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INDUSTRIAL SECURITY

Scenario Assessment in Industrial Emergencies

T. A. Gubina[a, *], A. S. Mosolov[b, **], and N. I. Akinin[b, *]**
[a]*AO PVP Amulet, Moscow, Russia*
[b]*Mendeleev Russian Chemical-Technology University, Moscow, Russia*
**e-mail: gubinata@jsc-amulet.ru*
***e-mail: asmosolov@yandex.ru*
****e-mail: akinin@muctr.ru*

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Abstract—An algorithm is proposed for determining the target development scenario for an industrial emergency arising from terrorist attack or other unsanctioned actions, by assessment of the threats to critical system elements. Criteria are selected for ranking possible scenarios. The target scenario is identified by multicriterial optimization—specifically, by means of the displaced ideal in fuzzy decision making. By means of the algorithm developed for fuel and power companies, a hazard class may be assigned to any unsanctioned intervention, and improved security measures may be developed.

Keywords: scenario assessment, emergencies, industrial security, integrated security measures, fuel and power companies, terrorist acts, threat levels, internal sabotage, fault-tree analysis, event-tree analysis, vulnerabilities

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An important aspect of industrial safety at fuel and power companies is industrial security. In accordance with Federal Law 256-F3, protective measures are formulated on the basis of assigning any unsanctioned intervention to a hazard class and establishing the level of protection of all critical elements [1]. When classifying fuel and power enterprises in accordance with statistical data from the Russian companies AO Amulet [2] and IPK TEK [3], the potential threat from some unsanctioned act at the enterprise is found, in 75% of cases, to be associated with an action aimed at destabilizing the operation of the enterprise and interrupting the industrial processes. Such threats to safe production are regarded as industrial terrorism.

The goal of a terrorist act is to produce economic, environmental, and social damage at fuel and power enterprises and to the state as a whole. Terrorists have the following goals:

—long-term disruption of the operation of the enterprise (or some part of the enterprise);

—disruption of the living conditions of the population within the affected zone;

—other acts of malicious intent.

Industrial security measures must protect the enterprise from terrorism. Therefore, it is essential to determine the target scenario for an industrial emergency in the light of terrorist goals.

Accordingly, we need a method with the following aims:

—identification of the most likely target scenario in an industrial emergency on the basis of terrorist goals and the apparent threat levels;

— improvement of security systems at the enterprise by developing compensation measures for protection against terroristic acts of any kind.

By this means, we may establish a sequence of actions for determining the target scenario in an industrial emergency provoked by an unsanctioned act. The method here outlined is intended for equipment employed by fuel and power enterprises [1]: petroleum processing, the petrochemical industry, the gas and electrical industries, heating, the use of petroleum derivatives, gas supply, and coal, shale, petroleum, and peat extraction.

TARGET SCENARIO

The target scenario for the terrorist is the scenario in which the negative consequences are most severe, with maximum probability.

The selection criteria for the target scenario are as follows.

1. The probability of system failure.
2. The most affected zone, m.
3. The economic damage, rub.
4. The number of human casualties.

Numerical values of these criteria may be established in each particular case. The number of criteria

