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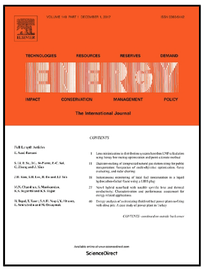

Formation of a list of critical facilities in the gas transportation system of Russia in terms of energy security

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Features of Russian gas transportation system
Principles for identification of critical facilities in the gas transportation system
Model base for the work of the software "Russia’s oil and gas".
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Abstract
The paper deals with the formation of a list of critical facilities in Russia's gas transportation system in terms of energy security, and the substantiation of potential ways to minimize the negative effects of emergency situations on operation of these facilities. To date the lists of critical facilities in the energy systems have been formed on the basis of the performance analysis of certain facilities. The paper addresses the problem of identification of such facilities depending on their impact on overall operability of the system. This is accomplished by analyzing the level of negative impact caused by termination or disturbance of operation of a certain facility on consumers. The analysis employs the software "Russia's Oil and Gas" ("ROG"). The principles of identifying critical facilities in Russia's gas transportation system are demonstrated, specific examples are shown, and potential ways to mitigate the negative impact of emergency situations at such facilities on gas consumers are formulated.

Keywords: gas transportation system, critical facilities, emergency situations, energy security.

1. Introduction

According to the methodology of classifying state-owned and non-state-owned facilities as critical or non-critical in terms of national security of the Russian Federation, which was approved by the Ministry of Emergency Situations of Russia in 2012 [1], critical facilities are the facilities which, when withdrawn from operation or failing to operate, cause loss of control over the economy of the Russian Federation oran entity of the Russian Federation, an irreversible negative change or destruction of the economy of the Russian Federation or an entity of the Russian Federation, or a considerable decrease in the security of the population's vital activity for a prolonged term. Consideration of an important national security component, i.e. energy security [2], requires that critical facilities be identified for the entire energy sector and for individual energy systems. We define energy security of Russia as state of protection of its citizens, society and national economy from shortage in provision of substantiated energy demands [3] thus focusing on the security of energy supply [4]. An overview of methodologies used for quantitative evaluations of supply security was provided in the [5].

Energy security of Russia concerns two main aspects:

– the need for long-term shortage-free supply of consumers with the required energy resources, provided the energy sector operates under nominal conditions;

– creation of conditions for providing consumers with energy resources under emergency conditions.

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Consideration of the second aspect calls for identification of critical facilities, i.e. energy facilities which, in case of partial or complete failure to operate, can cause severe damage to the country through the energy sector .

Identification of critical facilities of the energy sector is related to two objectives:

- identification and neutralization of different threats to stable fuel and energy supply to consumers (including threats of terrorist attacks of the energy facilities)
- advance preparation of energy facilities and systems to operation under emergency conditions caused by materialization of various threats.

2. Features of Russian gas transportation system

For European Russia, the main type of fuel is natural gas. The overall share of gas in furnace fuel balance across the country makes up around 77 percent. In a considerable part of regions its share in the balance exceeds 90-95 percent and sometimes reaches 99 percent. However, the territorial structure of gas supply system in Russia is the cause of its considerable flaws. For example the European part of the country consumes mainly natural gas, more than 90 percent of which is produced in a single gas production area (Urengoy area of the Tyumen region). This region is situated 2 - 2.5 thousand km away from the main gas consumption sites. Thus, virtually all Russian gas is transported over long distances by gas trunklines that have numerous mutual crossings. Moreover, the lines of large-scale gas trunkline are often laid at a short distance from each another. Scheme of Russian Unified Gas Supply System is presented as part of Fig. 1.

