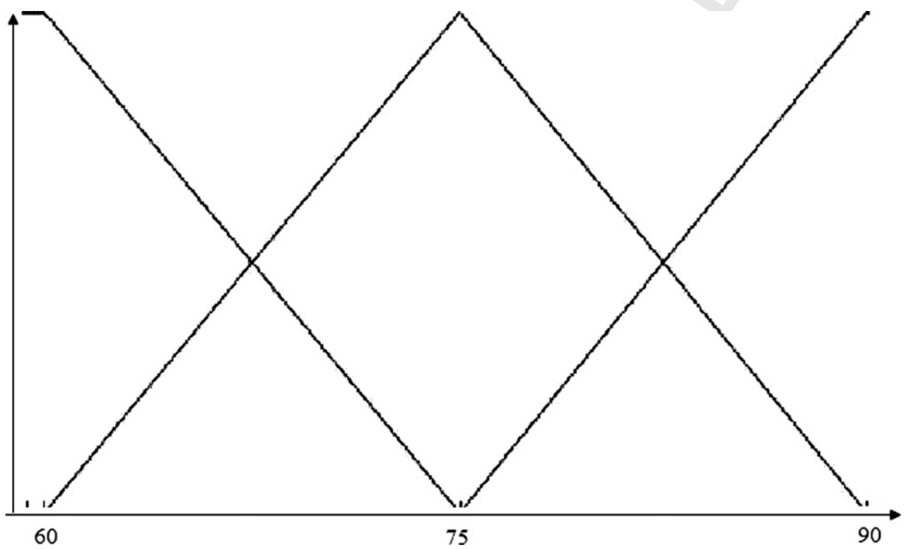

Fig. 5. The fuzzy membership function for one of the indicators.

- maximum center average (MCA),
- mean of maximum (MOM),
- smallest of maximum (SOM),
- largest of maximum (LOM).

Our fuzzy expert system uses centroid average (CA) method and center of gravity (CG). This is because the two approaches provide better solution than other methods via data engine. A useful defuzzification technique must first add the results of the rules together in some logical way. CA is used by considering the fact that the fuzzy set A' is the union or intersection of M fuzzy sets. Furthermore, we use the weighted average of M fuzzy sets with equal weights as the height of fuzzy sets. If $\bar{y}^h$ is the center of hth fuzzy set and w_h is its height then, we have the centroid average as shown in

$$y' = \frac{\sum_{h=1}^{M} \bar{y}^h w_h}{\sum_{h=1}^{M} w_h} \quad (2)$$

However, for the CG, $y^{'}$ is obtained as shown in

$$y' = \frac{\int_A y \mu_{A'}(y)\,\mathrm{d}y}{\int_A \mu_{A'}(y)\,\mathrm{d}y} \quad (3)$$

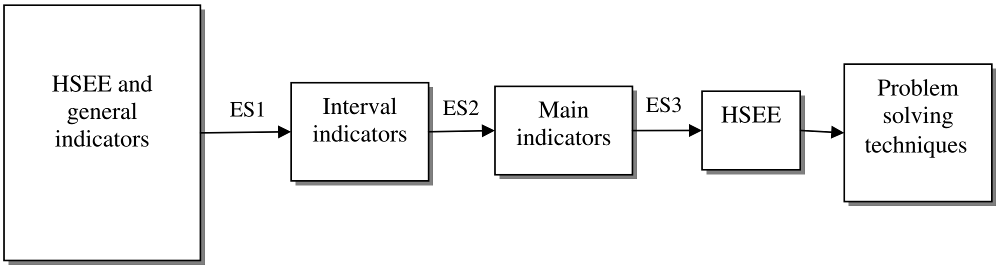

Fig. 6. Overall demonstration of hierarchical indicators.

4.4. Determining the rules

Sixty-eight indicators are identified for the HSEE expert system. In order to decrease the rules of fuzzy expert system, we consider the indicators in a hierarchical manner. It means that the indicators which have common specifications are classified into one group.

All indicators in hierarchical chart are shown in Appendix 2. The overall implication of the hierarchical indicators is shown in Fig. 6. The HSEE expert system is composed of three levels. As shown in Fig. 6, the input of ES1 is all indicators of five main factors (health, safety, environment, ergonomics and general indicators). We have considered the overlapping indicators as general indicators. These indicators are related to problem solving team. Output of ES1 shows the condition of interval indicators. For example, ES1 specifies the condition of interval indicator for medical examinations. The outputs of ES1 define inputs for ES2. ES2 specifies the conditions of main indicators (health, safety, environment, ergonomics and general indicators). The outputs of ES2 define inputs of ES3. It means that ES3 uses main indicators' condition to specify HSEE condition of the gas refinery. If HSEE is violated, according to its violation severity, problem solving techniques are recommended. The list of all problem solving techniques are shown in Appendix 3.

The magnitude of the deviation is determined by a set of rules in the system. By using this method we have totally over 1000 rules. Some examples of health, safety, environmental and general indicators for the fuzzy rule-based expert system are given as follows:

Level 1

Example 1 (Health indicator)
IF pre-employment medical examinations to number of employed people in a given period in Sarkhoon1 and 2 ARE acceptable,
AND pre-employment medical examinations to number of employed people in a given period in Gavarzin IS acceptable,
THEN pre-employment medical examinations ARE acceptable WITH 0.95.[1]

Example 2 (Safety indicator)
IF unsafe acts in Sarkhoon1 and 2 ARE acceptable,
AND unsafe acts in Gavarzin IS acceptable,
THEN unsafe acts ARE acceptable WITH 0.95.

Example 3 (Environmental indicator)
IF emitted NO_x gas from flare of Sarkhoon1 and 2 ARE acceptable,
AND emitted NO_x gas from flare of Gavarzin IS acceptable,
AND emitted NO_x gas from burning pit of Sarkhoon1 and 2 ARE acceptable,
AND emitted NO_x gas from burning pit of Gavarzin IS acceptable,
THEN emitted NO_x gas IS acceptable WITH 0.95.

Example 4 (Ergonomics indicator)
IF musculoskeletal disorders rate in Sarkhoon1 and 2 ARE acceptable,
AND musculoskeletal disorders rate in Gavarzin IS acceptable,
THEN musculoskeletal disorders rate IS acceptable WITH 0.95.

Example 5 (General indicator)
IF execution of tutorial program according to tutorial calendar in Sarkhoon1 and 2 ARE acceptable,
AND execution of tutorial program according to tutorial calendar in Gavarzin IS acceptable,
THEN execution of tutorial program according to tutorial calendar IS acceptable WITH 0.95.

[1] This is the weight of the rule which is calculated between 0 and 1.

Level 2

Example 1 (Health indicator)
IF pre-employment medical examinations to number of employed people IS low deviated,
AND number of periodic examinations from workers who were away from their work environment more than one month IS low deviated,
THEN health is low deviated.

Example 2 (Safety indicator)
IF unsafe acts ARE medium deviated,
AND safety culture score IS medium deviated,
THEN safety IS medium deviated.

Example 3 (Environmental indicator)
IF energy consumption IS high deviated,
AND emitted CO gas IS high deviated,
AND emitted particles IS high deviated,
THEN environment IS high deviated.

Example 4 (Ergonomics indicator)
IF musculoskeletal disorders rate IS low deviated,
AND noise level IS low deviated,
THEN ergonomics program IS low deviated.

Example 5 (General indicator)
IF execution of tutorial program according to tutorial calendar IS medium deviated,
AND execution of committee regulations IS medium deviated,
THEN general IS medium deviated.

Level 3
IF health indicators ARE acceptable,
AND safety indicators ARE acceptable,
AND environment indicators ARE acceptable,
AND ergonomics indicators ARE acceptable,
AND general indicators ARE acceptable,
THEN HSEE program IS acceptable.