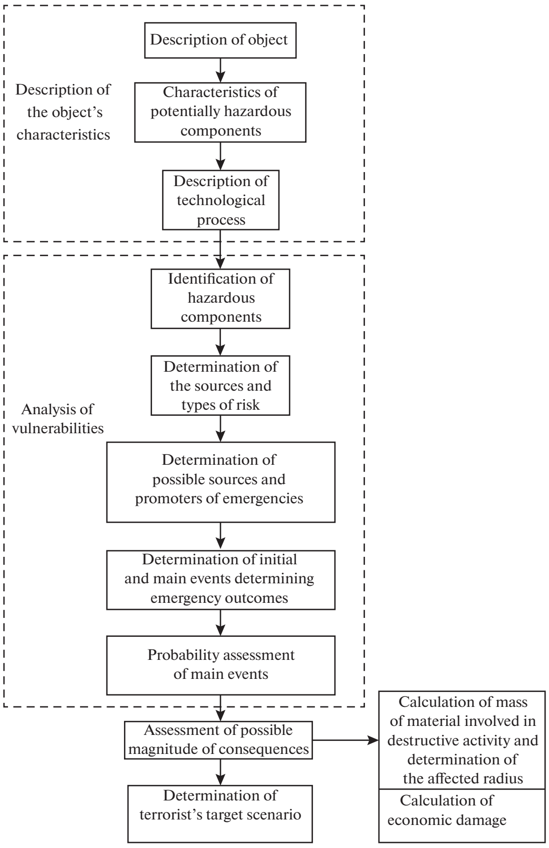

Fig. 1. Algorithm for determining the terrorist's target scenario for an emergency.

associated with the target scenarios of importance to the terrorist may be increased. Characteristics of the terrorist may also be significant here. In particular, a psychological portrait of the terrorist will imply certain behavioral models. In Fig. 1, we present an algorithm for determining the terrorist's target scenario.

As an example, consider the security of a hydrogen compression system for use in hydrogen production, with nine components: five cutoff valves (UV 1010, UV 1011, UV 1013, UV 10105, and UV 1018); two compressors (K-2A/2B), a separator S-3, and a hydrogen-cooling unit C-3.

The first step is to collect the initial information, including the following.

1. The name of the object: the hydrogen compression system for use in hydrogen production.

2. The system's design output: 15 000 m^3 m^3/h.

3. The production method: catalytic conversion of natural gas and processing of the converted gas by cyclic gas adsorption on solid sorbents, with the production of high-purity (99.9 vol %) hydrogen.

4. Description of the process: in the compression system, hydrogen processed in the cyclic adsorption unit is sent to separator S-3 for the removal of the remaining condensate. The condensate level is regulated by a valve in the condensate release valve. From separator S-3, the hydrogen proceeds to the intake of the compressor K-2A/2B, is compressed to a pressure of 48 kg/cm^2, is cooled to 40°C in cooling unit C-3, and leaves the system.

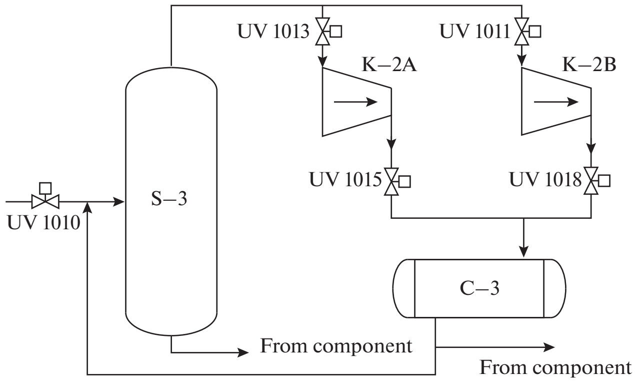

Fig. 2. Simplified system for hydrogen compression.

5. Description of the apparatus.

6. Data regarding the size of the staff and the working conditions: on average, eight workers (with a maximum of nine); bypassing of system once every 2 h.

7. Data regarding fault-free operation of the system components.

In Fig. 2, we show a simplified diagram of the hydrogen compression system. The probability P of fault-free operation of the system components is as follows: 0.9655 for the cut-off valve; 0.9805 for the K-2A/2B unit; 0.9711 for C-3; and 0.9885 for S-3 [4]. The probability Q of a fault is $Q = 1 - P$.

The probability of fault-free system operation is $P_{sys} = 0.9655^5 \times 0.9805^2 \times 0.9711 \times 0.9885 = 0.7743$; and the probability of a fault in the system is $Q_{sys} = 1 - 0.7743 = 0.2257$.

To ensure harmful consequences, the terrorist selects an initial event or group of events consistent with the ultimate goal: disruption of system operation. The initial event may be a single fault in the system components, an external event, or a staff error leading to disruption of the operating conditions and perhaps violation of operational limits and/or safety requirements. The initial event includes all the dependent faults present in the outcome [5].

