Safety Science 79 (2015) 229–242

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Some methodical aspects of critical infrastructure protection

Alexander Bochkov [a,*], Valery Lesnykh [a], Nikolai Zhigirev [a], Yuri Lavrukhin [b]

[a] NIIgazeconomika, LLC, 20/8, Staraya Basmannaya Str., Moscow 105066, Russia
[b] Gazprom, JSC, 16, Namiotkina Str., GSP-7, Moscow 117997, Russia

A R T I C L E I N F O

Article history:
Received 21 October 2014
Received in revised form 8 June 2015
Accepted 13 June 2015
Available online 3 July 2015

Keywords:
Critical infrastructure protection
Risk
Decision making
Theory of games
Ranking

A B S T R A C T

The priority ranking that relates to critical infrastructure facilities protection against acts of terrorism (as exemplified by the fuel and energy complex facilities) has been discussed. The ranking algorithm as applied to similar facilities, which is based on their systemic significance for the fuel and energy complex, has been suggested. Besides, the algorithm for forming the ranked list of different-type facilities of the fuel and energy complex has been suggested, too.

1. Introduction

The current and prospective structures of the global fuel and energy complex considerably complicate the matters related to ensuring its steady functioning and reliable supply to consumers. The fact that the above issues are of an intersectoral nature calls for developing such solutions which will be coordinated and aimed at ensuring reliability, safety and security of separate specialized subsystems within the fuel and energy complex. Also their interrelations, including the projected development of the energy systems for 15 years to 20 years and up to operating management of the systems during their operation need to be considered, too. Generally, stable functioning of the fuel and energy complex has the intersectoral nature and as such it is determined by interrelations between power industry and other sectors of the national economy, as well as by the social and economic development plans of countries and regions.

An intersectoral approach to ensuring security and stable functioning of the fuel and energy complex needs a comprehensive methodical approach to investigations into reliability, security, and stability of the fuel and energy complex components represented by various energy systems be developed. Such approach should account for the existence of certain specific features of various energy systems, that are generally widespread, which could ensure solving, both theoretically and methodically, the above issue from the generally shared standpoint. The above features of the fuel and energy complex include: interrelation with other national economy systems (industries); territorial distribution and complexity; continuity and persistence of development, etc. Inconsistent (adaptive) behavior principles under the conditions of potential risks and uncertainties inherently rest on the idea of management of the fuel and energy complex subsystems. Where such risks arising from heterogeneous circumstances exist this may block or cause changes in this or that way in development thus forcing the system to existence "under another scenario" that obviously differs from multiple previously generated plans.

The everlasting conditions of the changes in the scope and intensity of threats to stable development of the industry till pose a true problem that hinders search for the ways of ensuring security of the fuel and energy complex facilities (Gheorghe et al., 2006; Biringer et al., 2013; Flammini, 2012; Lewis, 2006).

The safety and security requirements established for the higher- and medium-grade hazard facilities are robust and considerably increase expenses borne by the facilities' owners. It is practically impossible to improve protection and security to the level required by the federal legislation at a single step. This brings up the issue of ranking the facilities within the preset grades for their prioritizing with respect to determining the order of priority for provision of the facilities required protection means. To do this, it is necessary to identify the criterion, relative to which the importance (and, accordingly, the serial number) of this or that facility in the ranked list will be determined.

* Corresponding author.
E-mail addresses: a.bochkov@econom.gazprom.ru (A. Bochkov), v.lesnykh@econom.gazprom.ru (V. Lesnykh), n.zhigirev@econom.gazprom.ru (N. Zhigirev).

http://dx.doi.org/10.1016/j.ssci.2015.06.008
0925-7535/

Nomenclature

r_i	systemic significance (integral criterion)
α_i	weighting factor (showing the importance of filling the unit of work)
β_i	weighting factor (reflects comparison of various types of the facilities by their attractiveness for attacker)
w_i	second-level basic criterion (criticality)
q_i	second-level basic criterion (unconditional vulnerability)
θ_{ii}, γ_{ij}	weights of indicators ($i = 1, 2, \ldots, \mu; j = 1, 2, \ldots, \rho$)
w_{ij}	criticality indicators (resource criterion)
q_{ij}	unconditional vulnerability indicators (resource criterion)
X	damage
$i = 0, 1, \ldots, I^{[k]}$	the protection level for the k-th facility
j	attacker preparedness level
$X^{[k]}(i,j)$	damage from attacker attack with preparedness level j is launched against the above k-th facility with the protection level i
$Q^{[k]}(i,j)$	probability varying
$Y^{[k]}(i^{[k]})$	expenses from creation and maintenance of protection of facility k at the ith level
Y	the total of all expenses required to protect the facilities provided protection system variant $i^{[k]}$ is selected for each facility k
$\lambda^{[k]}(j)$	probability of the attack against each kth facility by the attacker with the jth preparedness level
$R[k, i^{[k]}]$	median value of the risk from the attack against the kth facility by the attacker with the jth preparedness level, assuming the $i^{[k]}$ facility protection system
$\theta\lfloor k, i^{*[k]} \rfloor$	value of the prevented risk per unit of investments into protection
$\mu^{[k]}$	adjusting factor
O_i	object (or facilities)
$x_1, x_2, \ldots, x_N$	several describing variables (resource criteria)

2. Statement of the task

It is proposed to consider a possible approach to the security issue facilities using the example of the Unified Gas Supply System of Russia (hereinafter, "UGSS"), which is operated by JSC Gazprom. UGSS is characterized by a geographical mode of distribution in space, greater divergence and interaction between different facilities, the heterogeneous structure of the process chains, and unique conditions for different risks that threaten the subsystems' facilities and, generally, the system as a whole.

The current configuration of UGSS established by the mid-80s of the previous century features substantial reserves of various types and purposes. If need be, the networking of cross-country gas pipelines, gas distribution and gathering nets makes it possible to execute large-scale maneuvers of flows among the transport corridors or maneuvers within a local pipeline net, which increases reliability of supplies to the consumers. As to UGSS the structural redundancy methods include creation of standby pipelines (supply to essential consumers from various directions) and bridging gas pipelines. Redundancy on the site facilities is possible through selecting the process layout of the piping, i.e., the main and standby equipment connection layout. Pipeline divisions are segmented by way of constructing links between the parallel lines, laying the loop lines, and duplication of the pipelines at the high-risk areas, which are the typical methods of redundancy of the cross-country gas pipelines' infrastructure. Underground gas storage facilities are the most effective redundancy methods in UGSS. In case of major disasters and during the peak demand periods the gas reserves in the underground gas storage facilities make it possible to operate for certain time without disruption of supplies to the consumers. Irregularities of gas supply are partly compensated by means of the accumulating capacity of the end gas pipeline divisions, as well as by temporary well yield level variation.

Assuming that stable UGSS functioning is fulfillment of its development plan with permissible deviations of both the scope and deadlines of the tasks, then this system safety management minimizes extraordinary losses where an emergency situation occurs or measures to prevent its effect are undertook.

It should be noted here that JSC Gazprom, acting within the frameworks of preventing any anthropogenic threats on the regular basis, developed and introduced its corporate standards to ensure uniformity of the approaches toward organization of protection for certain facilities; besides those standards set forth the principles and rules for classification of protection sites broken down by potential aftereffects (risks) of terrorist acts. The above standards are instrumental to identify key vital facilities and the facilities first and foremost subject to be equipped with technical protection equipment sets, formulation of the requirements to anti-terrorism security of the protection sites, and determine where time-sensitive and long-term solutions for their protection prove to be adequate. While solving the problem of classification on the whole, these approaches do not result in an unambiguous rating of the facilities with allowance for their significance for the whole system of the fuel and energy complex. The differences in the tasks classification (rating) and ranking are shown in Figs. 1–3.

The economic aspects of security issues are always of close interest. The idea that there exist both complex protection of everybody from the threats of hazard actualization on the level of reasonable adequacy (first-type tasks) and the individual security needs, whose level is determined depending on the circumstances of place and time for the protected facilities (second-type tasks), has but a long history.

If the collective security mechanisms are ensured by the systems of the "armed forces", "common law-enforcement authorities", and "emergency action services" types, specific individual security of high-security facilities is provided by specialized bodies in compliance with the normative standards exceeding the normative standards for protection of average facilities.

The increased level of protection of the fuel and energy complex facilities is a sort of response to the growth of the terrorist threat and belongs to the second-type tasks. Where we have to deal with common criminal activities (thefts, vandalism, etc.), it is sufficient to satisfy the "average industry standards for all facilities"; meanwhile protection against terrorism implies that the acts of terrorism should be understood as single and rare events.

The requirements, which are adequate in case of collective population protective mechanisms, in their pure form turn to be ineffective and inappropriate and therefore cannot ensure improved functioning of the facilities as redundant equipment of the facilities which practically face no threats at all turns into a dramatic shortage of protection equipment for the facilities which are "attractive" for terrorists.

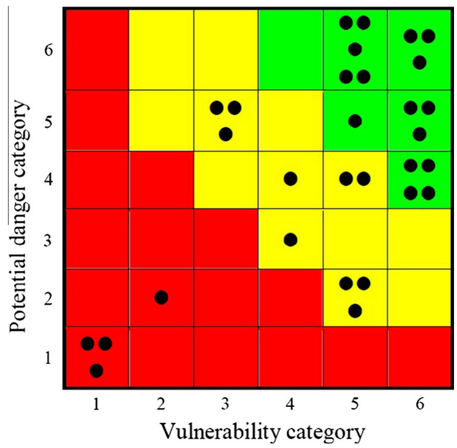

Fig. 1. Rating of facilities by potential danger and vulnerability.