4.5. Inference engine

The expert system uses feed forward and backward inference methods. They used to identify which aspects of the conditional rules are fulfilled.

4.5.1. Fuzzy inference

The following operators are used for fuzzy inference:

- *Aggregation operator*: It is used for fulfillments of the rules according to their initial conditions. The minimum operator is used as shown in Table 1.
- *Implication operator*: The severities of fulfillments are computed in this level. The algebraic product and minimum operators are used for this purpose.
- *Accumulation operator*: It is used for accumulation of inferences among the fulfilled rules. The algebraic sum and maximum operators are used for this purpose.

5. A sample run

There are outputs in levels 1–3 after defuzzification in which output in level 3 contains corrective actions. Output in level 1 clarifies the assessment of interval indicators (Fig. 7).

6. Verification and validation: HSEE fuzzy expert system

To verify and validate HSEE fuzzy expert system we selected 10 indicators randomly. The indicators are shown in Table 2.

Table 1
The operators for fuzzy inference of the expert system

Operator	Relationship
Minimum	$\min(\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x))$
Maximum	$\max(\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x))$
Algebraic product	$\mu_{\tilde{A}}(x) \cdot \mu_{\tilde{B}}(x)$
Algebraic sum	$\mu_{\tilde{A}}(x) + \mu_{\tilde{B}}(x) - \mu_{\tilde{A}}(x) \cdot \mu_{\tilde{B}}(x)$

According to Table 2 the first and second indicators of safety sub-system have deviation. According to the knowledge of the safety experts, the system has a medium to high deviations. Therefore, safety sub-system is moderately deviated. Safety experts assign score of 50–60 to safety sub-system of the refinery. This result is approximately close to the output of HSEE fuzzy expert system [65].

The first and second indicators of ergonomics are accepted: the first one has low deviation because it is close to standard-min and the second one is exactly the same as standard-max. Therefore, ergonomics program is almost accepted. Ergonomics experts assign score of 75–85 to ergonomics sub-system of the refinery. This result is approximately close to the output of HSEE fuzzy expert system [66]. The first and second indicators of health are accepted; perhaps the second one has low devi-

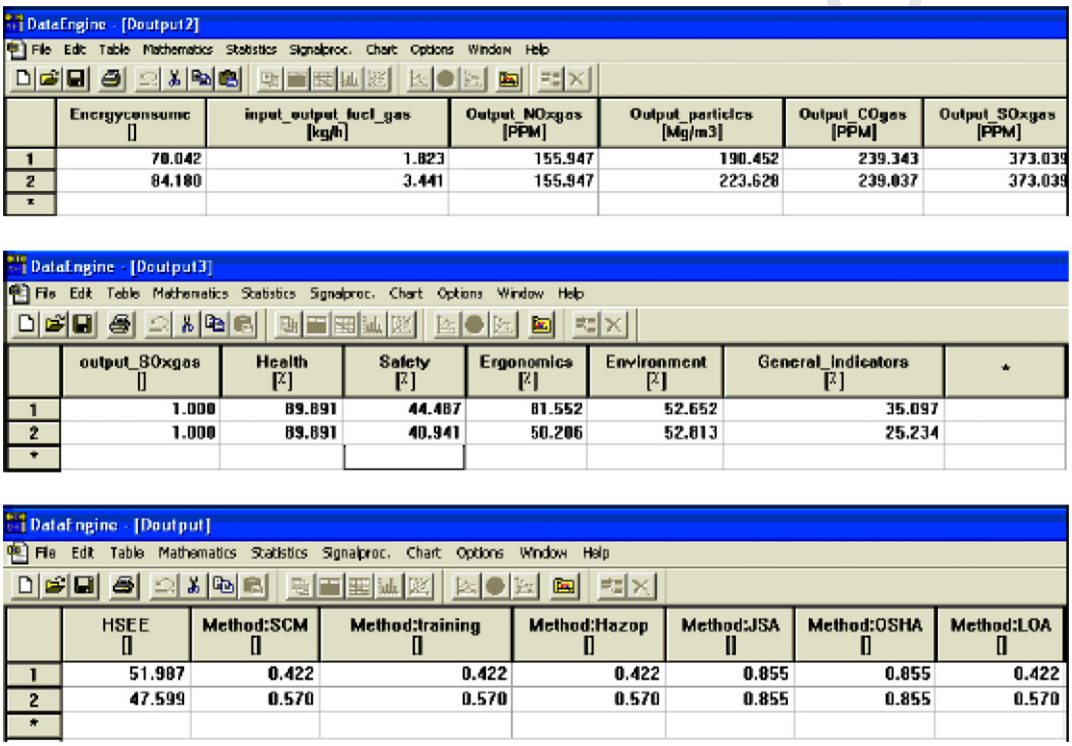

Fig. 7. Output in levels 1–3.

Table 2
A random selection of indicators for validation of the expert system

Main sub-systems	Indicator	Standard-max	Standard-min	Observed value
Safety	FA-rate (fatal accident rate)	10	0	12
	% Unsafe acts	40	0	48
Ergonomics	Light of work area	1000	200	300
	Confronting with noise	85	0	85
Health	Medical examinations before employment to number of employed people in a period	1	1	1
	Color (Pt-co)	20	0	19
Environment	Energy consumption in Sarkhoon1 and 2	2330	0	2650
	Output particles from unit 900 stake of solar turbines (Sarkhoon2)	350	0	400
General indicators	Corrective nonconformities	100	90	70
	Execution of tutorial program according to tutorial calendar	100	50	45

ation because it is close to the boundary. Thus, health sub-system is almost accepted. Health experts assign score of 92–100 to health sub-system of the refinery. This result is approximately close to the output of HSEE fuzzy expert system [67].

The first and second indicators of environment sub-system have deviations. According to the knowledge of the environment experts, there is medium to high deviations. Therefore, environment is approximately highly deviated. Environments experts assign score of 45–55 to environmental sub-system of the refinery. This result is approximately close to the output of HSEE fuzzy expert system [68].

The first and second indicators of general indicators have deviation. According to the knowledge of the general indicators expert, there is a high deviation. The result is general indicators are highly deviated. General indicators expert gives a grade about 40–45 to general indicators of the refinery. This result is approximately close to the output of HSEE fuzzy expert system.

Now the experts would like to determine the condition of HSEE in the gas refinery. The average of the above scores results is 60.45. The reader should note that it is assumed the general indicators have half total impact when compared with other indicators and therefore it is multiplied by 1/2. The output of HSEE fuzzy expert system is about 52 which reveals that the results of manual system and fuzzy expert system are approximately the same.

Furthermore, to formally test the results of manual and fuzzy expert systems one-way randomized block design (*F*-test) is conducted to foresee if the results of manual system (μ_1) is statistically the same as the fuzzy expert system (μ_2) based on a

Table 3
The average results of the 30 random samples for HSEE

	Safety	Ergonomics	Health	Environment	HSEE
Manual analysis	40	85	50	90	55
Fuzzy expert system	45	82	53	90	52

Table 4
F-Test for manual analysis and fuzzy expert system

Source	DF	SS	MS	*F*-Value	*p*-Value
Blocks	4	3569.60	892.40	139.44	0.000
Treatments (manual system and fuzzy expert system)	1	0.40	0.40	0.06	0.815
Error	4	25.60	6.40		
Total	9	3595.60			

95% Confidence interval for mean difference: (−4.84, 4.04).