The initial events leading to an emergency are faults of the most vulnerable system components (criterion 1), which may be discovered as follows:

—by considering the parts of the process that are of interest (with indication of all the fluxes and the basic and backup components);

—by calculating the probability of fault-free operation of each system component or taking the probability from handbook data;

Table 1. Decision table for system components

Combination	State of system components					Probability of system fault
	component 1	component 2	component 3	...	component 9	
1	Faulty	Operational	Operational	...	Operational	0.0277
2	Operational	Faulty	Operational	...	Operational	0.0090
3	Operational	Operational	Faulty	...	Operational	0.0277
4	Operational	Operational	Operational	...	Operational	0.0154
5	Operational	Operational	Operational	...	Operational	0.0230
...	...	...	...	...	...	...
260	Faulty	Faulty	Faulty	...	Faulty	6.1768×10^{-15}
Sum.						0.2257

—by calculating the probability of a fault in the whole system with various combinations of faults in its components.

The combinations with the greatest probability of a fault will be regarded as the most vulnerable points of the system. Table 1 presents the probability of an operative state of the system and the probability of a fault for different combinations of components (Table 1).

It follows from this decision table that the probability of a fault is greatest (0.0277 and 0.0230) in combinations 1, 3, 5, 6, 8, and 9 with a fault in one component. A fault is least likely for combination 260, with a probability of 6.1768×10^{-15} for a fault in all its components.

Next, information is collected regarding the behavior of the process—in particular, data regarding the hazardous materials formed in the equipment and the main types and sources of risk in the hydrogen compression system. The basic factors determining the explosion and fire safety of the system are as follows:

—the presence of hydrogen in the system, which travels more rapidly than other gases, is odorless, and explodes on ignition when two volumes of hydrogen are mixed with one volume of oxygen;

1 —pressures as high as 50 kgf/cm^2;

—high flow rates up to 15000 m^3/h;

—numerous flanged and welded joints and branched pipeline networks with many valves and regulators.

On the basis of the information regarding the main types and sources of risk and also the vulnerability analysis, the possible precursors of faults in the system components may be determined. In other words, the initial fault combinations are combined with the possible initial events preceding the onset of such combinations.

For combination 7, the following initial events are possible in the hydrogen compression system: mechanical actions raising the process parameters above the specified values; and mechanical incidents within the perimeter of the equipment. The main events may be selected for all fault combinations in the system components in accordance with the type of equipment in the hydrogen compression system and statistical data for emergencies and incidents in analogous equipment.

The following main events may be identified by analysis of the factors initiating and promoting accidents for the specific process (taking account of the properties and distribution of the hazardous materials) and also vulnerability analysis:

1. Failure and loss of sealing of the separator.

2. Failure and loss of sealing of the compressor.

3. Failure and loss of sealing of the water-cooling system.

4. Failure and loss of sealing of the pipeline.

The consequences of these events are now assessed. (Criteria 2–4 are calculated.)

For different combinations of system faults, the same primary events may be considered: for example, for combinations 1, 3, 5, 6, and 8 (Table 1), the primary event is failure and loss of sealing of the pipeline. We determine the main events analogously for the other combinations in Table 1. The results are summarized in Table 2.

Table 2. Correspondence between main events and combinations of faults in system components

Main event	Combinations
Failure and loss of sealing of separator	2; 10; 18; 20; 21; 23 etc.
Failure and loss of sealing of compressor	4; 7; 12; 15; 19; 22; 25; 28; 31; 32; 33; 34; 37; 40; 43 etc.
Failure and loss of sealing of water-cooling system	9; 24; 30; 35; 39; 42; 44; 45 etc.
Failure and loss of sealing of the pipeline	1; 3; 5; 6; 8; 11; 13; 14; 16; 26; 27; 29; 36; 38; 41 etc.