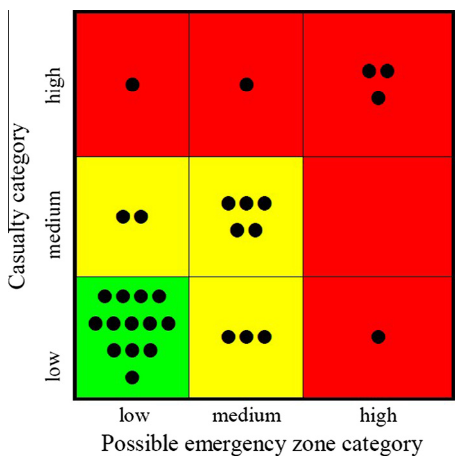

Fig. 2. Rating of facilities by possible emergency zone and casualties.

Generally, ranking should be understood as a procedure that allows for seriation of facilities by increase or decrease of a certain feature provided they actually possess this feature. For instance, the fuel and energy complex facilities can be ranked by their value and output of produced or pumped through products, R&Ds can be ranked by their importance for the Company's development strategy, investment projects can be ranked by NPV, etc.

3. Selection of ranking criterion

The *system-defined significance criterion* was selected as the criterion for the UGSS facilities ranking. The system-defined significance was determined as the facility's feature characterizing its importance for the infrastructure and the sustainability of the fuel and energy complex, within which it functions. This is a complex feature that can comprise the criticality and unconditional vulnerability, as well as a combination of these features.

The ranking task is not a new one. The facilities ranking methods are based on mathematical simulation, expert reports, decision-making theory, and interval estimation (Kostrov, 1996; Makhutov and Kryshevich, 2002; Gokhman, 1991). To any extent those methods take into account the interests of these facilities' operators, state supervisory agencies, and insurers. At the same time currently available ranking methods (for instance, ranking of the facilities by the extent of their protection in case of emergencies on railroad transport (Zinevich et al., 2006), ranking of the hazardous production facilities of the gas distribution systems (Buyko and Pantyukhova, 2010), etc.) fail to take into account the properties of the structural connectivity of the ranking facilities and importance of the specific facility operation for interfacing systems and subsystems.

The task of facilities ranking is a standard issue for the theory of measuring some complex synthetic features of the facilities (Bruck and Nikolayev, 1977). A formal result is obtained by way of plotting some validity or usefulness function that links the measured feature with simpler resource indicators (factors) measured in actual values (Neumann and Morgenstern, 2007). The value function is used to settle the issues of selecting the best variant from the set of alternatives (Larichev, 2002), and also composition issues, e.g., the issue of forming the portfolio of orders for works, provided the resources are limited (volume of financing the creation or modification of the facilities (Russman et al., 1991)). The factors used to obtain the ranks are often measured in qualitative scales rather than in quantitative ones, which results in use of expert evaluation methods and expert system technologies to construe relationships between utility and primary resource factors (Gokhman, 1991; Litvak, 2004). Development of computer engineering makes it possible to assess the facilities with description factors set with an error. This necessitates development of a specific apparatus for statistical processing of the primary data (Cox and Hinkley, 1979) and use of the fuzzy logic tools (Russman et al., 1991; Kuvshinov et al., 2002; Zhukovsky and Zhukovskaya, 2004; Melikhov et al., 1990).

Solution of the ranking issues is characterized by an adaptive nature of the decision-making procedure to be followed to select optimal variants (Zhukovsky and Zhukovskaya, 2004; Saaty, 2009), under which several experimental data and expert preferences correlation cycles for development of the final formula (Melikhov et al., 1990) must be performed.

All other things equal, a terrorist having some means for hitting a single target selects a facility that performs a greatest scope of the commodity-transport activity (W) (Fig. 4).

The first basic criterion for assessment as to the system-level significance of the UGSS facility, which is the fuel and energy complex component, may result from an assumption that the effect from the functioning disruption is linear within the wide variation range of W. The given criterion measures underdeliveries of products as compared with the ideal functioning mode of the UGSS as the whole system. This is a design indicator closely related to the power rating of the UGSS facility. To determine its value the facility functioning models are used. In particular, use is made of gas flow models in the UGSS for the compressor and gas distribution stations and the underground gas storage facilities, the daily volumes of shipped products for the processing plants, etc.

However, the facilities, owing to the specifics of place and time of their functioning (seasonality), are distinguished by the principle difference in the effects from the undersupplies. One and the same gas is used in different process chains. Therefore, it is more attractive for the terrorist (under otherwise equal conditions) to hit the facility fulfilling the more important, more vital, and more "highly expensive" work or the one that may entail great punitive sanctions (for instance, in case of violation of export commitments).

So, the facility acquires another indicator (let us call it α) showing the importance of fulfilling the unit of work. In other words, there can be cases, when $W_1 > W_2$, but at the same time $\alpha_1 \cdot W_1 < \alpha_2 \cdot W_2$, i.e. when another facility becomes more attractive for the terrorist due to the fact that the terrorist destroys a kind of a more "qualified facility " or a "more critical resource".

The third indicator (Q) used by the suggested approach is the indicator of potential feasibility of the planned action. This feasibility is associated with a possibility of weapon delivery and presence of potential accomplices in the region of the target facility. Similar

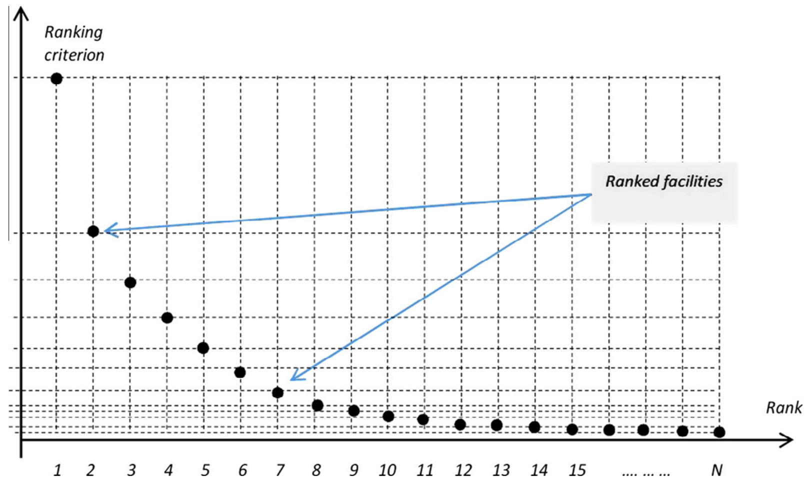

Fig. 3. Results of objects ranking.

to the technical systems, this indicator shows the aggression level of the external environment where the facility is operating.

The fourth indicator (β) reflects comparison of various types of the facilities by their attractiveness for terrorists. This indicator rates the average accessibility of the points of application of means of destruction depending on the "layout characteristics" of the facilities in the UGSS. In this indicator the values of the killing effects are adjusted. Thus, in case of the UGSS, the gas-distributing station (GDS) is closer to the consumer and often has no backup, while the gas-compressor station (GCS), on the contrary, has, as a rule, both intrashop switchover of gas compressor units (GCU) and a ramified system of loop lines on the multi-line mains. Figuratively speaking, this indicator is the scale parameter of the facility.

Basic criteria are developed with the use of folded resource indicators, expressed in natural terms, though the formulas of the folds are to be reconstructed through an expert approach. Specific nature of the use of the indicators' folds in the form of multipliers is associated with the specifics of perception by a human being of expected losses which has a logarithmic scale. To describe the relationships among the criteria, the oriented graph called the influence graph (see Fig. 4) was introduced for consideration. The independent criteria called the resource ones are arranged in pairs on the lower level of this graph. Unlike the lower-level criteria, the systemic significance criterion is called the basic one.

The UGSS is an intricate system and its openness implies interaction with the external environment and the effect of the latter on it. Generally, this effect can be construed rather widely: there can be natural calamities (for instance, earthquakes leading to destruction of dams and other engineering structures), major accidents (for instance, explosion at the nuclear power plant, blackout of the whole region), as well as illegal actions characterized by the widest spectrum of effects. Precisely these external effects are characterized by great uncertainty of time, place and method of action, as well as selection of a specific facility for commission of the action.

The facility has the same importance for both the system and violator, and thus the required facility protection level should be

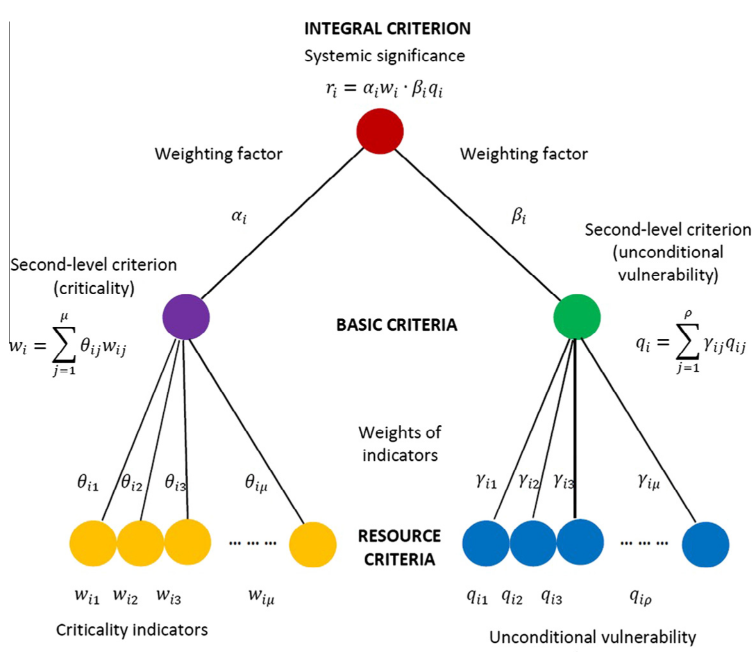

Fig. 4. Multilevel hierarchy of indicators and homogeneous facility assessment criteria.

a result of consideration of the nature of possible attacks. The following can be considered as such attacks.