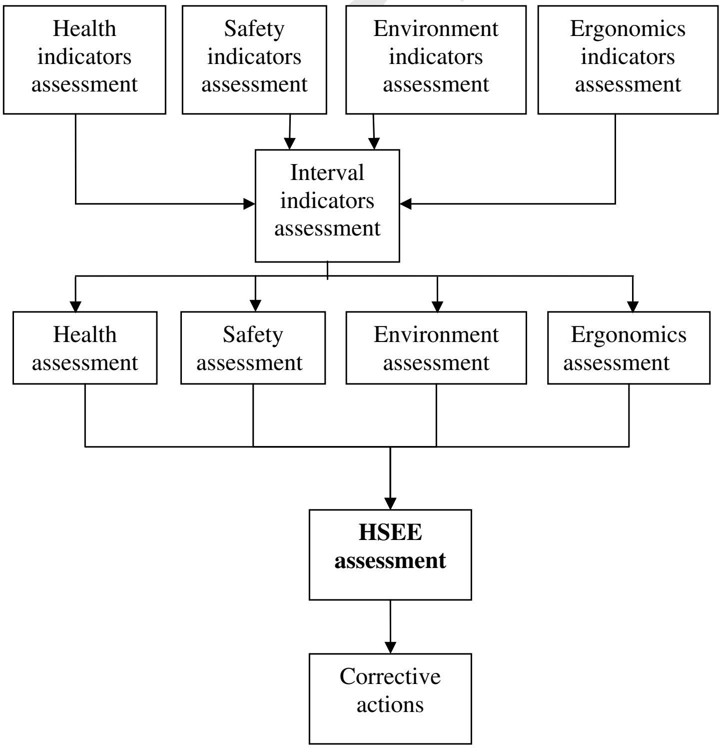

Fig. 8. HSEE fuzzy expert system assessment in all levels.

random sample of 30 indicators (refer to Eq. (4). The reader should note that we have increased the random sample to 30 to avoid bias. The result of the 30 random samples for each system is shown in Table 3:

$$\begin{aligned} &H_0: \quad \mu_1 = \mu_2 \\ &H_1: \quad \mu_1 \neq \mu_2 \end{aligned} \tag{4}$$

The null hypothesis is accepted and it is concluded that that health, safety, environment and ergonomics in particular and total HSEE in general are statistically the same for the two systems (Table 4). Moreover, the same performance as conventional system is reported by the expert system. However, the prescribed integrated HSEE system is much faster and more reliable than conventional manual system.

7. Capabilities of the proposed tool

HSEE fuzzy expert system uses a logical process by which an expert in the field would pursue the identification of the causes of good or bad performance. Furthermore, it assesses all indicators and acts as a decision support system (DSS).

7.1. Assessments of all levels

The procedure is shown in Fig. 8 and involves the following steps:

- detail level assessment (all indicators of the four main levels);
- interval level assessment;
- main level assessment (health, safety, environment, ergonomics and general indicators);
- total assessment (HSEE assessment).

The fuzzy expert system can warn managers about deviated indicators. It can also reveal the impact of each level to others. Therefore, the first, second and main level indicators and consequently the final output of the system or HSEE can be assessed (Appendix 2).

Table 5
The impacts of utilizing HSEE expert system in the refinery

Indicators		Year 2005	Year 2006
Safety indicators	Safety culture score	61	73
	% of unsafe acts	31.5	20.4
	Near miss rate	0.44	1.4
	Accident severity rate	0.64	0.42
	Accident frequency rate	55.95	48.44
Ergonomics indicators	Workplace lighting		
	• Refinery control room	555.3	610
	• Gavarzin control room	497.8	515
	WBGT of		
	unit 500	32.7	27.0
	unit 1000	33.0	29.1
	unit 700	31.3	31.3
	PMV_{PPD}		
	• Refinery control room	30	13
	• Gavarzin control room	41	17
	Musculoskeletal disorders rate	43	35.7
Environmental indicators	Emitted NO_x gases from unit 900 stake (PPM)	121	76
	Emitted SO_x gases from unit 500 stake (PPM)	230	45
	Emitted CO from unit 600 stake (PPM)	345	222
	Emitted dust from unit 900 stake (ml/m^3)	60	19
	Sound level – night (dB)	50	42
	Sound level – day (dB)	71	55
Health indicators	Pre-employment medical examinations to number of employed people in a given period (%)	93.7	100
	Periodic examinations from worker with harmful works to total number of workers (%)	76	97.3
	Periodic examinations from workers whose work has changed	0	67.8
	Periodic examinations from workers who were away from their work environment for more than one month	0	71.7
	Color (Pt-co) – Water	14	6
	PH – Water	11.3	8.7
	Darkness (JTU) – Water	17	6.4
General indicators	Suitability of HSEE committee discussions	64.8	87.4
	Execution of HSEE committee discussions	55.9	91.3
	Tasks clarification of HSEE committee members	37.3	100
	Execution of tutorial program according to tutorial calendar	46.9	87.2

7.2. HSEE fuzzy expert system as a DSS

Decision support systems (DSS) are a specific class of computerized information system that supports business and organizational decision-making activities [69,70]. A properly designed DSS is an interactive software-based system intended to help decision makers compile useful information from raw data, documents, personal knowledge, and/or business models to identify and solve problems and make decisions. HSEE fuzzy expert system can be used as a DSS in the gas refinery. It should be mentioned that the four conditions (acceptance, low deviation, moderate deviation and high deviation) are defined for HSEE which is the final output of the expert system.

8. Conclusion

A fuzzy expert system for assessment, control, monitoring and improvement of HSEE was described in this paper. The proposed expert system can help organizations such as gas refineries to develop their own comprehensive and dynamic HSEE program. The refinery was monitored for about one year after the implementation of fuzzy expert system. Moreover, data related to health, safety, environment and ergonomics factors were collected before and after (after approximately 12 months) implementation of the expert system. Table 5 shows the impacts of utilizing HSEE expert system with respect to some of the most important HSEE indicators in the refinery. As shown considerable improvement are reported with respect to these indicators.

The HSEE fuzzy expert system as a decision support system (DSS) can guide the manager to evaluate the impact of all HSEE indicators on organizational performance. It also analyzes the indicators which have the most impact on HSEE. This can help the manager to predict the future deficiencies and plan which part of the organization must be enhanced to have more success and less costs. Finally, this application could be integrated with other executive support systems for delivering a broader, systematic and dynamic information support system. Previous studies have introduced HSE expert system whereas this study introduced an integrated HSE and ergonomics expert system through fuzzy logic. Three important reasons to use fuzzy expert systems for establishment of HSEE are (1) reduction of human error, (2) creation of expert knowledge and (3) capability of dealing and interpreting large amount of vague data which is inevitable in the case health, safety, environment and ergonomics analysis. In addition, the indicators which have the most impact on efficiency could be identified. The practical actions to increase efficiency were also identified by the expert system. Therefore, an integrated HSEE decision support system was implemented for assessment of various indicators on outputs of the refinery. It is therefore suggested to utilize the integrated fuzzy expert system in complex systems such refineries, petrochemical plants, etc. This is of course achieved by utilizing the framework presented for the fuzzy expert system. The expert systems should be powerful enough to cover all areas of HSEE in a complex system. On the other hand, it should be integrated, flexible and easy to use.