Thus, calculation of the consequences reduces to analysis and assessment of the consequences of four main events. The types of possible emergencies in the hydrogen compression system and their environmental impact are determined by the range of hazardous materials produced, their physicochemical properties, the specifics of the process, the characteristics of the equipment, the safety system employed, and the configuration of the equipment. Analysis of statistical data regarding emergencies in the annual reports of the federal environmental, technological, and nuclear services shows that accidents accompanied by explosions may occur in the hydrogen compression system. In emergencies, the shock wave is the main source of fire.

For the first main event, failure and loss of sealing of the separator, the following development scenarios are possible.

1. Failure and loss of sealing of the separator → propagation of vapor and gas phase → explosion → destruction of equipment, injury of personnel within the affected area.

2. Failure and loss of sealing of the separator → release of hazardous material → formation of vapor and gas phase with concentration below the lower concentration limit of ignition → poisoning of personnel within the affected area.

Analogously, for the second main event, failure and loss of sealing of the compressor, the following development scenarios are possible.

1. Failure and loss of sealing of the compressor → propagation of vapor and gas phase → explosion → destruction of buildings, equipment, pipelines, injury and death of personnel within the affected area.

2. Failure and loss of sealing of the compressor → inundation with hydrogen-bearing gas → propagation of vapor and gas phase in free space → ignition → explosion → action of shock wave on personnel and equipment.

For the third main event, failure and loss of sealing of the water-cooling system, the following development scenarios are possible.

1. Failure and loss of sealing of the water-cooling system → propagation of vapor and gas phase → explosion → destruction of buildings, equipment, pipelines, injury and death of personnel within the affected area.

2. Failure and loss of sealing of the water-cooling system → release of hazardous material → formation of vapor and gas phase with concentration below the lower concentration limit of ignition → poisoning of personnel within the affected area.

For the fourth main event, failure and loss of sealing of the pipeline, the following development scenario is possible.

Failure and loss of sealing of the pipeline → release of hazardous material → propagation of vapor and gas phase → explosion → destruction of buildings, equipment, pipelines, injury and death of personnel within the affected area.

In Fig. 3, we show the event tree of possible development scenarios for emergencies in the hydrogen compression system.

As a rule, the most affected zones are calculated in meters (the radius of a circle with its epicenter at the terrorist act) and also characterized as an area or volume. The determination of the damage from the emergency at a hazardous production object is governed by Reference Document RD 03-496–02 [6].

The economic damage consists of direct losses at the organization operating the hazardous production object; costs for localization (elimination) and analysis of the emergency; social and economic losses; direct damage; environmental damage; and losses of labor resources by death or injury (estimated in rubles).

The number of workers at the enterprise and third parties whose wellbeing is irreversibly or reversibly affected by the emergency must be calculated in accordance with Methodological Recommendations 1-4-60-9-9 (September 1, 2007). Software such as TOKSI^{+risk} and other methods have been approved by the Russian government.

Table 3. Numerical values of the consequences of fault combinations

Combination	Criteria			
	probability of system failure	most affected zone, m	economic damage, rub	human casualties
C_1	0.0277	28.05	70508.7	5
C_2	0.0090	28.52	73877.5	7
C_3	0.0277	30.24	464319.1	7
C_4	0.0154	35.15	468433.9	7
C_5	0.0277	62.52	1075618.8	19
C_6	0.0277	62.52	1075618.8	19
...	...	...	...	...

TOKSI^{+risk} software (v. 4.3.5) may also be used to calculate the explosion parameters for fuel–air mixture, the most affected zone, and the number of injured personnel, in accordance with the recommendations in [7]. The material losses for the most affected zones are assessed in accordance with [6].

The next step is to formulate a table of numerical values of the consequences of the target scenario for each combination of faults in the system components (Table 3). From the results, the target scenario may be determined mathematically—for example, by means of the displaced ideal in fuzzy decision making [9].

ANALYSIS BY THE DISPLACED-IDEAL METHOD

This method consists of five stages. In the first, we form an ideal object and an anti-ideal object. To this end, we select the maximum value k_j^+ of the criterion for all the objects ($k_j^+ = \max_i k_j^i$) and the minimum value k_j^- of the criterion for all the objects ($k_j^- = \min_i k_j^i$). The results are presented in Table 4.