First, the most commonly encountered local criminal activities/practice and the offences of the law hereto related, do harm to the economic activity of the facility. As a rule, those are thefts. Such local criminal activities/practice also includes hooliganism (vandalism) and protest actions. Its level most probably correlates with the level of general criminal offences in the region of the facility location. The latent (hidden) part of this kind of criminality can be rather adequately measured by such indicators as the unemployment level, share of migrants, and educational level of the population.

Second, is the migration of the intrastate criminal and terrorist activities. The zones of intensive terrorist activities tend to expand: criminal gangs forced out by the law-enforcement authorities migrate together with able-bodied population from the flash points. The most significant indicator reflecting this kind of offences is remoteness of the facility from the zones of intensive terrorist activities.

Third, specially trained terrorist and guerrilla parties penetrating, in full strength or partly, as instructors from abroad. Their actions are characterized by good forethought, preparedness, and definiteness (planned nature of activity and weighted measurement of implementability of this or that action by infliction of damage).

There can be mixed variants, as well. For instance, the local criminal gangs and arriving "emissaries" merge on a common ideological or religious platform. This is particularly important under the conditions of the current-day Russia, when the ideals and values of co-existence of different nationalities and population groups are under protection of a strong paternalistic state.

For the purpose of the key task – determining the system-level significance of the UGSS facilities we considered the criminal underworld as a source of various external attacks against the facilities, though with limited resources. We are interested to a great extent in the attacks with high and medium levels of preparedness and it is suggested to consider that the criminal underworld involves the whole of its means and potential. More specifically, one should expect both launching large-scale attacks in order to devastate the owner of the fuel and energy complex facilities by forcing him to immense spending to reinforce the facilities' physical protection; besides, the criminal underworld uses to launch its attacks with medium-level preparation as excessive preparedness of the attacks is not expedient under the conditions when the entity lacks resources needed to protect all its facilities according to the variant of the protection systems of the best industrial prototypes.

4. Algorithm for ranking of facilities of the similar type

Thus, let us consider a certain (k-th) UGSS facility. As a result of the anticipated attack by trained intruders a certain damage (X) will be inflicted to this facility through its full (or partial) outage. Note that not every attack will be a priori successful for the attacker and, therefore, the protection profile of the kth facility can be described by interval representations through application of the following four matrixes:

$$Q^{[k]}_{min}(i,j), Q^{[k]}_{max}(i,j), X^{[k]}_{min}(i,j), X^{[k]}_{max}(i,j) \tag{1}$$

where $i = 0, 1, \ldots, I^{[k]}$ is the protection level for the k-th facility. The zero level ($i = 0$) shows the current protection state. The matrix elements may be interpreted as follows: if the attacker attack with preparedness level j is launched against the above k-th facility with the protection level i, damage ranging from $X^{[k]}_{min}(i,j)$ to $X^{[k]}_{max}(i,j)$ will be inflicted to the facility owner with a probability varying from $Q^{[k]}_{min}(i,j)$ to $Q^{[k]}_{max}(i,j)$.

It is obvious that the $Q^{[k]}_{min}(i,j), Q^{[k]}_{max}(i,j), X^{[k]}_{min}(i,j), X^{[k]}_{max}(i,j)$ values will grow as the preparedness level j grows and will decrease progressively as protection level i of the facility grows. Besides, protection at any level will require certain material expenses on part of the entity and the state. Now we will determine expenses from creation and maintenance of protection of facility k at the ith level as $Y^{[k]}(i^{[k]})$. As the resource allocated for protection of all facilities in their aggregate is limited, the following inequation should be implemented:

$$\sum_k Y^{[k]}(i^{[k]}) \leqslant Y \tag{2}$$

where Y is the total of all expenses required to protect the facilities provided protection system variant $i^{[k]}$ is selected for each facility k.

If the criminal does not possess the advantage of choosing the target and variant of attack, i.e., criminal activities/practice is non-selective like the Nature or technological failures, the optimal facilities' protection profile could be attained through sequential execution of the below algorithm:

(a) First, probability $\lambda^{[k]}(j)$ of the attack against each kth facility by the attacker with the jth preparedness level must be measured.

(b) Second, the median value of the risk from the attack against the kth facility by the attacker with the jth preparedness level, assuming the $i^{[k]}$ facility protection system, must be calculated:

$$R[k, i^{[k]}] = \sum_{j=0}^{J} \left\{ \lambda^{[k]}(j) \times \left(\frac{Q^{[k]}_{min}(i^{[k]}, j) + Q^{[k]}_{max}(i^{[k]}, j)}{2} \right) \times \left(\frac{X^{[k]}_{min}(i^{[k]}, j) + X^{[k]}_{max}(i^{[k]}, j)}{2} \right) \right\} \tag{3}$$

(c) Third, the value of the prevented risk per unit of investments into protection must be determined:

$$\theta\lfloor k, i^{*[k]} \rfloor = \frac{R[k, i^{*[k]}]}{Y^{[k]}(i^{[k]})} \tag{4}$$

(d) Forth, the maximum value of the prevented risk for each kth facility must be selected:

$$\theta\lfloor k, i^{*[k]} \rfloor = \max_{i^{*[k]}} \{\theta\lfloor k, i^{*[k]} \rfloor\} \tag{5}$$

i.e., the maximum risk reduction per unit of finances invested into protection for the kth facility is observed with respect to the selected variant $i^{*[k]}$.

(e) Fifth, the ranked list of the facilities must be developed where those will be arranged by indicator $\theta\lfloor k, i^{*[k]} \rfloor$ in the descending manner; then the first $\widetilde{K}$ facilities must be identified, provided expenses from their protection are within the investments Y and out of the resources for the $(\widetilde{K} + 1)$th facility.

The above procedure is simple: it is not expedient to raise funds for additional protection of facilities that are under threat which is either insignificant or negligibly small (attack threat values $\lambda^{[k]}(j)$ are small). It is also unreasonable to additionally protect the facilities if the temporary loss of their operating capability practically does not affect the value of the entity's total losses (the values of $X^{[k]}_{max}(i^{[k]}, j)$ are accordingly small). And, at last, no additional protection is expedient in case of well protected facilities, so that reduction of losses is possible only through allocation of inadequately great funds (i.e., the values of $\theta\lfloor k, i^{*[k]}\rfloor$ are small).

The key point of the above algorithm is compiling the ranked list of the facilities based on the minimization criterion for the losses' mathematical expectation per one unit of investments into their protection (their stable functioning).

In the formula for $R[k, i^{[k]}]$ one can easily trace the necessity of the data collection and their assessment by three components:

1. Values $X^{[k]}_{min}(i,j)$ and $X^{[k]}_{max}(i,j)$ of the losses caused by implementation of attacks.
2. Criminal environment aggressiveness indicator $\lambda^{[k]}(j)$.
3. Dependence of risks on the types of facilities k.

As the facilities of JSC Gazprom are not stand-alone facilities, losses X should reflect the systemic impact (or socio-economic multi-effect), which significantly amasses depending on what users of the attacked facility's products will suffer from the loss of the enterprise operating capability. So, it is required to consider the ceiling of the damage indications, and also introduce an additional indicator, which is the 4th one, namely, to show importance of the ongoing operation of the facility pertinent to a possibility of the cascading effect of the multiplied consequences of the facility outage for other national economy facilities.

At last, it is expedient to introduce the 5th component required for adequate ranking of the facilities. It is necessary as the would-be attack is target-oriented. The attacker has the validity factors and priorities displacing the values of $\lambda^{[k]}(j)$ from the "weighted average" not known either to the owner's security service, or to the competent state authorities. Sometimes these additional values have a specific nature: some attackers are prone to excessive blood-shedding and taking hostages, ritual killings, etc. Systemic significance of specific facilities often grows for a short period of time, for instance, during the stay of top public officials or ministers and, particularly so, during the commissioning of the politically important production facilities of both the international and regional (domestic) levels.

The above-mentioned fifth component is adjusting factor $\mu^{[k]}$, initially equal to 1 for all facilities, which can be (for instance, according to the security service, top management of the company, etc.) increased so that to increase the priority of inclusion of precisely the kth facility in the list of facilities to be provided with additional protection measures due to the reasons out of the general rules.

Notwithstanding the fact that the considered issue theoretically has quite a large dimensionality and features great combinatorial complexity, it is perfectly well at hand due to monotonicity of the criteria employed and linearity of the systems of given constraints.

The key issues of approaches toward solution are of the informational and technological nature rather than the mathematical one:

- Assessments of the aftereffects of possible attacks by the attackers with the preparedness level j should be available for each kth facility, which is not attainable for the time being.
- Risks threat UGSS within the complex of possible threats, including the weakly formalized ones (the more precise the assessment of the attacker's potential capabilities, which are both technologically and regionally non-homogeneous, the more effective the optimization of protection) and thus must be measured.

Within the framework of the considered setting allowing for the complex impact from the potential attacker activity the understanding of the protection systems' efficiency assessment cardinally changes. Thus, owing to limitedness of the resources immediately available for the use by the criminal underworld one can obviously expect that the terrorists will shift the target setting from well protected facilities (with low expected effectiveness of the attacks) to less protected facilities (with greater effectiveness, but with lower one-time damages).

Another key component of the issue is that the search for effective solutions by both opposing forces is in the informational sphere:

- While preparing for the attack against the facility, the attacker seeks for accomplices, which could help him choose such force application target which comforts his preparedness and equipment level.
- Protection system is capable of a greater concentrated counteraction provided it has been informed on the intentions of the attack.