Appendix 1. Indicators and standards

ID	Safety indicators	Standard-max	Standard-min
1	Safety culture score	100	40
2	% of unsafe acts	40	0
3	AS-rate (accident severity rate)	10	0
4	AF-rate (accident frequency rate)	6	0
5	FA-rate (fatal accident rate)	1	0
6	ADI-rate (alternate duties injury)	5	0
ID	**Ergonomics indicators**	**Standard-max**	**Standard-min**
7	Light of work environment	500	250
8	Noise level	85	0
9	WBGT	30	0
10	PMV_{PPD}	10	0
11	Musculoskeletal disorders rate	60	0
12	LI	1	0
ID	**Health indicators**	**Standard-max**	**Standard-min**
13	Pre-employment medical examinations to number of employed people in a given period	1	1
14	Number of periodic examinations from worker with harmful works to number of those workers	1	1
15	Number of periodic examinations from workers whose work has changed	1	1
16	Number of periodic examinations from workers who were away from their work environment for more than one month	1	1

(continued on next page)

Appendix 1 (*continued*)

ID	Health indicators	Standard-max	Standard-min
17	Pre-employment and periodic medical test of employment from workers	1	1
18	Color (Pt-co) – Water	20	0
19	PH – Water	9.2	6.2
20	Darkness (JTU) – Water	25 mg/l	0

ID	Environment indicator	Standard-max	Standard-min
21	Energy consumption in Sarkhoon1 and 2	2330 kw h	0
22	Energy consumption in Gavarzin	30 kw h	0
23	Input fuel gas of unit 500	3.17 kg/h	0
24	Input fuel gas of unit 900	3.17 kg/h	0
25	Input fuel gas of unit 600	3.17 kg/h	0
26	Input fuel gas to LP and HP network	3.17 kg/h	0
27	Emitted fuel gas from LP and HP	3.17 kg/h	0
28	Emitted NO_x gas from unit 900 stake of solar turbines (Sarkhoon2)	PPM 350	0
29	Emitted NO_x gas from unit 500 stake of Restun turbines (Sarkhoon2)	PPM 350	0
30	Emitted NO_x gas from unit 600 stake of reboilers (Sarkhoon2)	PPM 350	0
31	Emitted NO_x gas from glycol unit stake of reboilers (Gavarzin)	PPM 350	0
32	Emitted NO_x gas from flare of Sarkhoon1	PPM 350	0
33	Emitted NO_x gas from flare of Sarkhoon2	PPM 350	0
34	Emitted NO_x gas from flare of Gavarzin	PPM 350	0
34	Emitted NO_x gas from burning pit of Sarkhoon1 and 2	PPM 350	0
36	Emitted NO_x gas from burning pit of Gavarzin	PPM 350	0
37	Emitted SO_x gas from unit 900 stake of solar turbines (Sarkhoon2)	PPM 800	0
38	Emitted SO_x gas from unit 500 stake of Restun turbines (Sarkhoon2)	PPM 800	0
39	Emitted SO_x gas from unit 600 stake of reboilers (Sarkhoon2)	PPM 800	0
40	Emitted SO_x gas from Glycol unit stake of reboilers (Gavarzin)	PPM 800	0
41	Emitted SO_x gas from flare of Sarkhoon1	PPM 800	0
42	Emitted SO_x gas from flare of Sarkhoon2	PPM 800	0
43	Emitted SO_x gas from flare of Gavarzin	PPM 800	0
44	Emitted SO_x gas from burning pit of Sarkhoon1 and 2	PPM 800	0
45	Emitted SO_x gas from burning pit of Gavarzin	PPM 800	0
46	Emitted CO gas from unit 900 stake of solar turbines (Sarkhoon2)	PPM 130	0
47	Emitted CO gas from unit 500 stake of Restun turbines (Sarkhoon2)	PPM 130	0
48	Emitted CO gas from unit 600 stake of reboilers (Sarkhoon2)	PPM 130	0
49	Emitted CO gas from Glycol unit stake of reboilers (Gavarzin)	PPM 130	0
50	Emitted CO gas from flare of Sarkhoon1	PPM 130	0
51	Emitted CO gas from flare of Sarkhoon2	PPM 130	0
52	Emitted CO gas from flare of Gavarzin	PPM 130	0
53	Emitted CO gas from burning pit of Sarkhoon1 and 2	PPM 130	0
54	Emitted CO gas from burning pit of Gavarzin	PPM 130	0
55	Emitted particles from unit 900 stake of Solar turbines (Sarkhoon2)	350 mg/m^3	0
56	Emitted particles from unit 500 stake of Restun turbines (Sarkhoon2)	350 mg/m^3	0
57	Emitted particles from unit 600 stake of reboilers (Sarkhoon2)	350 mg/m^3	0
57	Emitted particles from Glycol unit stake of reboilers (Gavarzin)	350 mg/m^3	0
59	Emitted particles from flare of Sarkhoon1	350 mg/m^3	0
60	Emitted particles from flare of Sarkhoon2	350 mg/m^3	0
61	Emitted particles from flare of Gavarzin	350 mg/m^3	0
62	Emitted particles from burning pit of Sarkhoon1 and 2	350 mg/m^3	0
63	Emitted particles from burning pit of Gavarzin	350 mg/m^3	0

ID	General indicators	Standard-max	Standard-min
64	Suitability of committee regulations	100%	80%
65	Execution of committee regulations	100%	80%
66	Tasks clarification of committee members	100%	100%
67	Execution of tutorial program according to tutorial calendar	100%	90%
68	Corrective nonconformities	100%	50%