Table 4. Ideal and anti-ideal objects

Criterion	Ideal object	Anti-ideal objectобъект
Probability per year	0.0277	0.0002
Most affected zone, m	62.52	3
Economic damage, rub	1075618.8	1939.6
Human casualties	19	0

In the second stage, we switch from physical units to relative values (Table 5)

$$d_j^i = (k_j^i - k_j^-)\big/(k_j^+ - k_j^-). \quad (1)$$

As a result, all the criteria vary within the interval [0; 1].

With decrease in d_j^i, the object moves closer to the anti-ideal with respect to k_j.

In the third stage, making judgments regarding the relative importance of the criteria, we determine the

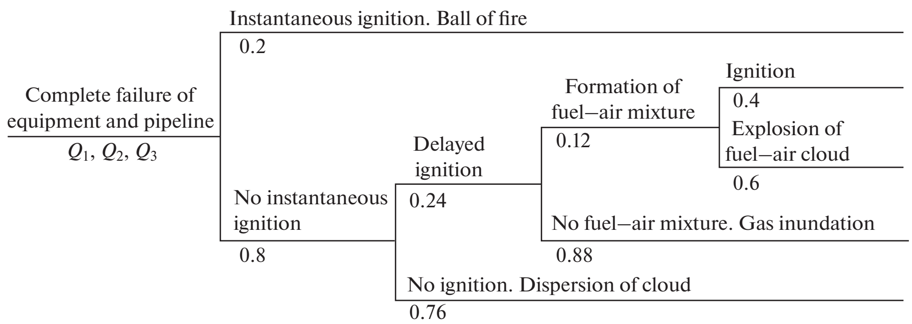

Fig. 3. Event tree for emergencies in chambers and compressors and in the pipeline.

Table 5. Relative values of the criteria in determining the target scenario

Combination	Relative values			
	probability	most affected zone	economic damage	human casualties
C_1	1	0.420867	0.063864	0.263158
C_2	0.32	0.428763	0.067001	0.368421
C_3	1	0.457661	0.43065	0.368421
C_4	0.552727	0.540155	0.434482	0.368421
C_5	1	1	1	1
C_6	1	1	1	1
C_7	0.552727	0.540155	0.569781	0.368421
C_8	1	1	1	1
C_9	0.829091	0	0	0
C_{10}	0.003636	0.428763	0.067001	0.368421
C_{11}	0.029091	0.420867	0.063864	0.263158
C_{12}	0.014545	0.540155	0.434482	0.368421
C_{13}	0.029091	1	1	1
C_{14}	0.029091	1	1	1
C_{15}	0.014545	0.540155	0.569781	0.368421
C_{16}	0.029091	1	1	1
C_{17}	0.021818	0	0	0
C_{18}	0.003636	0.428763	0.067001	0.368421
C_{19}	0	0.540155	0.434482	0.368421
C_{20}	0.003636	0.457661	0.43065	0.368421
C_{21}	0.003636	0.428763	0.067001	0.368421
C_{22}	0	0.540155	0.569781	0.368421
C_{23}	0.003636	0.428763	0.067001	0.368421
C_{24}	0.003636	0	0	0
C_{25}	0.014545	0.457661	0.43065	0.368421
C_{26}	0.029091	1	1	1
C_{27}	0.029091	1	1	1
C_{28}	0.014545	0.540155	0.569781	0.368421
C_{29}	0.029091	1	1	1
C_{30}	0.021818	0	0	0
C_{31}	0.014545	0.540155	0.434482	0.368421
C_{32}	0.014545	0.540155	0.434482	0.368421
C_{33}	0.003636	0.540155	0.434482	0.368421
C_{34}	0.014545	0.540155	0.434482	0.368421
C_{35}	0.010909	0	0	0
C_{36}	0.029091	1	1	1
C_{37}	0.014545	0.457661	0.43065	0.368421
C_{38}	0.029091	1	1	1
C_{39}	0.021818	0	0	0
C_{40}	0.014545	0.540155	0.569781	0.368421
C_{41}	0.029091	1	1	1
C_{42}	0.021818	0	0	0
C_{43}	0.014545	0.540155	0.569781	0.368421
C_{44}	0.010909	0	0	0
C_{45}	0.021818	0	0	0