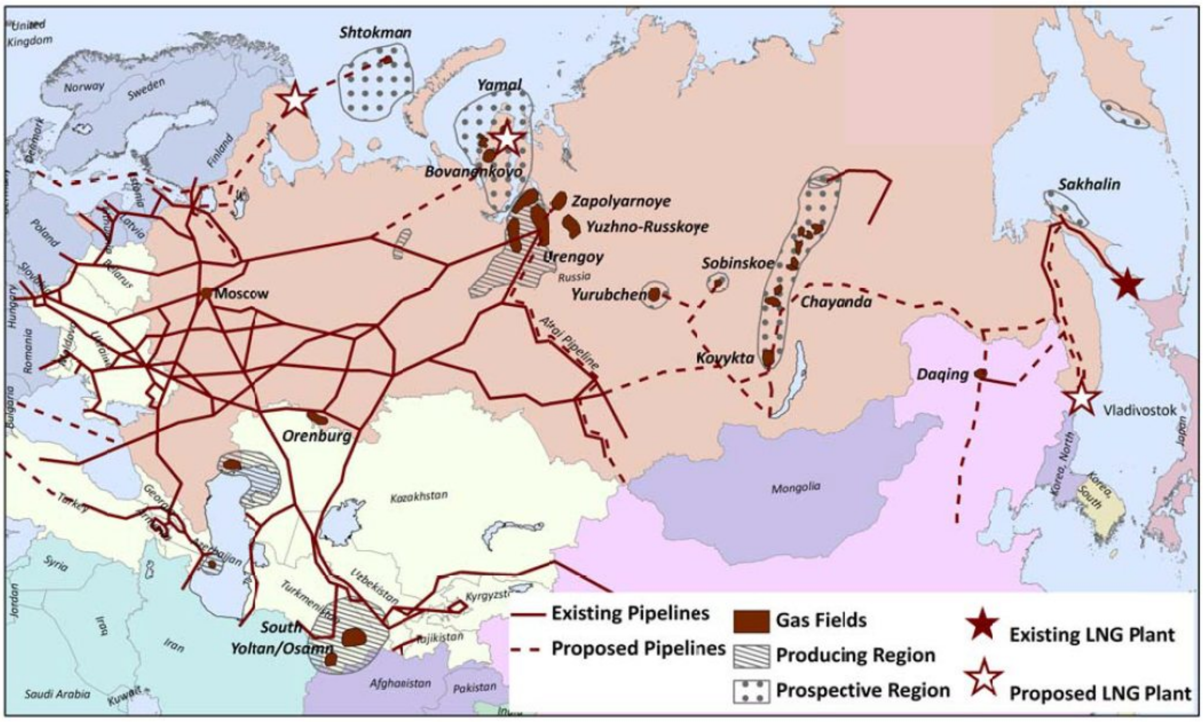

Fig. 1. Unified Gas Supply System of Russia (as part of scheme), [6]

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The effects of different nonstandard situations in the energy systems due to large-scale negative natural-climatic processes, for example abnormally cold periods in winter with a peak increase in demand for additional fuel, can be much more severe. This issue is especially relevant for territories of the European part of Russia that have a small share of their own energy and fuel resources in the fuel balance.

3. Review of available experience.

When analyzing the available experience, it is vital to establish prior publications on the topic and what resources might be helpful to solve the questions posed.

Current literature includes numerous works on modeling of the operation of gas transmission networks in abnormal operating conditions. The most suitable ones are listed below.

TIGER model [7-9] represents the model of the European gas market with over 500 nodes covering all major long-distance transmission pipelines individually. TIGER was used to analyze the European natural gas supply security [10, 11] and to identify bottlenecks in the European gas transmission network [12]. A similar linear optimization approach is used in the InTraGas model [13]. Bottlenecks between nodes are identified. The World Gas Model (WGM) covers the most of world natural gas production [14]. Model MC-GENERCIS [15] is able to evaluate the risk in a gas shortage situation by using a Monte-Carlo based analysis. Model GEMFLOW based on the MC-GENERCIS can assess the possible outcomes of a supply disruption beforehand and minimize losses during an emergency by finding the optimal distribution of flows [16]. Two network models to evaluate the overall security level and related characteristics of China's natural gas supply system from 2000 to 2012 are described in [17]. US natural gas network model [18] was created in order to represent the network on a regional basis and evaluate its possible respond to disruptions. Strategic Eurasian natural gas market model is presented in [19]. It differs from earlier ones in its detailed representation of the structure and operations of the former Soviet Union gas sector. European gas network model simplified with linear programming was developed and used to investigate the impact of the loss of Ukraine's transit capacity on gas supply from Russia to Europe [20].