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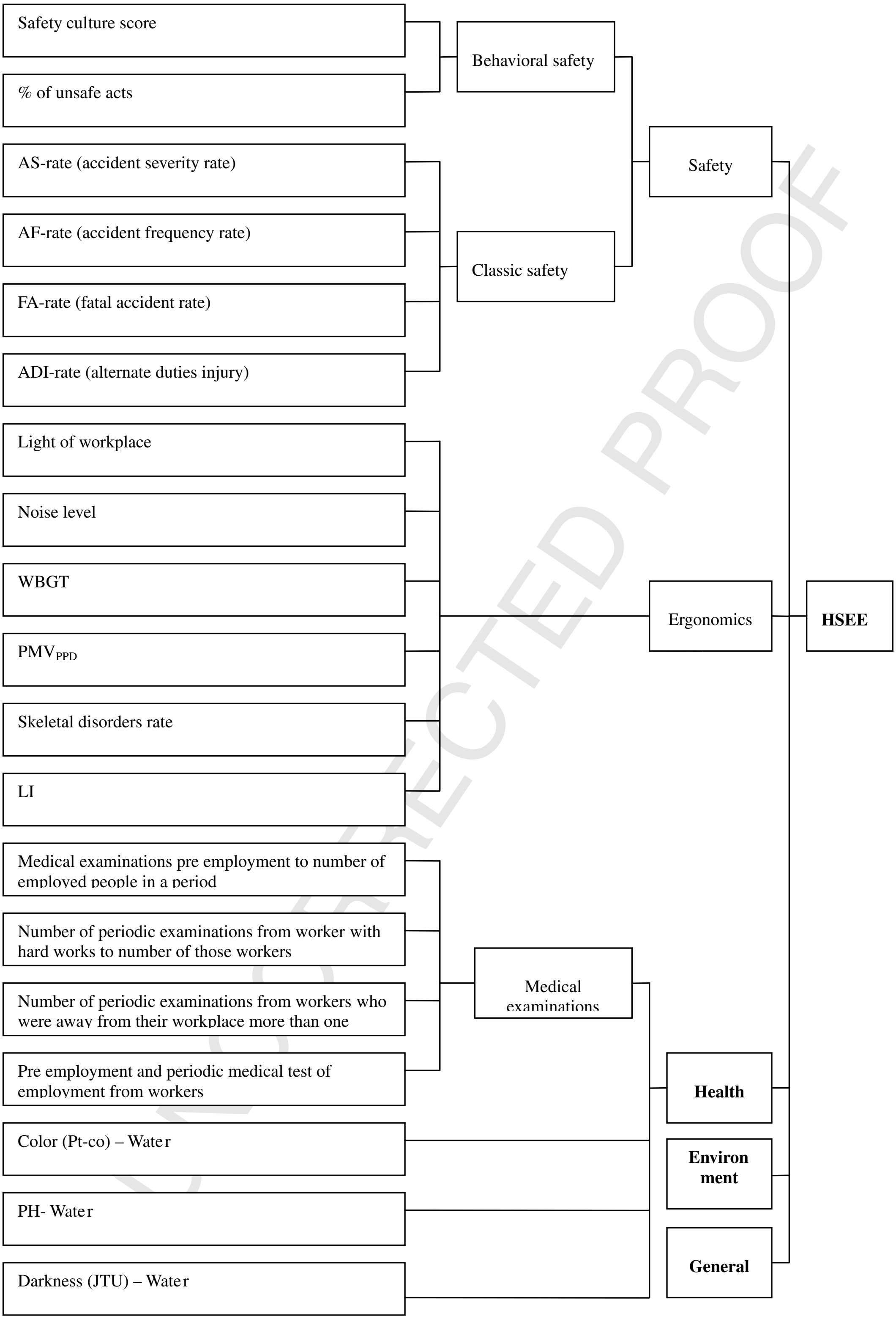
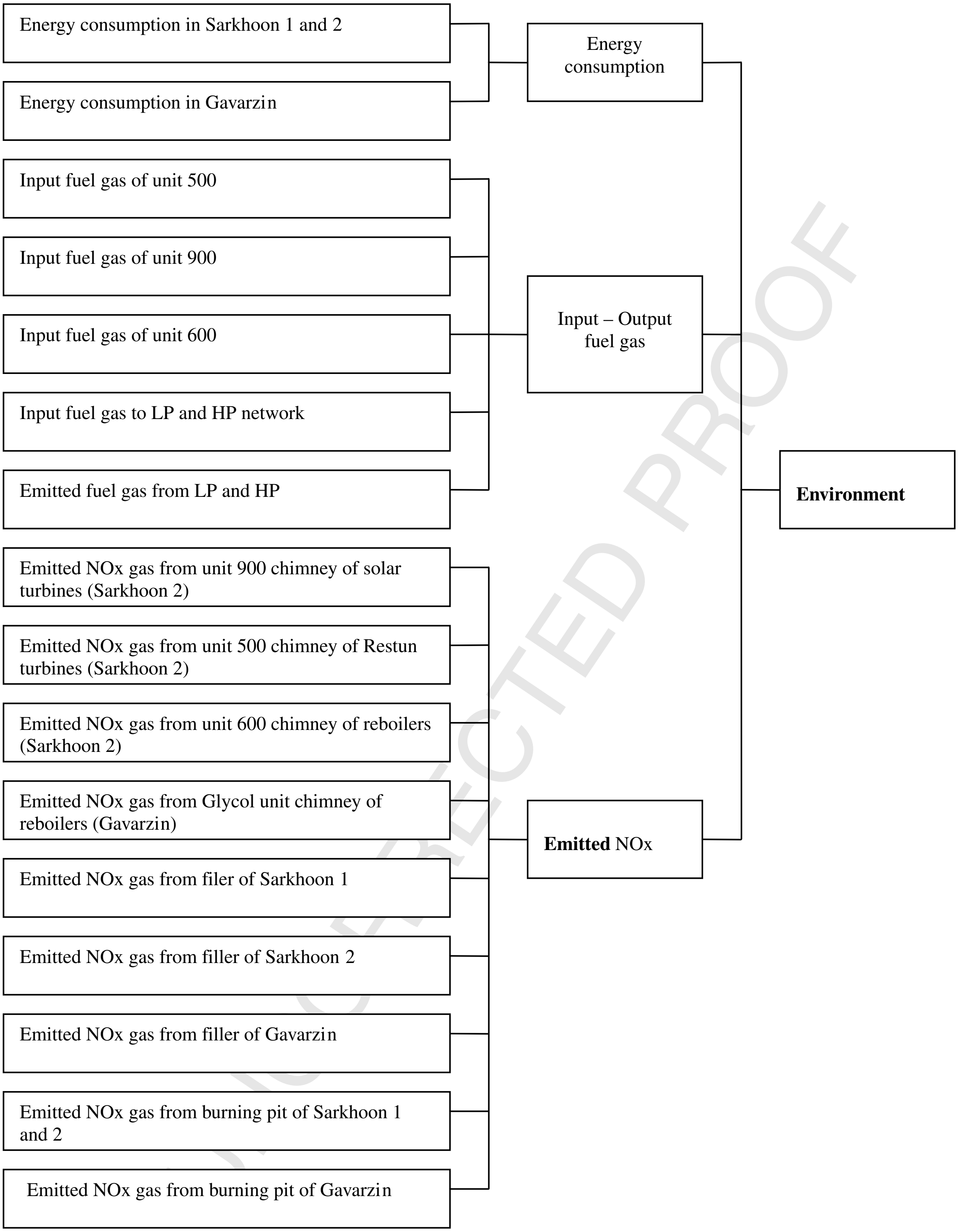
Appendix 2. Hierarchical design of the HSEE indicators