Therefore, when describing the above procedure, it was repeatedly emphasized that we deal only with the appraisals made by both sides. As it is hardly probable to remedy uncertainty of appraisals development of strategy and tactics for promoting the protection of the UGSS facilities against possible attacks, including the acts of terrorism and attacks of subversive groups, may be so to say coarsening the game formulation. In case of coarsening the attacker capabilities should be idealized and the characteristics of possible losses should be made more stringent, for instance, by way of changing over from the median risk assessments to the maximum ones.

So, the suggested approach uses the following three key notions:

- Systemic significance.
- Criticality.
- Unconditional vulnerability.

Systemic significance has been defined earlier.

Criticality is the feature of the facility determining the extent of its influence on operating capability of the whole system with allowance for weighted consequences caused by its disconnection from various categories of consumers. Criticality cannot be determined by some component features, but should be determined within the framework of the whole system and its functional structure.

Unconditional vulnerability is the facility characteristic which shows the extent of reduction of its operating capability under the conditions of the environmental effects exceeding the boundaries of the normal operation conditions of the facility. A specific class of external impacts associated with deliberate acts of human beings, for instance, diversion can be singled out. Unconditional vulnerability characterizes a potential hazard for the facility functioning at the preset levels of the external factors, which are essentially the hazard characteristics of its location.

The methodological approach being the basic concept of the suggested method has an advantage over the cost approaches. This advantage is that multi-criterion usefulness actually absorbs, on a shared basis, all factors, rather than only those expressed in monetary terms. Many present-day rating systems proceed only from the results of assessing one of the indicators describing the facilities (for instance, activity of economic subjects, their criticality, etc.) (Karminskiy et al., 2005; Baranov and Skuf'ina, 2005). However, as practically both criticality and unconditional vulnerability of the facilities (in the facilities ranking by their systemic significance) arise from a great number of assessments, whose importance is not known beforehand, there appears a multi-criterion ranking task (Larichev, 2002; Keeney and Raiffa, 1993; Nogin, 2005; Podinovskiy and Nogin, 1982; Podinovskiy, 2004). This issue relates to the multi-criterion decision making (selection) issues under the uncertainty conditions (Kuvshinov et al., 2002; Mazurov, 1990) having a great importance for the analysis of the systems, which widely differ from each other purposes (Zhukovsky and Zhukovskaya, 2004; Quade, 1964).

Generally, the complex system facilities perform different functions and the results of their activity (or consequences of their outage) are differently assessed; thus, it is important to know to what extent (how many times) one same-type facility is more significant than another, as well as to be able to compare the assessments of the facilities of various types. To do this, it will be necessary to introduce additional axioms specifying the classes of the functions of selection among heterogeneous facilities (Table 1).

It should be understood that the general problem of selecting such axioms for the collections of facilities comprising various types of facilities has not been solved yet. There are several reasons, of which the most significant ones are as follows:

1. A great dimensionality of the selection task: the number of variants (facilities, from which the choice should be made) and the number of indicators describing the state of each facility are rather great. Data aggregation is required as the time (number of operations) required for selection fundamentally grows with the increased dimensionality. Sorting and grouping of similar facilities are used most frequently. In this case, simplifications of the real data (change-over from the quantitative indicators to the scoring and other ones) are implemented in the course of execution of the procedures, which permit deliberate accuracy decrease and information loss.
2. Diversity of the data types: different attributes are measured against different scales, and different facilities are described by means of different sets of indicators.
3. Presence of omitted values: the so-called ovality is often observed in statistics (due to various reasons). The authors of documents (especially text ones) omit the implied words and values by default. It is often unjustified and explained by lack of time.
4. Noisy data: existence of indistinct and random indicators. The measured values used for selection are, as a rule, not equal to the true values, but just close to them. It is desirable to correct the systemic errors for the distorted values. The features of additional distortions are different for the facilities of various types and the selection variants should be agreed against the variants of processing those distortions.
5. Multi-criteriality: it is practically impossible to indicate any single aim of functioning with respect to complex facilities. The scales determining the target setting components are called the criterial scales and the respective variables, the criteria. As has been stated above, the practical selection tasks are essentially the multi-criterial ones.

Owing to the above causes it is expedient to solve the heterogeneous facilities ranking task in several steps. At the first step, particular models of systemic significance of the selected type of facilities should be developed for each type of facilities and then used for ranking. As the second step, it is necessary to carry out bringing together of the ranked lists of facilities into a combined list. At the third step, the values of the assessments are adjusted if the necessity arises to take into account special functioning conditions of individual facilities.

Uniformity of facilities - assumes that several describing variables (resource criteria) $x_1, x_2, \ldots, x_N$ can be suggested for them and also the $Q(x_1, x_2, \ldots, x_N)$ scalar function can be set. This function for each facility O takes on a value of $Q(x_1(O), x_2(O), \ldots, x_N(O))$.

By now several standardized approaches to description of the choice have been developed. The simplest variant is to imply that certain function Q, called the criterion (quality criterion, objective function, preference function, utility function, etc.), can be set for all alternatives. This function possesses the feature establishing that, if alternative x_2 is preferable to alternative x_1, then $Q(x_2) > q(x_1)$.

However, it is either difficult or practically impossible to construct such a function. At the same time the ideas of constructing, for instance, the utility functions for selection can be applicable at the primary variants selecting steps, when we try to interpolate a certain nonlinear utility scale on the basis of a limited amount of the data.

Moreover, to implement the procedure of selecting the most system-relevant significant facility, in a "stepwise" manner we are interested only in the groups and their component facilities, which are among the bidders for "the best of the best position" at each step. Selection of such facilities in the simplest cases is reduced to the fact that the describing variables are considered to be a certain "test" (examination), while the attained values for the facility are taken to be marks/credits under this test.

So if there is certain limited amount M of describing variables (tests), the most system-relevant significant facility is the one that will gain the greatest composite score. The scores can be summed up with certain weighting factors reflecting relative significance of the m-th test ($m = 1, \ldots, M$) with respect to the average test. The properly chosen tests generally should be adequate tools for exposition of criterial function $Q(x_1, x_2, \ldots, x_N)$ that will allow for assessment of systemic significance of the facilities of a single type, but this is true only in cases when the level of attaining a set of the facility functioning purposes (as real facilities are always

Table 1
Axiomatics of arrangement of selection procedures.

Basic axioms	Explanations
Inheritance axiom: if $O' \subseteq O$, then $\pi(o') \supseteq (\pi(o) \cap O')$	The axiom means that with the limited choice the "facilities are the best of the best" variants belonging to $\pi(o) \cap O'$ and the facilities, which are the best of those available in limited sampling $O' \subseteq O$, but would not be selected, if the choice is available in all alternatives O
Concordance axiom: $\prod_i \pi(O_i) \subseteq \pi(\bigcup_i O_i)$	If some facility O was chosen as the best in each of sets O_i, it should be chosen from the whole aggregate of sets $\cup_i O_i$ as well
Omission axiom: $(\pi(o) \subseteq O' \subseteq O) \Rightarrow (\pi(o') = \pi(o))$	The axiom holds that if any part of the "rejected" facilities is omitted, the selection result will not change

Note. $\pi(o)$ is the true logic function, if the facility is chosen to be the best; if O is the set of facilities, $\pi(o)$ is the subset of the best of them multipurpose) can be adequately described by a linear combination of levels of attaining each specific purpose.

Now we can turn back to solution of the initial task, which requires that all lists be united into one: here, if all pair-wise comparisons of different scales are sown together, there exists the procedure of arranging all facilities in their common list, which will produce, after renormalized into a certain basic type (for instance, comparison scale of gas-distributing stations), general assessments of systemic significance in accordance with a unified scale of the facilities of all types.

After all facilities are arranged in the common list, the review of such list will result in exceptions to the rules as certain facilities will be underestimated by the suggested method. The main cause of underestimation is the failure to take account of the factors (ecological, geological, ethnic, and other) and/or their combinations, which have not been included in the lists of resource indicators due to the fact that they do not feature the required generality for inclusion into a set of state variables of all facilities.

In this case the experts should have a limited capability of shifting the facility to the left in the list of the systemic significance facilities by way of increasing the above-mentioned fifth factor from unity to a certain level. However, we need to prevent unscrupulous overestimation of this factor, and therefore the number of the ranks (as percent) by which the facility significance can be elevated as compared with the initial rank determined according to the procedure needs to be limited. For instance, if the displacement limitation is taken to equal 20%, the 100th facility can be advanced to the 80th rank, the 500th facility, to the 400th one, and the 10th facility by its significance, only to 8th rank and not higher.

5. Solution algorithm for different-type objects ranking

After the facilities are ranked within the homogeneous groups (types) a new task, which is rather sophisticated, arises: developing a unified ranked list of the UGSS facilities. The authors have suggested an innovative algorithm to be applicable to arrangement of the merger of the heterogeneous ranked lists.

Please note that actually to any assessment it is necessary to treat as an assessment of provision of dynamically changing object dimension near its balance. Equilibrium value practically never equals to assessment value, but the assessment always is in domain of attraction of equilibrium point with dimensionality $\Delta x_{\text{abs}}(O)$ (in case of linear analogs of objects O), proportional to dimensionality of the measured objects $x(O)$, i.e. $\Delta x_{\text{abs}}(O) = \delta_{\text{abs}} \cdot x(O)$.