As for critical infrastructure and the search for the most important objects from the standpoint of system health, interesting points are presented in the following papers.

A probabilistic model based on Monte-Carlo simulations with graph theory to study security of supply in a gas network is presented in [21]. It identifies critical network nodes in terms of security of supply and provides their numerical ranking. The drawback is a large number (1 million and more) of model runs for Monte-Carlo simulations.

The assessment method of energy system critical infrastructures is presented in [22]. It can be applied for the evaluation of interdependent energy system infrastructures, simulating functional connections between infrastructures and their elements. It can identify critical elements and their groups in terms of final energy consumers' requirements taking into account random operation of all energy systems. Gas supply networks are investigated with district heat generation technologies, power generation technologies and final consumers of heat and electricity.

Approach [21] is based on probability assessment, and in [22] its preference over deterministic approach is justified in that it reflects the operation of power equipment more realistically.

The source [23–25] suggests methodological approaches to modeling a set of interconnected technical infrastructures, such as energy systems, in the form of a single structure or "system of systems," such as the fuel and energy sector. So in [23, 24] the modeling of interconnected technical systems is constructed as follows. Modeling the infrastructure of each system is divided into two parts: structural and functional. The structural model represents the topology of the system. The functional model describes the distribution of the physical flow through the system and the response of the system to the effects of perturbations. Then, individual infrastructures are combined with the help of intersystem connections into the general model. To model the infrastructure of a technical system, this infrastructure is divided into the structural and functional part. Both parts of the system can be subject to disturbances such as structural failure, deliberate attack, or physical flow limitations due to disturbances. External perturbation in relation to the system can be expressed in two different ways: structural or functional disturbances. In this case, structural disturbance is described as the removal of an element from the graph, and the functional perturbation can be realized through a change in the functional capabilities of the system. Analysis of the interrelated model should take into account the results of calculations of all functional models. For example, if the critical node of one infrastructure depends on the functioning of the second infrastructure, and some critical node of the second infrastructure in turn depends on the health of the other node of the first infrastructure. Failure of any node of the second infrastructure can cause cascades of accidents in both infrastructures, which in the end will lead to their mutual reinforcement. Such research technology can be adopted as basis, but it does not accomplish concrete modeling of complex technical systems. This requires further steps, to apply imitational mathematical models and to solve a specific task of searching for critical objects of the system from the standpoint of ensuring its operability.

In [8] attention was paid to identification and analysis of bottlenecks and assessment of transport opportunities and the cost of transporting gas along the arcs of the graph. This is done on the basis of calculation and assumption of gas prices at the nodes of the graph. This approach points at potential bottlenecks that may arise in the long term and allows estimating the economic costs of various options for the development of the gas transportation network. This is useful and important, but it affects other aspects of presence of bottlenecks in the system.

The work [26] identifies the load and fault-resistant backbones of the trans-European gas pipeline network. The maximum possible load of the gas pipeline network and its resistance to possible failures are estimated. For that purpose, the authors apply two complementary methods generalized from the between centrality and the maximum flow. In the first approach, transport occurs along the shortest paths in geographical space. They search for a global backbone characterized by the presence of flow corridors. In the second approach, they look at fault tolerance when single

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components fail. The conducted studies allow the authors to state that the Trans-European Gas Network is reliable, that is, resistant to failures of high-loaded links.
From the above-listed models of the gas industry, only TIGER has the necessary level of detail to describe the technical capabilities of gas trunking networks. This is what is needed to find the critical objects. In other models, the gas transportation network is presented at a much more detailed level. Also, the models presented above are mostly focused on the study of economic issues, for example, the gas markets of Europe, and not on the technical side of the flow distribution.
Model [21], on the contrary, requires a very detailed representation of the gas transportation network. Besides, the applicability of probabilistic approach widely used in the mathematical theory of reliability to investigate the survivability of energy sys-tems raises doubts due to difficulty of predicting large perturbations.
Approaches [22-25] are applicable only for interconnected energy supply systems functioning in a single complex with consideration of several types of energy resources.
The approach [26], which uses the methods of graph theory, is to a large extent labor-consuming and requires considerably more computing resources for carrying out calculations.
Thus, in this article we propose a more economical in the computing plan research apparatus, which will allow us to obtain sufficiently accurate results of calculations. Such a device is the most convenient for the study of individual energy systems. At the same time, it allows to overcome the shortcomings of probabilistic research methods in connection with less stringent requirements for the composition of information and avoidance of unnecessary details. For the study, it is sufficient to know the enlarged characteristics of the operation of the gas pipeline corridor without specifying details about the operation of each pipeline that enters this corridor.
The proposed method is useful for solving the tasks. At the same time, the method of analyzing the significance of each object of the gas transportation network for its total operability is fairly simple in implementation and allows to identify all potentially significant objects. Then a list of the most significant such objects is constructed, i.e. Critical objects. They should be handled by experts in their studies in order to develop ways of reducing the significance of their influence on the work of the system as a whole.