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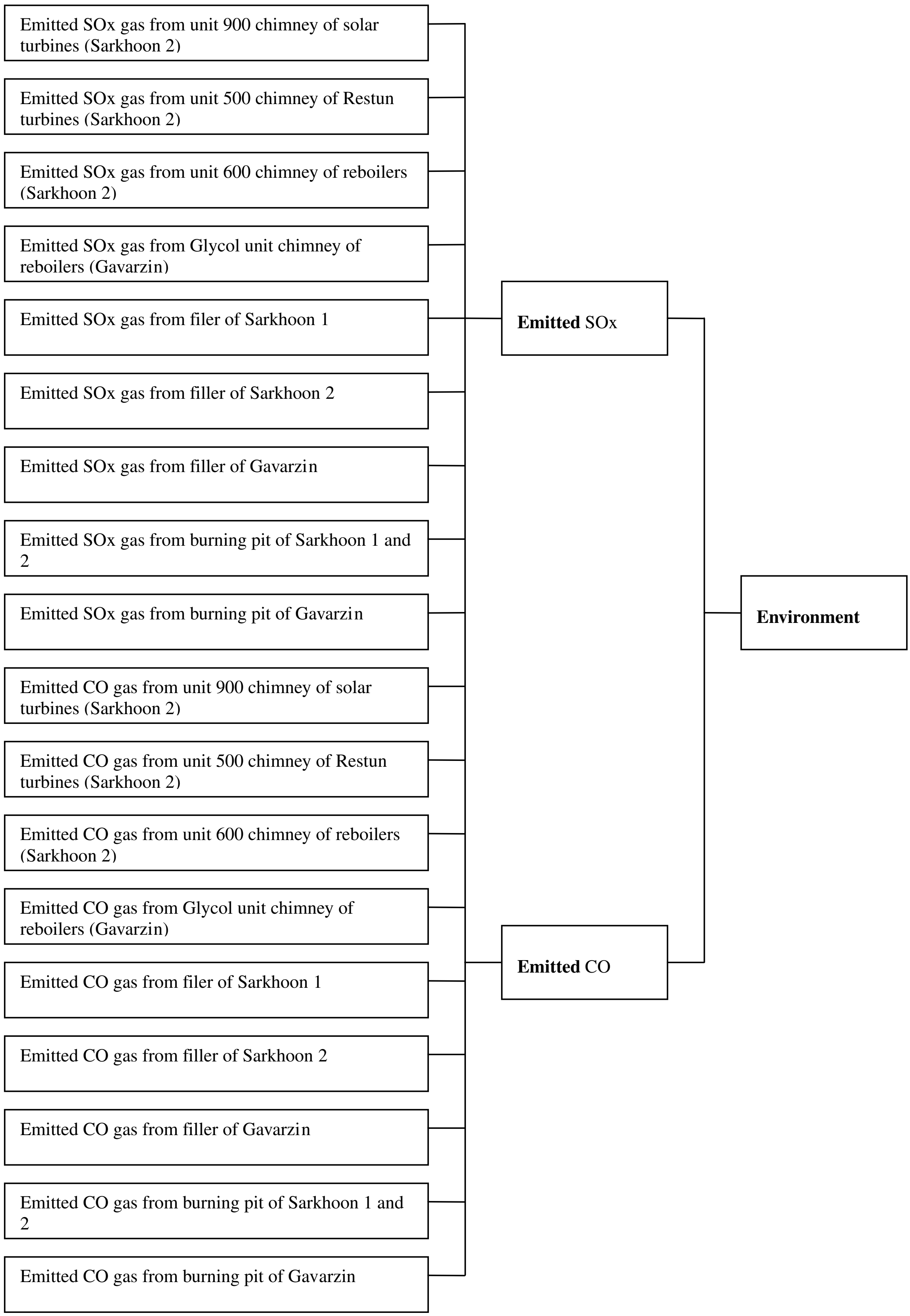
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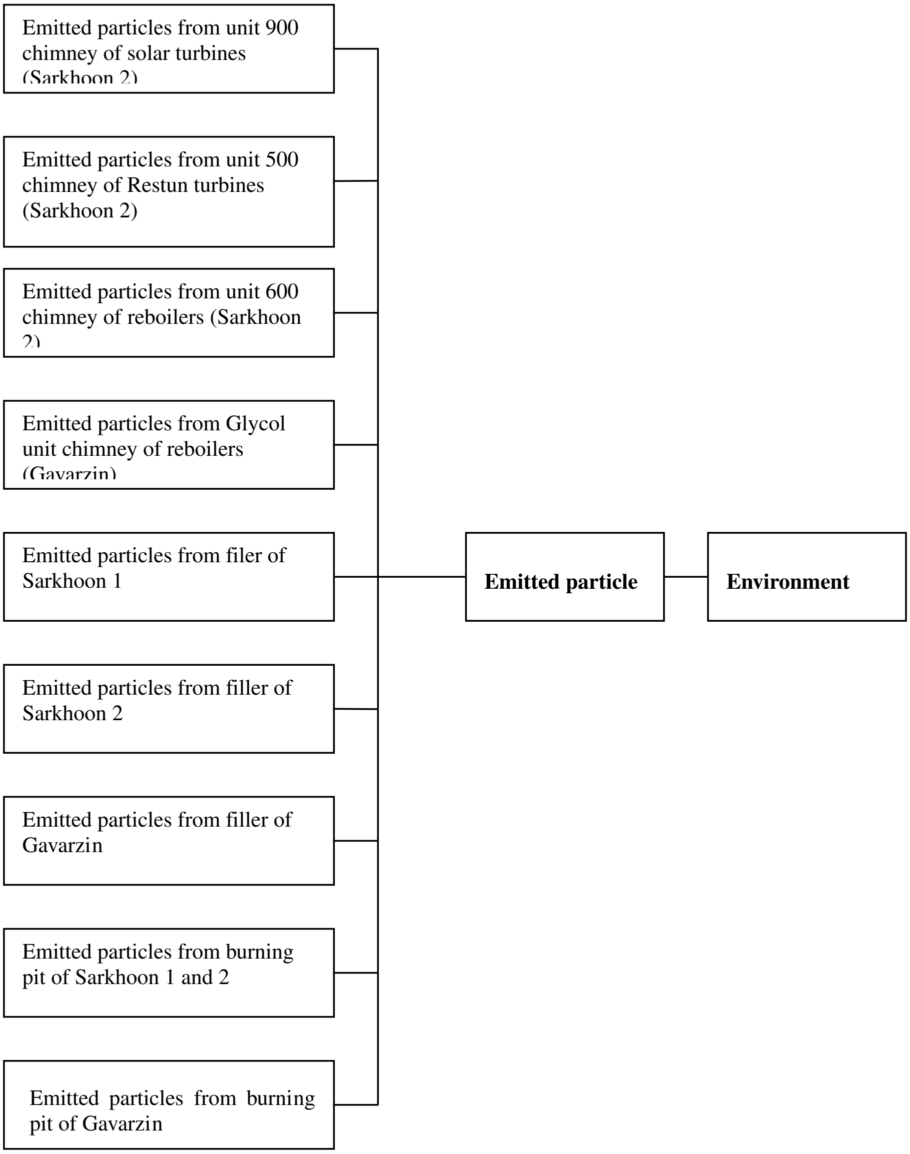
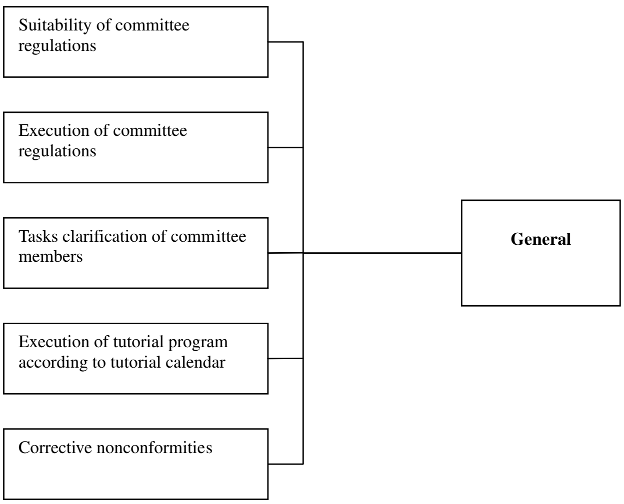
Emitted SOx gas from unit 500 chimney of Restun turbines (Sarkhoon 2)
Emitted SOx gas from unit 600 chimney of reboilers (Sarkhoon 2)
Emitted SOx gas from Glycol unit chimney of reboilers (Gavarzin)
Emitted SOx gas from filer of Sarkhoon 1
Emitted SOx gas from filler of Sarkhoon 2
Emitted SOx gas from filler of Gavarzin
Emitted SOx gas from burning pit of Sarkhoon 1 and 2
Emitted SOx gas from burning pit of Gavarzin
Emitted CO gas from unit 900 chimney of solar turbines (Sarkhoon 2)
Emitted CO gas from unit 500 chimney of Restun turbines (Sarkhoon 2)
Emitted CO gas from unit 600 chimney of reboilers (Sarkhoon 2)
Emitted CO gas from Glycol unit chimney of reboilers (Gavarzin)
Emitted CO gas from filer of Sarkhoon 1
Emitted CO gas from filler of Sarkhoon 2
Emitted CO gas from filler of Gavarzin
Emitted CO gas from burning pit of Sarkhoon 1 and 2
Emitted CO gas from burning pit of Gavarzin
Emitted SOx
Emitted CO
Environment


Emitted particles from unit 900 chimney of solar turbines (Sarkhoon 2)
Emitted particles from unit 500 chimney of Restun turbines (Sarkhoon 2)
Emitted particles from unit 600 chimney of reboilers (Sarkhoon 2)
Emitted particles from Glycol unit chimney of reboilers (Gavarzin)
Emitted particles from filer of Sarkhoon 1
Emitted particles from filler of Sarkhoon 2
Emitted particles from filler of Gavarzin
Emitted particles from burning pit of Sarkhoon 1 and 2
Emitted particles from burning pit of Gavarzin
Emitted particle
Environment


Suitability of committee regulations
Execution of committee regulations
Tasks clarification of committee members
Execution of tutorial program according to tutorial calendar
Corrective nonconformities
General