In classical theories of measurements relating to domain of attraction dimensions they speak about absolute measurement errors $\Delta x_{\text{abs}}(O)$, and to have characteristics of measurement errors estimates independent of objects dimension they often take logarithm and then domain of attraction will be estimated by the value of a relative logarithmic error $\delta_{\text{rel}} = \log(1+\delta_{\text{abs}})$. The value δ_{abs} is often measured in percentage of the value of an assessment $x(O)$. It is considered that the object O has changed its state, or we deal with estimates of other object O', if $x(O') - x(O) > \delta_{\text{abs}}\delta_{\text{abs}} \cdot x(O)$ or $|\log(x(O')) - \log(x(O))| > \delta_{\text{rel}}$. It should be pointed out that δ_{rel} (in linear models of objects) does not depend any more on the value that assists the subsequent creations.

Assume that object O_1 is more significant, than object O_2 if l $\log(x(O')) > \log(x(O)) + \delta_{\text{rel}}$. Though as it was already noted above, as a rule, self-assessment of object O is not equal to the estimate obtained for the same object, but in other time; nevertheless we consider that they are estimates of the same object as the domain of attraction borders provision is steady.

To specify the provision of objects O_1, O_2 and O_3 on the importance scale it is necessary to compare the marked objects to some objects of other types. Let us consider possible cases (see Fig. 5).

Case A. Each from objects of one type in expert terms is admitted equal to the corresponding object of other type, i.e. $O_1 \sim \widetilde{O}_1, O_2 \sim \widetilde{O}_2, O_3 \sim \widetilde{O}_3$ (Fig. 5a).

In this connection on measurements scale (estimates calculation scheme)

$$\begin{cases} \log(\tilde{x}(\widetilde{O}_1)) > \log(\tilde{x}(\widetilde{O}_2)) + 2\tilde{\delta}_{\text{rel}} \\ \log(\tilde{x}(\widetilde{O}_2)) > \log(\tilde{x}(\widetilde{O}_3)) + 2\tilde{\delta}_{\text{rel}} \end{cases} \tag{6}$$

In this situation estimates $x(O_1)$ and $x(O_3)$ must be moved aside from estimate $x(O_2)$, i.e.

$$\begin{cases} \log(x(O_1)) > \log(x(O_2)) + 2\delta_{\text{rel}} \\ \log(x(O_3)) > \log(x(O_2)) - 2\delta_{\text{rel}} \end{cases} \tag{7}$$

It is considered that the object O_1 was underrated and the object O_3 was overrated. Equations $O_1 \approx O_2$ and $O_2 \approx O_3$, therefore, are changed to inequation $O_1 > O_2$ and $O_2 > O_3$. Contradiction with $O_1 > O_3$ disappears.

Case B. All objects of the first type in expert terms are admitted equal to the same object $\widetilde{O}_2$ of the second type (Fig. 5b). It means that values $x(O_1)$ and $x(O_3)$ must be "moved up" to each other and to the assessment of $x(O_2)$ assessment, i.e.

$$\begin{cases} \log(x(O_1)) = \log(x(O_2)) + \delta_{\text{rel}} \\ \log(x(O_3)) = \log(x(O_2)) - \delta_{\text{rel}} \end{cases} \tag{8}$$

It will allow "to exclude" contradiction $O_1 > O_3$. The obtained system $O_1 \approx O_2$, $O_2 \approx O_3$ and $O_1 \approx O_3$ stops to be the inconsistent.

Case C. The first two objects of the first type in expert terms are admitted equal to the same object $\widetilde{O}_1$ of the second type. The third object is admitted equal to less significant $\widetilde{O}_2$. In this case estimates $\log(x(O_3))$ and $\log(x(O_2))$ must be moved apart. Thereby formation of two domains of attraction is observed.

The considered cases show that the indistinct estimation lying in acceptance as the means of comparison of indistinct equality results in need of grouping (clustering) of the objects of one type O_1, O_2, O_3 presented to estimation through comparing them with objects of other type. Actually, at such approach it is possible to use more than two compared scales, but thus the features appear connected, for example, with "competition" of the second and third scales during formation process of cluster borders in a scale of objects of the first type. Each type of objects differing from others is estimated by its technique. Naturally, various ordered lists of the objects measured with various error, and, therefore, with various characteristic size of clusters come out.

The essence of the algorithm is well explained by the following analogy. An uphill road corresponds to each type of facilities, i.e., each scale. The "mile stones" – assessments of their significance are placed near the facilities located along this road and it be considered acceptable that the assessments are given with errors. These assessments increase incrementally and the locality sea level increases at the same time. Comparison of the facilities of different types satisfies the requirements of the same situation, when it is asserted that the ith facility of type t_1 is compared types can theoretically coincide, which in particular asserts that the respective "road" from the "smaller" facility to the "larger" facility is slightly sloping and runs over a flat terrain. In accordance with this analogy all facilities participating in the comparisons, as well as those, which turn out to be nearly at the same sea level due to the aggregate of comparisons, are grouped into clusters. An arbitrary set of facility of various types can exist in each cluster. The non-compared facilities form, in their turn, the clusters consisting of a single facility.

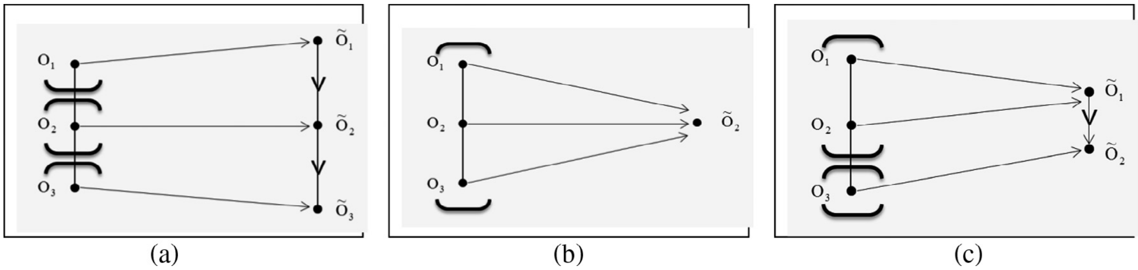

Fig. 5. Cases of comparison of objects of different types.

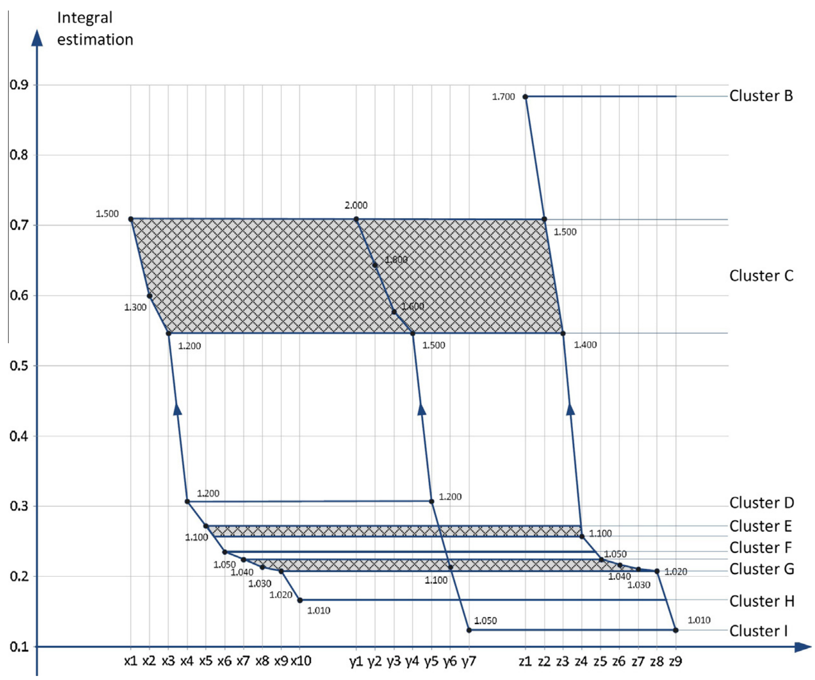

Fig. 6. Developing integral estimation of systemic significance.

All conditions are satisfied by normalizing the arrangement of clusters and projecting the real data (own assessments of the facilities included in the clusters) into the interval determined by the clusters' boundaries: the approximate parities of the compared facilities are ensured by inclusion of these facilities into one cluster, while the descending sorting of the facilities' significance is ensured by the order of arrangement of clusters.

Schematically finite solution is shown by the diagram in Fig. 6.

In Fig. 6 the ordinate axis contains the assessments of the general integral scale of significance of the facilities of three types. Digital marks standing for the initial own assessments of the facilities' significance are plotted on the individual graphs for the facilities of different types.

The clusters comprising the approximately equisignificant facilities are shown by means of horizontal strips and Latin letters. The algorithm proper consists of two parts. The data are prepared for calculations in the first part of the algorithm. In the second part of the algorithm, significance of the facilities is assessed in all available types of the scales and the convolution of these assessments is finally formed to obtain the non-dimensional integral estimation of significance of the facilities.

For the practical use of the algorithm see Appendix A.

6. Conclusions

The suggested methodology and adaptive algorithm for ranking the similar facilities fuel and energy complex by their systemic significance take into account the case of ambiguity of the given data on the resource and basic criteria or their partial absence and substantiate a possibility of using the expert approach to the facilities' ranking.

To merge the ranked lists of similar facilities into a unified ranked list, use has been made of several novelties ensuring correctness of the procedure of comparing the facilities of various types on the basis of partial expert findings of equisignificance of their separately selected representative pairs for solution of more general tasks related to enhanced protection of the fuel and energy complex facilities.

The suggested approach can be used by the units in charge of security of the fuel and energy complex facilities. A complex analysis of interrelated risks for separate industries and the fuel and energy complex as a whole will allow for substantiated recommendations as to determination of the required and sufficient security levels of hazardous production facilities proceeding from their significance for solution of a wide spectrum of management problems.