4. Principles for identification of critical facilities in Russian gas industry

All things considered, as the first step we suggest investigating the gas industry as a case study, including:
- identification of critical facilities of the gas industry;
- determination of negative effects of the materialization of emergency situations at the critical facilities of the gas industry;
- development of measures to minimize negative effects of emergency situations at critical facilities of the gas industry.

After the critical facilities in the gas transportation system are identified (and their impact on the capabilities of fuel and energy supply to consumers is assessed) we can

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formulate the main ways to eliminate them or potential measures which will enable to reduce the significance of such critical facility for potential operability of the system.

After the experience of identifying critical facilities in the gas industry has been gained, similar work can be continued for other energy systems.

To solve the stated problem we can apply special model tools which adequately describe all the aspects of interrelated operation of energy industries within the energy sector in terms of energy security. Such model tools will allow us to determine whether or not the energy sector of the country and energy supply systems of certain regions can meet the demand for various types of energy in individual areas, which is formed in different conditions (including emergency conditions).

Currently, to make up a list of critical facilities for the unified gas supply system we can consider the following types of facilities: main compressor stations, underground gas storage, and linear part of the gas trunklines. At the same time, there are certain specific features of the formation of the list of critical facilities, depending on different types of the facilities. All the facilities associated with gas production, or storage and supply from underground storage, and pipeline transportation at each considered time interval can be either classified as critical facilities or not classified as such, depending on the extent of their influence the process of meeting domestic demand for gas and gas export obligations. This extent of the influence can be determined by special calculations using the software package "ROG". Here it is suggested to consider each facility whose failure to operate causes relative gas undersupply to consumers in the amount of 5 percent and more of the total demand for gas throughout the system as critically important. This value (5 percent) is substantiated by multi-iterative simulation studies and allows us to speak of a small amount of potential critical facilities. All the facilities of the gas industry are undoubtedly important to provide its operability, but for example 50 percent of the system facilities cannot be critically important as in this case it will be impossible to identify the top-priority facilities for funding. The goal is to create a priority of ensuring operability of the most important facilities of the gas transportation industry.

An approximate process of justifying a threshold of 5% is presented below. The conducted studies show that total gas deficit of 4% or more can occur if one of the 47 facilities is disconnected. It is 35% of all crossings (there are 132 intersections in the Russian gas transportation network). In the opinion of the authors, it appears excessive from the perspective of priority financing of additional measures to classify all these objects as critical facilities with the implementation of appropriate measures to protect them. On the other hand, a total gas deficit of 6% or more may occur in the event of disconnection of only one of 16 objects, i.e. only 12% of all crossings analyzed. In the opinion of the authors, this value is too small for the extremely branched Russian main gas transmission network. The authors consider it logical to define as critical the facility, which, when disconnected, forms a gas deficit in the country of 5% or more. Such a deficit may occur when any of the various 33 intersections of main gas pipelines are cut off, which is 25% of all crossings considered. The choice of principles for the formation of a list of critical facilities of the gas transportation network is interesting in itself and can be further discussed. Meanwhile, in order to explain the principles of the formation of invariant measures to minimize the gas deficit in the event of disconnection of the most important gas transportation network objects, we propose to dwell on the 5% threshold justified above.