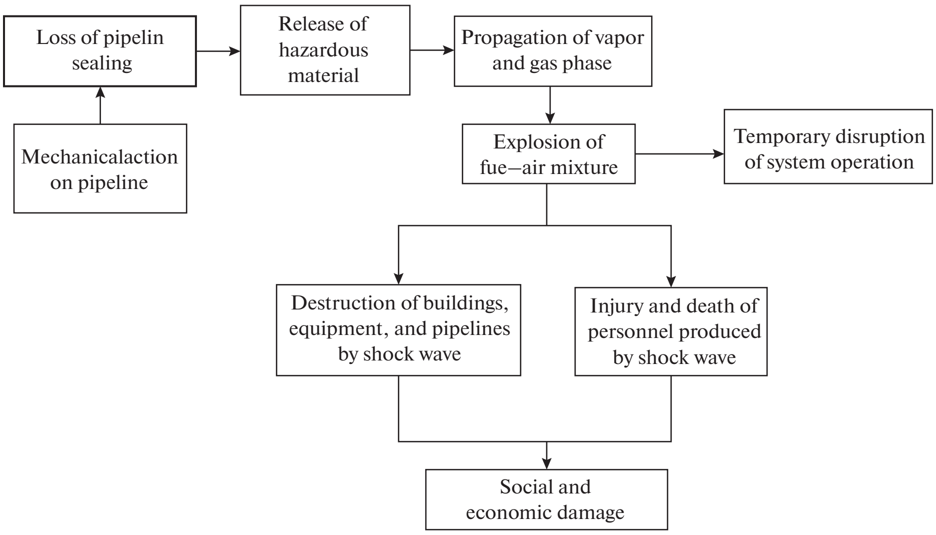

Fig. 4. Development of target scenario at hydrogen compression system.

corresponding weighting factors V_j ($j = 1, 2, ..., m$). By assigning different weights to the criteria, we obtain various ordered metrics. Table 6 presents different assignments of the weights.

Then, in the fourth stage, we calculate the distance of the objects from the anti-ideal. The metric employed is

$$L_i^p = \left[\sum_{j=1}^{m} (V_j d_j^i)^p\right]^{1/p}. \quad (2)$$

Using different values of p, we may obtain different metrics. With increase in L_i^p, the object is further from the anti-ideal and closer to the ideal. For comparison with the ideal, we specify metrics with different p. We select $p = 1, 2, 3$, and 0.3 and then determine the total value of these metrics for each combination.

In the fifth, stage, all the objects are ordered in terms of closeness to the ideal on the basis of L_i^p, so as to eliminate options of little significance (Table 7). To that end, we use the formula

$$k_i^p = \frac{n(n+1)}{2}, \quad (3)$$

where n is the number of combinations.

It is evident from the results that, if $p > 50$, the combination may be eliminated, since it is far from the ideal. Then, for the combinations with p no greater than 50, we repeat all the stages in the selection of the ideal. The results are summarized in Table 8.

From the remaining combinations, we select combinations C_5, C_6, and C_8, with $p = 8$. Combinations C_5, C_6, and C_8 correspond, respectively, to faults in the cutoff valves UV 1015, UV 1018, and UV 1020. In other words, they correspond to emergencies in the pipeline beyond the compressor K-2A/2B. Thus, analysis of the onset of emergencies yields the scenarios in Fig. 4.

In the categorization and standardization of fuel and power enterprises, one of the greatest challenges is to determine the method by which the terrorist intervenes in the industrial process so as to create a threat. The proposed algorithm for determining the target development scenario for an emergency addresses this problem, since all the criteria determining the significance with respect to vulnerable points within the system are taken objectively into account.