Table A.1
Objects estimates in their own importance scale.

Object name	Object estimate	Object name	Object estimate	Object name	Object estimate
GCS1	10.96	GDS1	12.59	UGS1	11.22
GCS2	15.85	GDS2	63.10	UGS2	10.23
GCS3	10.23	GDS3	31.62	UGS3	50.12
GCS4	31.62	GDS4	11.22	UGS4	12.59
GCS5	11.22	GDS5	15.85	UGS5	10.96
GCS6	10.47	GDS6	100.00	UGS6	10.47
GCS7	10.72	GDS7	39.81	UGS7	25.12
GCS8	11.75			UGS8	10.72
GCS9	19.95			UGS9	31.62
GCS10	12.59				

Table A.2
Borders of change of system indexes for objects of different types.

Type number	Objects type	Objects quantity	Quantity of objects together with boundary objects	Index of the beginning of area of placement of data on objects of the specified type	Index of the end of area of placement of data on objects of the specified type	Mnemonic name of objects type	Measurement error ($\delta_{OTH,m}$)	Size of cluster (Δ_m)	Ponderability of set type scale (ρ_m)
1	2	3	4	5	6	7	8	9	10
1	GCS	10	12	1	12	X	7.9%	0.20	0.600
2	GDS	7	9	13	21	Y	6.3%	0.10	0.300
3	UGS	9	11	22	32	Z	15.8%	0.50	0.100
Total		26	32	1	32				1.000

Appendix A. The algorithm of ranking description

Let us consider practical use of the algorithm of ranking described earlier by a conditional example.

Step 1. Rating of objects in one type by the algorithm stated in Sections 3 and 4 of the article is carried out. The example of such rating is presented in Table A.1.

For convenience object types are given the mnemonic name (column 7 of Table A.2) and two fictitious are added for each type of the value: *TOP* (further *T*-objects) and *OTTOM* (further *B*-objects) – precalculated borders of possible change of all object estimates in the corresponding measurement scale. Loaded estimates for each type of data are obtained with own ratio error (column 8) that allows to determine the limit maximum size of a cluster in measurement scales of the corresponding type (column 9). For calculation of upper and lower bounds of estimation scales knowing maximum and minimum values, we define by means of addition of value of the corresponding cluster to maximum value for -objects and subtraction of the size of the corresponding cluster from minimum value for *B*-objects (for example for objects of the first type $TX = X1 + \Delta_X; BX = X10 - \Delta_m$).

Closeness in estimation of object in this or that scale depends both on the cluster size, and on quantity of objects of that basic type which corresponds to a scale and through which values of estimates, estimates of objects of other types are recalculated. If in any scale the error is big or objects are few, it is obvious that estimates of all objects in this scale will have less "confidence" than more exact estimates for bigger quantity of objects. To consider the specified inadequacy of the used scales, in expert terms the ponderability index ρ_m is attributed to scales and this index reflects an object estimate contribution share in the specified scale into an integrated estimate of system importance.

Step 2. Object estimates are taken as logarithm (for example, column 3 Table A.3 for the first type of objects).

Step 3. Objects of each type in own scales are ordered on decrease of estimates taken the logarithm (column 5 Table A.3).

Step 4. After all tables data sorting (one for each objects type) it is possible to unite data with insert – objects and *B*-objects into the

Table A.3
Algorithm output in the early steps.

Object name 1	Object estimate 2	Denary logarithm of estimate 3	Mnemonic name of object 4	Object index 5
T_GCS		1.70	TX	1
GCS1	10.96	1.04	X7	8
GCS2	15.85	1.20	X3	4
GCS3	10.23	1.01	X10	11
GCS4	31.62	1.50	X1	2
GCS5	11.22	1.05	X6	7
GCS6	10.47	1.02	X9	10
GCS7	10.72	1.03	X8	9
GCS8	11.75	1.07	X5	6
GCS9	19.95	1.30	X2	3
GCS10	12.59	1.10	X4	5
B_GCS		0.81	BX	12

Table A.4
Summary table of expert objects comparison.

Rule 1	Equalities set by experts 2	Record in mnemonic names 3	Record in system object indexes 4
1	GCS2∼GDS6	X3 = Y1	{2,4,14}
2	GCS10∼GDS5	X4 = Y5	{2,5,18}
3	GCS6*∼GDS1*	X9 = Y6	{2,10,19}
4	GCS4∼UGS7	X1 = Z3	{2,2,25}
5	GCS8∼UGS4	X5 = Z4	{2,6,26}
6	GCS1∼UGS6	X7 = Z8	{2,8,30}
7	GCS6*∼UGS1*	X9 = Z5	{2,10,27}
8	GDS3∼UGS9	Y4 = Z2	{2,17,24}
9	GDS1*∼UGS1*	Y6 = Z5	{2,19,27}
10	GDS4∼UGS2	Y7 = Z9	{2,20,31}

Table A.5
Canonical form of record of comparison rules.

Rule	Equalities set by experts	Record in mnemonic names	Record in system object indexes
1	GCS4∼UGS7	X1 = Z3	{2,2,25}
2	GCS2∼GDS6	X3 = Y1	{2,4,14}
3	GCS10∼GDS5	X4 = Y5	{2,5,18}
4	GCS8∼UGS4	X5 = Z4	{2,6,26}
5	GCS1∼UGS6	X7 = Z8	{2,8,30}
6	GCS6∼GDS1∼UGS1	X9 = Y6 = Z5	{3,10,19,27}
7	GDS3∼UGS9	Y4 = Z2	{2,17,24}
8	GDS4∼UGS2	Y7 = Z9	{2,20,31}

united list in the following order: $TX, X1, \ldots, X10, BX; TY, Y1, \ldots, Y7, BY; TZ, Z1, \ldots, Z9, BZ$. Number of place thereby becomes the universal system index which definitely specifies both object type and object itself. Creation of general list allows to make calculations with the use of these objects without obvious indication of object type. Object index for "subsequent interpretation" includes all necessary information. Such form of data presentation we will call canonical. Values of object in the created united column, we will mark as $\|O_j\|_{[0]}$.

Step 5. Expert comparisons of objects of different types among themselves. The organization of an appointment procedure of estimate to experts is independent task which is not considered in this article. Experts are not obliged to know either the order of types which we chose for expert evaluation, or value of intrasystem indexes. It is desirable that they knew results of object comparisons given by other experts. Questions of coordination of different expert estimates in this article are not considered. It is supposed that a resultant estimate of pairs – the estimate coordinated by all experts on the results of discussion.

So, for procedure of "sewing together of lists" initial material is the list of "approximate equalities" (fuzzy equivalences) made by experts (column 2 Table A.4). Thus it is not important that any compared objects in this table are absent, and some objects are present several times. As in the considered system there are only "equality" rules; therefore, the summary table a priori does not contain internal contradictions. Besides, to each object O the system index is unambiguously attributed, for the subsequent processing to each rule there corresponds record of "expert equality" in the form of the list consisting of three arguments.

For example, the value of the first argument equal to 2 indicates paired objects comparison. Further there are indexes of the objects participating in equality. So, equality 8, for example, contains the mentioned GDS3 ($Y4$, system index 17). The expert specified that it is approximately equal in importance to UGS9 ($Z2$, system index 24).

Step 6. As in the compared pairs there can be objects which were exposed to comparison more than once ("star"); for the purpose of optimization of the subsequent calculations on this step all compared to the same object (for example with $X9$ (KC6)) are united into one list (in Table A.5, line 6). As a result record in system indexes takes the form {3,10,19,27} that is equivalent to the record GCS6∼GDS1∼UGS1.

Such form of record is more economic, as with growth of the size of a chain of equivalent objects (L) one record $\{L, arg1, \ldots, argL\}$ replaces $\frac{L(L-1)}{2}$ of records of paired comparisons.

Step 7. Calculation of estimates of the integrated importance of objects assumes calculation of estimates of each object in all types of scales. To receive the estimate in any scale it is necessary to estimate borders of possible changes of values of these estimates, that is to obtain: the lower guaranteed estimates for maximum value of estimates which objects – $\|O_j\|^{\max}_{[m]}$ can have, and the upper guaranteed estimates for minimum value of estimates which the same objects $\|O_j\|^{\min}_{[m]}$ can have. The group of objects (which can consist even of one object) in which values of pairs $\{\|O_j\|^{\max}_{[m]}, \|O_j\|^{\min}_{[m]}\}$ coincide is in fact equivalent objects which according to measurement logic must get into one cluster. For effective calculation of the sizes $\|O_j\|^{\max}_{[m]}$ and $\|O_j\|^{\min}_{[m]}$ it is expedient to create from canonical forms of equalities lists and own canonical forms of estimates $2M$ of working tables of equalities and $2M$ of initial starting values of object estimates for calculation algorithms of values of the upper $\|O_j\|^{\max}_{[m][start]}$ and the lower $\|O_j\|^{\min}_{[m][start]}$ bounds. The upper estimates of value of each object O in any scale m (X, Y or Z) $\|O_j\|^{\max}_{[m]}$ are calculated by means of the current object estimate values raising. For objects of basic type (what type of objects will be considered as a basic one is decided at step 1) coinciding with scale type m, starting values are taken equal to values from canonical form.

In Table A.6 they are marked in bold type and are situated in columns 4, 6 and 8 consequently for scale type X, Y and Z.

To B-object types which are not coinciding with basic type the values of -object scale type are attributed, i.e. starting BY values for 21 objects (B-object type Y) and BZ value for 32 objects (B-object of type Z) take BX values (in the concerned example it is equal to 0.81). All -objects (the 13th object TY and the 22nd object TZ) take the values equal to TX (respectively

1.70). All other objects of the types which are not coinciding with basic take *BX* values as before algorithm works we can guarantee only the most minimum values of estimates. Please note that if any objects of the types which are not coinciding with basic during algorithm would not be compared to other objects, their values will remain minimum in this scale of *m* though in their own scale they cannot be the most little significant objects.