Whereas the number of gas production and underground storage facilities in the gas transportation system is relatively small and calculations on the consequences of their failure can be performed manually, the number of lines in the gas trunkline system and the number of crossings of these lines is so large that it is impossible to manually check the significance of each gas pipeline facility to solve the general problems of the system.

To make a list of critical facilities first it is necessary to carry out calculations not for each edge of the linear part of the gas trunkline that enters the detailed calculation graph but for numerous crossings of edges of the gas trunklines. The rules of classifying certain crossings of the gas trunklines as critical facilities are the same as for the other facilities of the unified gas supply system: i.e. failure of a crossing to operate leads to relative gas supply shortage throughout the entire system in the amount of 5 percent and more. For each certain crossing to be included in the list of critical facilities it is necessary to carry out calculations to determine relative gas shortage for consumers in the case where certain edges that constitute this crossing fail to operate. If the failure in operation of one or several such edges also leads to the total relative gas undersupply in the amount of 5 percent and more, such edges should also be included in the list of critical facilities of the gas transportation system.

Thus, for the gas transportation system of Russia we will consider numerous crossings of gas trunklines corridors or individually running gas trunklines in order to form a list of critical facilities in terms of energy security. In this case we will have to deal with both the crossings of gas trunklines at the nodal compressor stations and the crossings outside the compressor stations.

4.1. Identification of critical facilities of the gas transportation system with the software "Russia's Oil and Gas".

To solve the task of the formation of a list of critical facilities of the gas transportation system we use the software "Russia's Oil and Gas" ("ROG"). This software is an updated release of the software "Oil and Gas" [27].

In [27] ways of minimizing negative consequences at failure of any arbitrarily appointed objects of the gas transportation network have been discussed. In that study, by using the model we identified those sections of the network where it is necessary to increase the capacity in any accident. As a result of this increase in capacity in other sectors, gas deficit among consumers has been reduced. The approach proposed in this article is based on what is shown in [27], but the main task is to find and form a list of the existing critical objects of the gas transportation network. The output of such objects can be detrimental to the operation of the system. Then, bypassing bottlenecks, as in [27], we are trying to reduce possible negative consequences from the failure of these critical facilities. In some cases it may result in reducing gas deficit in the system to less than 5%. Such critical objects can be omitted from the general list of critical facilities.

Thus, finally, only those objects for which it is impossible to minimize negative consequences through redirection of gas flows will remain in the list of critical objects.
Formation of a list of critical facilities of the gas transportation system includes the following stages:

– the software “ROG” automatically forms the complete list of crossings of gas trunklines;
– based on the multi-variant calculations (the number of calculations corresponds to the number of crossings) we determine total gas shortage for consumers when each of the crossings fails;
– all crossings are ranked in the list depending on the value of the total relative gas undersupply to consumers in case a certain crossing fails to operate;
– all crossings whose failure to operate caused the total relative gas undersupply to consumers in the amount of 5 percent and more of the total demand for gas in the system are considered to be critical and constitute a list of critical facilities of the gas transportation system;
– the software “ROG” solves the gas transportation system optimization problem for each crossing from the list of critical facilities and determines the measures to minimize gas shortage for consumers based on the solution through elimination of “bottlenecks” resulting from the malfunction of this crossing;
– based on the multi-variant calculations, we form a list of invariant measures which, when implemented, will minimize the adverse consequences of the malfunction of a greater number of crossings from the list of critical facilities, and decrease the criticality of certain critical facilities with their exclusion from the list of critical facilities.

Of great assistance in such studies can be geo-information systems as a tool for visualization of information describing complex spatially distributed systems such as energy systems. The main principles of mapping the energy system schemes and searching for the bottlenecks were developed while creating and using the problem-oriented geo-information system “ROG” to research the survivability problems of individual energy systems, in particular, gas, oil and oil product supply systems [2, 3]. The scheme of energy system in geo-information system is represented as a map consisting of two layers with vector data. The first layer represented by point objects characterizes the state of producers and also demonstrates if the needs of consumers for the energy resource are satisfied completely. The second layer represented by lines shows the extent to which the transport subsystem is loaded. The point objects of the first layer are related to the attribute data on production and consumption of energy resources, and the lines of the second layer – to the data on the trunkline sections (capacity, diameter of pipes, etc.). Crossing of gas trunklines corridors is determined as crossings lines of the second layer.