Appendix 3. The list of all problem solving techniques

	Techniques	Description
1	Hazard and operability studies (Hazop)	HAZOP entails the investigation of deviations from design intent for a process by a team of individuals with expertise in different areas
2	Failure mode and effect analysis (FMEA)	FMEA is a bottom-up approach that looks at the failure of each element of a system or process and identifies the consequence of each failure
3	Fault tree analysis (FTA)	A fault tree is a logical diagram which shows the relation between system failure, i.e., a specific undesirable event in the system, and failures of the components of the system [2]. It is a technique based on deductive logic
4	Job safety analysis (JSA)	A job safety analysis (JSA) is a method that can be used to identify, analyze and record: (1) the steps involved in performing a specific job, (2) the existing or potential safety and health hazards associated with each step, and (3) the recommended action(s)/procedure(s) that will eliminate or reduce these hazards and the risk of a workplace injury or illness.
5	Quick exposure checklist (QEC)	This technique allows for various exposure scores for the back area, the shoulder/arm area, the wrist/hand area and neck to be assessed. It uses a grid system to calculate the scores for the various body parts, based on the assessment of the analyst and also of the worker
6	Nordic Questionnaire	The Nordic Questionnaire is designed for the assessment of psychological, social, and organizational working conditions: (1) to provide a basis for implementing organizational development and interventions, (2) for documentation of changes in working conditions, and (3) for research into associations between work and health.
7	Predictive Human error analysis (PHEA)	The quantitative methods for prediction and analysis of human errors during work
8	Anthropometrics measurements	The systematic collection and correlation of measurements of the human body. Anthropometrics are used to describe the "user" or "target" population for a product
9	Zero defects	At the heart of HSEE is a commitment to continuous improvement, the basis of which is the belief that within any situation or activity, there is always room to improve. However, here the goal is perfection or "Zero Defects," nothing less. This goal applies to every piece in the puzzle: people, processes and products. All must work together to provide the foundation for zero-defect
10	Is/Is not matrix	Determining the template of similar cases' specifications by means of a classified structure
11	Nominal group technique	The nominal group technique is a structured decision-making process designed to involve all group members, encourage multiple ideas, insure thorough consideration of ideas, and generate an optimal group decision
12	Cause and effect analysis	Cause–effect analysis is a well-documented diagrammatic technique designed to unearth the root cause of problems and subsequent effects Cause–effect analysis diagram use standard grouping categories to ensure that all possible causes are considered
13	Idea writing	Making partnership among people in team working
14	Criteria testing	Evaluating and comparing the replaced solutions by ranking them on the basis of determined gauges
15	Contingency planning	Contingency planning is a systematic approach to identifying what can go wrong in a situation. Rather than hoping that everything will turn out OK or that "fate will be on your side", a planner should try to identify contingency events and be prepared with plans, strategies and approaches for avoiding, coping or even exploiting them
16	Safety behavior sampling	Determining of unsafe behaviors' portion and the type and importance of them among people
17	System diagrams	System diagrams are particularly helpful in showing you how a change in one factor may impact elsewhere. They are excellent tools for flushing out the long term impacts of a change. Importantly, a good system diagram will show how changing a factor may feed back to affect itself

(*continued on next page*)

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Appendix 3 (*continued*)

	Techniques	Description
18	SWOT analysis	Discover new opportunities. Manage and eliminate threats. SWOT analysis is a powerful technique for understanding your strengths and weaknesses, and for looking at the opportunities and threats you face
19	Porter's five forces	The Porter's five forces tool is a simple but powerful tool for understanding where power lies in a situation. This is useful, because it helps you understand both the strength of your current competitive position, and the strength of a position you're looking to move into
20	PEST analysis	PEST analysis is a simple but important and widely-used tool that helps you understand the big picture of the *P*olitical, *E*conomic, *S*ocio-Cultural and *T*echnological environment you are operating in

References

[1] M.G. Abou-Ali, M. Khamis, An integrated intelligent defects diagnostic system for tire production and service, Expert Systems with Applications 24 (2003) 247–259.
[2] A.A. Shikdar, M.N. Sawaqed, Ergonomics, occupational health and safety in the oil industry: a managers' response, Computers and Industrial Engineering 47 (2004) 223–232.
[3] M.A. Awadallah, M. Morcos, Application of AI tools in fault diagnosis of electrical machines and drives – an overview, EEE Transactions on Energy Conversion 18 (2003) 245–251.
[4] M.A. Ayoub, Ergonomic deficiencies: I. Pain at work, Journal of Occupational Medicine 32 (1) (1990) 52–57.
[5] M.A. Ayoub, Ergonomic deficiencies: II. Probable causes, Journal of Occupational Medicine 32 (2) (1990) 131–136.
[6] W. Blanchard, J. Fabrychy, System Engineering and Analysis, Prentice-Hall International, Inc., USA, 1998, pp. 112–123.
[7] R.W. Blanning, Management applications of expert systems, Information and Management 7 (1984) 311–316.
[8] R. Bryden, P.T.W. Hudson, Because we want, Safety and Health Practitioner 23 (2005) 51–54.
[9] G.J. Burri, M.G. Helander, A field study of productivity improvements in the manufacturing of circuit boards, International Journal of Industrial Ergonomics 7 (1991) 207–215.
[10] M. Cabrero-Canosa, M. Castro-Pereiro, M. Graña-Ramos, E. Hernandez-Pereira, V. Moret-Bonillo, M. Martin-Egana, H. Verea-Hernando, An intelligent system for the detection and interpretation of sleep apneas, Expert Systems with Applications 24 (2003) 335–349.
[11] N.H.M. Caldwell, B.C. Breton, D.M. Holburn, Remote instrument diagnosis on the Internet, IEEE Intelligent Systems and their Applications 13 (1998) 70–76.
[12] D. Champoux, J.J. Brun, Occupational health and safety management in small size enterprises: an overview of the situation and avenues for intervention and research, Safety Science 41 (2003) 301–318.
[13] C. Changchit, C.W. Holsapple, Supporting managers' internal control evaluations: an expert system and experimental results, Decision Support Systems 30 (2001) 437–449.
[14] J.R. Chen, Y.T. Yang, A predictive risk index for safety performance in process industries, Journal of Loss Prevention in the Process Industries 17 (2004) 233–242.
[15] J.G. Chen, R.E. Schlegel, J.B. Peacock, A computer assisted system for physical ergonomics analysis, Computers and Industrial Engineering 20 (1991) 261–269.
[16] K. Chin, K. Pun, H. Lau, Development of a knowledge-based self assessment system for measuring organizational performance, Expert Systems with Applications 24 (2003) 443–456.
[17] E. Coakes, K. Merchant, B. Lehaney, The use of expert systems in business transformation, Management Decision 35 (1997) 53–57.
[18] B. Das, A. Sengupta, Industrial workstation design: a systematic ergonomic approach, Applied Ergonomics 27 (1996) 157–163.
[19] H. Deng, Multicriteria analysis with fuzzy pairwise comparison, International Journal of Approximate Reasoning 21 (3) (1999) 215–231.
[20] Y. Duan, Z. Fu, D. Li, Toward developing and using Web-based telediagnosis in aquaculture, Expert Systems with Applications 25 (2003) 247–254.
[21] A. Dubois, L.E. Gadde, Systematic combining: an abductive approach to case research, Journal of Business Research 55 (2002) 553–560.
[22] J. Eklund, Development work for quality and ergonomics, Applied Ergonomics 31 (2000) 641–648.
[23] S.B. Eom, A survey of operational expert systems in business (1980–1993), Interfaces 26 (1996) 50–70.
[24] S.B. Eom, S.M. Lee, A. Ayaz, Expert systems applications development research in business: a selected bibliography (1975–1989), European Journal of Operational Research 68 (1993) 278–290.
[25] D.P. Fang, F. Xie, X.Y. Huang, H. Li, Factor analysis-based studies on construction workplace safety management in China, International Journal of Project Management 22 (2004) 43–49.
[26] R. Flin, K. Mearns, P. O'Connor, R. Bryden, Measuring the safety climate: identifying the common features, Safety Science 34 (2000) 177–192.
[27] C. Foltin, L. Garceau, Beyond expert systems: neural networks in accounting, National Public Accountant 41 (1996) 26–32.
[28] C. Foltin, L.M. Smith, Accounting expert systems, CPA Journal 64 (1994) 46–51.
[29] G. Grote, C. Künzler, Diagnosis of safety culture in safety management audits, Safety Science 34 (2000) 131–150.
[30] F.W. Guldenmund, The nature of safety culture: a review of theory and research, Safety Science 34 (2000) 215–257.
[31] G. Hagg, Corporate initiatives in ergonomics – an introduction, Applied Ergonomics 34 (2003) 3–15.
[32] S.R. Hornik, M. Bernadette, Expert systems usage and knowledge acquisition: an empirical assessment of analogical reasoning in the evaluation of internal controls, Journal of Information Systems 11 (1997) 57–74.
[33] M.G. Na, S.H. Shin, S.M. Lee, D.W. Jung, S.P. Kim, J.H. Jeong, B.C. Lee, Prediction of major transient scenarios for severe accidents of nuclear power plants, IEEE Transactions on Nuclear Science 51 (2) (2004) 313–321.
[34] J. Kacprzyk, R.R. Yager, Emergency-oriented expert systems: a fuzzy approach, Information Sciences 37 (1–3) (1985) 143–155.
[35] C. Kahraman, D. Ruan, I. Doğan, Fuzzy group decision-making for facility location selection, Information Sciences 157 (2003) 135–153.
[36] S.D. Kaminaris, T.D. Tsoutsos, D. Agoris, A.V. Machias, Assessing renewables-to-electricity systems: a fuzzy expert system model, Energy Policy 34 (2006) 1357–1366.
[37] R. Kennedy, B. Kirwan, Development of a hazard and operability-based method for identifying safety management vulnerabilities in high risk systems, Safety Science 30 (1998) 34–41.
[38] D. Laurence, Safety rules and regulations on mine sites – the problem and a solution, Journal of Safety Research 36 (2005) 39–50.
[39] M.J. Lawrie, D. Parker, P.T.W. Hudson, Investigating employee perceptions of a framework of safety culture maturity, Safety Science 44 (2006) 259–276.