Similarly, in columns 3, 5, and 7 of Table A.6 there are starting values for the calculation of the lower estimates of each object –

Table A.6
Samples of filling of estimates' calculation effective range in every scale types.

Field index 1	Mnemonic name 2	For calculation clusters lower borders in scale X 3	For calculation clusters upper borders in scale X 4	For calculation clusters lower borders in scale Y 5	For calculation clusters upper borders in scale Y 6	For calculation clusters lower borders in scale Z 7	For calculation clusters upper borders in scale Z 8
1	TX	**1.700**	**1.700**	TY	TY	TZ	TZ
2	X1	**1.500**	**1.500**	TY	BY	TZ	BZ
3	X2	**1.300**	**1.300**	TY	BY	TZ	BZ
4	X3	**1.200**	**1.200**	TY	BY	TZ	BZ
5	X4	**1.100**	**1.100**	TY	BY	TZ	BZ
6	X5	**1.070**	**1.070**	TY	BY	TZ	BZ
7	X6	**1.050**	**1.050**	TY	BY	TZ	BZ
8	X7	**1.040**	**1.040**	TY	BY	TZ	BZ
9	X8	**1.030**	**1.030**	TY	BY	TZ	BZ
10	X9	**1.020**	**1.020**	TY	BY	TZ	BZ
11	X10	**1.010**	**1.010**	TY	BY	TZ	BZ
12	BX	**0.810**	**0.810**	BY	BY	BZ	BZ
13	TY	TX	TX	**2.100**	**2.100**	TZ	TZ
14	Y1	TX	BX	**2.000**	**2.000**	TZ	BZ
15	Y2	TX	BX	**1.800**	**1.800**	TZ	BZ
16	Y3	TX	BX	**1.600**	**1.600**	TZ	BZ
17	Y4	TX	BX	**1.500**	**1.500**	TZ	BZ
18	Y5	TX	BX	**1.200**	**1.200**	TZ	BZ
19	Y6	TX	BX	**1.100**	**1.100**	TZ	BZ
20	Y7	TX	BX	**1.050**	**1.050**	TZ	BZ
21	BY	BX	BX	**0.950**	**0.950**	BZ	BZ
22	TZ	TX	TX	TY	TY	**2.200**	**2.200**
23	Z1	TX	BX	TY	BY	**1.700**	**1.700**
24	Z2	TX	BX	TY	BY	**1.500**	**1.500**
25	Z3	TX	BX	TY	BY	**1.400**	**1.400**
26	Z4	TX	BX	TY	BY	**1.100**	**1.100**
27	Z5	TX	BX	TY	BY	**1.050**	**1.050**
28	Z6	TX	BX	TY	BY	**1.040**	**1.040**
29	Z7	TX	BX	TY	BY	**1.030**	**1.030**
30	Z8	TX	BX	TY	BY	**1.020**	**1.020**
31	Z9	TX	BX	TY	BY	**1.010**	**1.010**
32	BZ	BX	BX	BY	BY	**0.510**	**0.510**

Table A.7
Working tables of rules record for procedures of calculation of object cluster borders in all types of scales.

Rule	Record in mnemonic names	Working table for definition of upper estimates of objects in scale X [4]	Rule	Record in mnemonic names	Working table for definition of lower estimates of objects in scale X [3]
1	X1 = Z3	{2,2,25}	1	X9 = Y6 = Z5	{3,10,19,27}
2	X3 = Y1	{2,4,14}	2	X7 = Z8	{2,8,30}
3	X4 = Y5	{2,5,18}	3	X5 = Z4	{2,6,26}
4	X5 = Z4	{2,6,26}	4	X4 = Y5	{2,5,18}
5	X7 = Z8	{2,8,30}	5	X3 = Y1	{2,4,14}
6	X9 = Y6 = Z5	{3,10,19,27}	6	X1 = Z3	{2,2,5}
7	Y4 = Z2	{2,17,24}	7	Y7 = Z9	{2,20,31}
8	Y7 = Z9	{2,20,31}	8	Y4 = Z2	{2,17,24}
1	Y1 = X3	{2,14,4}	1	Y7 = Z9	{2,20,31}
2	Y4 = Z2	{2,17,24}	2	Y6 = X9 = Z5	{3,19,10,27}
3	Y5 = X4	{2,18,5}	3	Y5 = X4	{2,18,5}
4	Y6 = X9 = Z5	{3,19,10,27}	4	Y4 = Z2	{2,17,24}
5	Y7 = Z9	{2,20,31}	5	Y1 = X3	{2,14,4}
6	X1 = Z3	{2,2,25}	6	X7 = Z8	{2,8,30}
7	X5 = Z4	{2,6,26}	7	X5 = Z4	{2,6,26}
8	X7 = Z8	{2,8,30}	8	X1 = Z3	{2,2,25}
1	Z2 = Y4	{2,24,17}	1	Z9 = Y7	{2,31,20}
2	Z3 = X1	{2,25,2}	2	Z8 = X7	{2,30,8}
3	Z4 = X5	{2,26,6}	3	Z5 = X9 = Y6	{3,27,10,19}
4	Z5 = X9 = Y6	{3,27,10,19}	4	Z4 = X5	{2,26,6}
5	Z8 = X7	{2,30,8}	5	Z3 = X1	{2,25,2}
6	Z9 = Y7	{2,31,20}	6	Z2 = Y4	{2,24,17}
7	X3 = Y1	{2,4,14}	7	X4 = Y5	{2,5,18}
8	X4 = Y5	{2,5,18}	8	X3 = Y1	{2,4,14}

Table A.8
Definition of upper estimates of objects in scale X.

	Scale Type X	Cyclic implementation of comparison rules with alignment of arguments to the maximum values	Upper estimate of objects in scale X
1	TX	1.70	1.70
2	X1	1.50	1.50
3	X2	1.30 > 1.50(2/2 cycle)	1.50
4	X3	1.20 > 1.50(2/2 cycle)	1.50
5	X4	1.10	1.10
6	X5	1.07	1.07
7	X6	1.05	1.05
8	X7	1.04	1.04
9	X8	1.03 > 1.04(6/1 cycle)	1.04
10	X9	1.02 > 1.04(6/1 cycle)	1.04
11	X10	1.01	1.01
12	BX	0.81	0.81
13	TY	1.70	1.70
14	Y1	0.81 > 1.20(2/1 cycle) > 1.50(7/1 cycle)	1.50
15	Y2	0.81 > 1.10(3/1 cycle) > 1.50(7/1 cycle)	1.50
16	Y3	0.81 > 1.10(3/1 cycle) > 1.50(7/1 cycle)	1.50
17	Y4	0.81 > 1.10(3/1 cycle) > 1.50(7/1 cycle)	1.50
18	Y5	0.81 > 1.10(3/1 cycle)	1.10
19	Y6	0.81 > 1.04(6/1 cycle)	1.04
20	Y7	0.81	0.81
21	BY	0.81	0.81
22	TZ	1.70	1.70
23	Z1	0.81 > 1.50(1/1 cycle)	1.50
24	Z2	0.81 > 1.50(1/1 cycle)	1.50
25	Z3	0.81 > 1.50(1/1 cycle)	1.50
26	Z4	0.81 > 1.07(4/1 cycle)	1.07
27	Z5	0.81 > 1.04(5/1 cycle)	1.04
28	Z6	0.81 > 1.04(5/1 cycle)	1.04
29	Z7	0.81 > 1.04(5/1 cycle)	1.04
30	Z8	0.81 > 1.04(5/1 cycle)	1.04
31	Z9	0.81	0.81
32	BZ	0.81	0.81

$\|O_j\|^{\min}_{[m][start]}$. Object data of basic type are also copied from canonical form.

B-objects and *T*-objects of the types which are not coinciding with basic one accept values of *B*-object and *T*-object of basic type, and to the rest objects of the types which are not coinciding with basic type values of *T*-object of basic type are given. Such distinction in marking is caused by that estimates of the lower bounds of objects are calculated by decrease of the current estimate values.

In order that procedures of definition of upper and lower estimates of objects are carried out the most quickly it is necessary to modify comparison rules of canonical table into 2*M* of working tables of comparison rules. Working tables do not differ from canonical table according to the content. It is only necessary to change the order of consideration of comparison rules in them, that is to carry out permutation of lines. The content of six working tables is given in summary Table A.7.

Step 8. The integral estimate of object importance $O - \|O\|_{\text{int}}(O)$ – is calculated through contribution of object estimates *O* in scales of each of types of objects – $\|O\|_{[m]}$ by the formula

$$\|O\|_{[m]} = \sum_m \rho_m \cdot \frac{\|O_j\|_{[m]} - \|B_m\|_{[m]}}{\|T_m\|_{[m]} - \|B_m\|_{[m]}}, \qquad (*)$$

where $\|B_m\|_{[m]}$ – value of BOTTOM-object in scale type *m*; $\|T_m\|_{[m]}$ – value of TOP-object in scale type *m*; ρ_m – a control indicator of ponderability of scale type *m* (Table A.1 column (x)); $\|O_j\|_{[m]} - O$ object estimate in scale type *m*.

By formula (∗) for all types of scales (in our case for scales of objects of type *X*, *Y* and *Z*) to execute a number of additional steps for receiving estimates $\|O\|_{[m]}$. We will illustrate sequence of

Table A.9
Calculation of integral estimate of objects through their estimates in all private scales.