The proposed algorithm permits more detailed analysis of the system's vulnerabilities, not only in classification but in other aspects of protecting equipment in fuel and power enterprises. The results regard-

Table 6. Assignment of weights to criteria

Criterion	Weight of criterion					
	N_1	N_2	N_3	N_4	N_5	N_6
Probability (V_1)	0.1	0.1	0.1	0.1	0.1	0.4
Most affected zone (V_2)	0.7	0.1	0.1	0.2	0.7	0.3
Economic damage (V_3)	0.1	0.7	0.1	0.3	0.1	0.2
Human casualties (V_4)	0.1	0.1	0.7	0.4	0.1	0.1

Table 7. Ordering of objects by closeness to ideal

Combination	Sum $p(N_n)$					
	$p(N_1)$	$p(N_2)$	$p(N_3)$	$p(N_4)$	$p(N_5)$	$p(N_6)$
C_5	8	8	8	8	8	8
C_6	8	8	8	8	8	8
C_8	8	8	8	8	8	8
C_3	16	80	70	52	65	34
C_1	22	113	120	117	120	58
C_7	35	53	53	56	53	50
C_4	39	57	75	60	70	54
C_{13}	49	32	32	32	32	36
C_{14}	49	32	32	32	32	36
C_{16}	49	32	32	32	32	36
C_{26}	49	32	32	32	32	36
C_{27}	49	32	32	32	32	36
C_{29}	49	32	32	32	32	36
C_{36}	49	32	32	32	32	36
C_{38}	49	32	32	32	32	36
C_{41}	49	32	32	32	32	36
C_9	50	148	148	148	148	107
C_2	71	116	121	111	119	97
C_{15}	81	69	64	71	66	77
C_{28}	81	69	64	71	66	77
C_{40}	81	69	64	71	66	77
C_{43}	81	69	64	71	66	77
C_{12}	100	88	90	91	90	97
C_{22}	100	88	83	90	86	95
C_{31}	100	88	90	91	90	97
C_{32}	100	88	90	91	90	97
C_{34}	100	88	90	91	90	97
C_{33}	112	101	102	103	102	109
C_{25}	117	110	108	109	108	117
C_{37}	117	110	108	109	108	117
C_{19}	122	107	109	109	109	116
C_{20}	125	117	115	116	116	124
C_{11}	137	140	140	140	140	142
C_{10}	140	133	133	133	133	137
C_{18}	140	133	133	133	133	137
C_{21}	140	133	133	133	133	137
C_{23}	140	133	133	133	133	137
C_{17}	160	160	160	160	160	160
C_{30}	160	160	160	160	160	160
C_{39}	160	160	160	160	160	160
C_{42}	160	160	160	160	160	160
C_{45}	160	160	160	160	160	160
C_{35}	174	174	174	174	174	174
C_{44}	174	174	174	174	174	174
C_{24}	180	180	180	180	180	180

Table 8. Ordering of objects by closeness to ideal

Combination		Sum $p(N_n)$				
	$p(N_1)$	$p(N_2)$	$p(N_3)$	$p(N_4)$	$p(N_5)$	$p(N_6)$
C_5	8	8	8	8	8	8
C_6	8	8	8	8	8	8
C_8	8	8	8	8	8	8
C_3	16	49	46	43	46	16
C_1	22	64	64	64	64	31
C_7	26	44	44	47	44	52
C_4	30	48	51	60	60	56
C_9	35	68	68	68	68	64
C_{13}	51	35	35	34	34	41
C_{14}	51	35	35	34	34	41
C_{16}	51	35	35	34	34	41
C_{26}	51	35	35	34	34	41
C_{27}	51	35	35	34	34	41
C_{29}	51	35	35	34	34	41
C_{36}	51	35	35	34	34	41
C_{38}	51	35	35	34	34	41
C_{41}	51	35	35	34	34	41

ing process vulnerability permit specialists to develop measures improving the industrial security.

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Translated by Bernard Gilbert

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