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[40] M. Lee, Expert system for nuclear power plant accident diagnosis using a fuzzy inference method, Expert Systems 19 (2002) 201–207.
[41] D. Li, Z. Fu, Y. Duan, Fish-expert: A Web-based expert system for fish disease diagnosis, Expert Systems with Applications 23 (2002) 311–320.
[42] P. Lillrank, A.B. Shani, P. Lindberg, Continuous improvement: exploring alternative organizational designs, Total Quality Management 12 (2001) 41–55.
[43] B.D. Mahaman, P. Harizanis, I. Filis, E. Antonopoulos, C.P. Yialouris, A.B. Sideridis, A diagnostic expert system for honeybee pests, Computers and Electronics in Agriculture 36 (2002) 17–31.
[44] G. Mattioli, M. Castagnetti, S. Leggio, V. Jasonnni, Complications of mechanical suturing in pediatric patients, Journal of Pediatric Surgery 38 (2003) 1051–1054.
[45] M. Mearns, S.M. Whitaker, R. Flin, Safety climate, safety management practice and safety performance in offshore environments, Safety Science 41 (2003) 641–680.
[46] R.E. Moore, Interval Analysis, Prentice-Hall, New Jersey, 1996. pp. 46–70.
[47] U. Munck-Ulfsfält, A. Falck, A. Forsberg, C. Dahlin, A. Eriksson, Corporate ergonomics programme at Volvo Car Corporation, Applied Ergonomics 34 (2003) 17–22.
[48] E.W.T. Ngai, T.C.E. Cheng, A knowledge-based system for supporting performance measurement of AMT projects: a research agenda, International Journal of Operations and Production Management 21 (2001) 223–234.
[49] S. Nguyen, T. Hung, E. Walker, A First Course in Fuzzy Logic, Chapman and Hall, London, 1999. pp. 56–75.
[50] C.R. Plott, Markets as information gathering tools, Southern Economic Journal 67 (2000) 2–15.
[51] C. Prez-Carretero, L.M. Laita, E. Roanes-Lozano, L. Lázaro, J. González-Cajal, L. Laita, Logic and computer algebra based expert system for diagnosis of anorexia, Mathematics and Computers in Simulation 58 (2002) 183–202.
[52] P.J. Pronovost, D.A. Thompson, C.G. Holzmueller, L.H. Lubomski, L.L. Morlock, Defining and measuring patient safety, Critical Care Clinics 21 (2005) 1–19.
[53] A. Pun, E. Roca, J.M. Lema, An expert system for monitoring and diagnosis of anaerobic wastewater treatment plants, Water Research 36 (2002) 2656–2666.
[54] R. Qien, Risk indicators as a tool for risk controls, Reliability Engineering System Safety 74 (2001) 147–167.
[55] A.A. Qureshi, J.K. Shim, J.G. Siegel, Artificial intelligence in accounting and business, National Public Accountant 43 (1998) 13–18.
[56] M.L. Resnick, A. Zanotti, Using ergonomics to target productivity improvements, Computers and Industrial Engineering 33 (1997) 185–188.
[57] L.M. Rocha, Evidence sets: modeling subjective categories, International Journal of General Systems 27 (1997) 457–494.
[58] R. Santhanam, J. Elam, A survey of knowledge-based systems research in decision sciences (1980–1995), Journal of the Operational Research Society 49 (5) (1998) 445–457.
[59] N.K. Taylor, E.N. Corlett, D. Alfie, Auxiliary logistics for industrial engineering, International Journal of Industrial Ergonomics 1 (1987) 15–25.
[60] B. Verma, J. Zakos, A computer-aided diagnosis system for digital mammograms based on fuzzy-neural and feature extraction techniques, IEEE Transactions on Information Technology in Biomedicine 5 (2001) 46–54.
[61] W.P. Wagner, M.K. Najdawi, Q.B. Chung, Selection of knowledge acquisition techniques based upon the problem domain characteristics of production and operations management expert systems, Expert Systems 18 (2001) 76–87.
[62] W.P. Wagner, J. Otto, Q.B. Chung, Knowledge acquisition for expert systems in accounting and financial problem domains, Knowledge-Based Systems 15 (2002) 439–447.
[63] J.R. Wilson, E.N. Corlett, Evaluation of Human Work: A Practical Ergonomics Methodology, Taylor and Francis, USA, 1992. pp. 141–169.
[64] B.K. Wong, J.A. Monaco, A bibliography of expert system applications for business (1984–1992), European Journal of Operational Research 85 (1995) 416–432.
[65] B.K. Wong, J.A. Monaco, Expert system applications in business: a review and analysis of the literature (1977–1993), Information and Management 29 (1995) 141–152.
[66] L.A. Zadeh, Is there a need for fuzzy logic?, Information Sciences 178 (13) (2008) 2751–2779
[67] L.A. Zadeh, From imprecise to granular probabilities, Fuzzy Sets and Systems 154 (2005) 370–374.
[68] L.A. Zadeh, From search engines to question-answering systems – the role of fuzzy logic, Progress in Informatics 1 (2005) 1–3.
[69] L.A. Zadeh, Toward a generalized theory of uncertainty (GTU) – an outline, Information Sciences 172 (1–2) (2005) 1–40.
[70] L.A. Zadeh, Precisiated natural language (PNL), AI Magazine 25 (2004) 74–91.