Field index 1	Mnemonic name 2	Object estimates in their own scales 3	Object estimate in scale X 4	Object estimate in scale Y 5	Object estimate in scale Z 6	Integral estimate of object 7
1	TX	**1.700**	1.700	2.100	2.200	**1.000**
2	X1	**1.500**	1.450	1.800	1.500	**0.711**
3	X2	**1.300**	1.317	1.733	1.433	**0.600**
4	X3	**1.200**	1.250	1.700	1.400	**0.546**
5	X4	**1.100**	1.100	1.200	1.250	**0.304**
6	X5	**1.070**	1.070	1.200	1.100	**0.275**
7	X6	**1.050**	1.050	1.100	1.075	**0.234**
8	X7	**1.040**	1.040	1.100	1.050	**0.226**
9	X8	**1.030**	1.030	1.100	1.035	**0.218**
10	X9	**1.020**	1.020	1.100	1.020	**0.211**
11	X10	**1.010**	1.010	1.025	0.765	**0.170**
12	BX	**0.810**	0.810	0.950	0.510	**0.000**
13	TY	**2.100**	1.700	2.100	2.200	**1.000**
14	Y1	**2.000**	1.450	1.800	1.500	**0.711**
15	Y2	**1.800**	1.370	1.760	1.460	**0.644**
16	Y3	**1.600**	1.290	1.720	1.420	**0.579**
17	Y4	**1.500**	1.250	1.700	1.400	**0.546**
18	Y5	**1.200**	1.100	1.200	1.250	**0.304**
19	Y6	**1.100**	1.030	1.100	1.035	**0.218**
20	Y7	**1.050**	0.915	1.050	1.010	**0.127**
21	BY	**0.950**	0.810	0.950	0.510	**0.000**
22	TZ	**2.200**	1.700	2.100	2.200	**1.000**
23	Z1	**1.700**	1.600	2.050	1.700	**0.889**
24	Z2	**1.500**	1.450	1.800	1.500	**0.711**
25	Z3	**1.400**	1.250	1.700	1.400	**0.546**
26	Z4	**1.100**	1.070	1.150	1.100	**0.262**
27	Z5	**1.050**	1.040	1.100	1.050	**0.227**
28	Z6	**1.040**	1.033	1.100	1.040	**0.221**
29	Z7	**1.030**	1.027	1.100	1.030	**0.216**
30	Z8	**1.020**	1.020	1.100	1.020	**0.211**
31	Z9	**1.010**	0.915	1.050	1.010	**0.127**
32	BZ	**0.510**	0.810	0.950	0.510	**0.000**

Final rating objects list is given in Table A.10.

Table A.10
Rating objects list.

Rating	Object name	Integral estimate of object
1	Z1	**0.889**
2	X1, Y1, Z2	**0.711**
3	Y2	**0.644**
4	X2	**0.600**
5	Y3	**0.579**
6	X3, Y4, Z3	**0.546**
7	X4, Y5	**0.304**
8	X5	**0.275**
9	Z4	**0.262**
10	X6	**0.234**
11	Z5	**0.227**
12	X7	**0.226**
13	Z6	**0.221**
14	X8, Y6	**0.218**
15	Z7	**0.216**
16	X9, Z8	**0.211**
17	X10	**0.170**
18	Y7, Z9	**0.127**

actions by the example of calculations of *O* object estimates in scale type *X*.

To receive the required result given in column 4 Table A.8 it is necessary to consider the following properties of estimate: estimate value of any object must be increased on two bases:

1. object, owing to comparison rules gets value bigger than current, from other object with which it is compared in comparison rules;
2. object, more significant in its own scale, in any of scales cannot have value less than less significant object in its own scale.

Step 8.1. Consistently, from the first to the last rule in the working table it is necessary to carry out check of arguments on equality of estimate values. In case of non-performance of equality in the rule correction of smaller values of arguments to the maximum value is made.

Step 8.2. To carry out check of need of change of object estimate values on the second basis, but only for those objects which stand directly above the object modified on the first basis. If during check of all working list of rules at least one adjustment was carried out (on the end of cycle), the cycle of rules of check should be renewed.

Step 8.3. All list of objects divided into subgroups which we form by sorting pair <the upper estimate of object, the lower estimate of object> on decrease of values of the first argument, and at equality of the first arguments, in addition to decrease of the second argument of the specified pair. In that case when the difference between estimates of upper and lower bounds of clusters is positive and exceeds the cluster size for the object estimated in scale of this type it is necessary to analyze clusters at a size of admissible sizes by introduction of correction statement that estimates of the most significant objects of a cluster are overestimated, and estimates of the least significant objects of a cluster are underestimated. If in this type of objects there is a unique object entering a cluster, it must be always placed in the middle of a cluster.

Step 9. The integrated estimate of object importance (column 7 Table A.9) is calculated by a formula $(*)$ on the basis of estimates in private scales of X, Y and Z (column 4, 5 and 6 Table A.9).

References

Baranov, S., Skuf'ina, T., 2005. Analysis of interregional differentiation and development ratings of russian federation regions. Vop. Ekonomiki 8, 54–75.

Biringer, B., Vugrin, E., Warren, D., 2013. Critical Infrastructure System Security and Resiliency. CRC Press, 229 p. ISBN-10: 1466557508.

Bruck, V.M., Nikolayev, V.I., 1977. Fundamentals of General Systems Theory. L.: SZPI Publishers.

Buyko, K.V., Pantyukhova, Yu.V., 2010. Approaches to Assessment of Industrial Safety in Organizations Operating Hazardous Industrial Facilities. No. 10.

Cox, D., Hinkley, V., 1979. Theoretical Statistics, first ed. Chapman and Hall/CRC, 528 p.

Flammini, F., 2012. Critical Infrastructure Security: Assessment, Prevention, Detection, Response, first ed. WIT Press/Computational Mechanics, 326 p. ISBN-10: 1845645626 (February 13, 2012).

Gheorghe, A.V., Masera, M., Weijnen, M., De Vries, L.J., 2006. Critical Infrastructures at Risk. In: Securing the European Electric Power System. Series: Topics in Safety, Risk, Reliability and Quality, vol. 9, XXV. – 371 p.

Gokhman, O.G., 1991. Expert Assessment. Voronezh University Publishers, Voronezh, 152 p.

Karminskiy, A.M., Peresetskiy, A.A., Petrov, A.Ye., 2005. Ratings in Economics: Methodology and Practice. M.: Finansy i Statistika Publishers, 240 p.

Keeney, R.L., Raiffa, H., 1993. Decisions with Multiple Objectives – Preferences and Value Tradeoffs. Cambridge University Press, Cambridge & New York, 569 p.

Kostrov, A.V., 1996. Interval ranking of objects by many indicators. Problemy Bezopacnosti i Chrezvychainykh Situatsiy (1), 46–68.

Kuvshinov, B.M., Shaposhnik, I.I., Shiryayev, V.I., Shiryayev, O.V., 2002. Use of committees in pattern-classification problems with inexact expert estimations. J. Comput. Syst. Sci. Int. (Izvestia Rossiiskoi Akademii Nauk. Teoriya i Systemy Upravleniya) (5), 81–88.

Larichev, O.I., 2002. Features of decision making methods in multicriterion individual choice problems. Avtomatika i Telemekhanika (2), 146–158.

Lewis, T.G., 2006. Critical Infrastructure Protection in Homeland Security: Defending a Networked Nation. Wiley-Interscience, 486 p. ISBN-10: 0471786284.

Litvak, B.G., 2004. Expert Technologies in Management. M.: DELO Publishers, 400 pages.

Makhutov, N.A., Kryshevich, O.V., 2002. Possibility of "Man-Machine-Environment" Systems of Machine-Building Profile Based on Fuzzy Sets, No. 2, pp. 94–103.

Mazurov, V.D., 1990. Committees Method in Optimization and Classification. M.: Nauka Publishers, 248 p.

Melikhov, A.N., Berstein, L.S., Korovin, S.Ya., 1990. Situational Advising Systems with Fuzzy Logic. M.: Nauka Publishers.

Neumann, J., Morgenstern, O., 2007. Theory of Games and Economic Behavior (60th Anniversary Commemorative Edition). One of Princeton University Press's Notable Centenary Titles, 776 p.

Nogin, V.D., 2005. Decision Making in Multicriterion Environment: Quantitative Approach. M.: PHYZMATLIT Publishers, 176 pages.

Podinovskiy, V.V., 2004. Analysis of solutions with multiple estimations of criteria significance factors and probabilities of indefinite factor values and objective function. Avtomatika i Telemekhanika (11), 141–158.

Podinovskiy, V.V., Nogin, V.D., 1982. Pareto Optimal Solutions of Multicriterion Problems. M.: Nauka Publishers, 256 p.

Quade, E.S. (Ed.), 1964. Analysis for Military Decisions. RAND Corporation, 389 p.

Russman, I.B., Kaplinskiy, A.I., Umyvakin, V.M., 1991. Modeling and Algorithmization of Underformalized Problems of Selecting Best System Variants. VGU Publishers, Voronezh, 168 p.

Saaty, Thomas L., 2009. Mathematical Principles of Decision Making. Principia Mathematica Decernendi. RWS Publications, 531 p.

Zhukovsky, V.I., Zhukovskaya, L.V., 2004. Risk in Multicriterion and Conflicting Systems in Uncertainty. M.: Yeditorial URSS Publishers, 267 p.

Zinevich, S.V., Tarasenko, V.A., Usolov, E.B., 2006. Criteria of objects ranking by emergency hazard levels. In: Proceedings of the 11th Research and Practical Conference. East-Siberian Institute of RF Ministry of Interior, Irkutsk, pp. 220–223.