4.2. Model base for the work of the software "Russia’s Oil and Gas".

Mathematically, Russia’s unified gas supply system is represented as a network that varies with time, whose nodes have the facilities for production, conversion and

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consumption of material flows relating the enterprises. When solving the problem of estimating the state of the system after a disturbance, the criterion of flow distribution optimality is represented by the minimum shortage of the energy resource for consumer at the minimum costs of its delivery.

A change in the state of system facilities requires solving the problem of flow distribution in the system in order to supply energy carriers to the maximum extent possible, i.e. the model can be formalized as a problem related to the maximum flow [4, 5]. Then it is necessary to add two fictitious nodes to the graph scheme: O – total source, S – total sink, and introduce additional sections connecting node O with all sources, and all consumers with node S. Mathematically, the stated problem has the following form:

$$\max f \tag{1}$$

subject to

$$\sum_{i\in N_j^+} x_{ij} - \sum_{i\in N_j^-} x_{ji} = \begin{cases} -f, & j=O \\ 0, & j\neq O,S \\ f, & j=S \end{cases} \tag{2}$$

$$0 \le x_{ij} \le d_{ij}, \text{ for all (i, j)} \tag{3}$$

Here N_j^+ - a subset of edges incoming to node j; N_j^- - a subset of edges outgoing from node j; f - a value of the total flow in the network; x_{ij} - a flow in edge (i, j); d_{ij} - constraints on the flow in edge (i, j).

Problem (1)-(3) about the maximum flow in a general case has a non-unique solution. The next step suggests solving the problem of maximum flow of the minimum cost, i.e. the cost functional

$$\sum_{(i,j)} C_{ij} x_{ij} \to \min \tag{4}$$

is minimized, where C_{ij}- price or specific costs of the energy resource transportation. The comprehensive approach to solving the stated problems throughout the entire technological chain from receiving gas by the network to its transportation to the distribution network or export makes it possible to obtain the total estimate of the production capabilities of the entire system in extreme conditions to make appropriate decisions. Solution to the problem is represented by the values of gas shortage at the consumption nodes under emergency conditions.

It is obvious that using this model in the conditions of a large-scale disturbance we face the problem of potential limitation of supplies of the energy resources to consumers. After this, it is necessary to identify bottlenecks that limit the system's ability to meet the demand of consumers for the required resource. It is necessary to rank these bottlenecks by importance of their influence on the production capabilities of the system. Such ranking will be useful for determining the priority of measures to increase the production capacity of the system. In general, this will help reduce the negative consequences of disabling any object in the system. A solution of this task was proposed in [27-30].

To fully meet the demand of consumers the obtained maximum flow f from problem (1)–(4) should be increased by the amount of the total shortage of the resource for consumers. Within certain limits this can be done owing to the technological characteristics of the system (by putting a backup compressor at compressor stations into operation and hence increasing the pressure in the pipelines, where possible). Thus, *the question arises by which amount and where to increase the capacity of edges to obtain the desired increased flow with the minimum costs of this increase*.

Such problem can be expressed as follows:

$$\sum_{(i,j)} (C_{ij} q_{ij} + A_{ij} y_{ij}) \rightarrow \min \tag{5}$$

subject to

$$h_{ij} = q_{ij} + y_{ij} \tag{6}$$

$$\sum_{i \in N_j^+} h_{ij} - \sum_{i \in N_j^-} h_{ji} = \begin{cases} -v, & j = O \\ 0, & j \neq O, S \\ v, & j = S \end{cases} \tag{7}$$

$$0 \leq q_{ij} \leq d_{ij} - x_{ij} \tag{8}$$

$$0 \leq y_{ij} \leq Y_{ij} \tag{9}$$

where v -value of the total shortage of resource for consumer; d_{ij} - constraint on the flow in edge (i, j);. h_{ij} - an increase in the flow along edge (i, j); q_{ij} - increase in the flow along edge (i, j) up to d_{ij}; y_{ij} - increase in the capacity of edge (i, j) above d_{ij}; Y_{ij} – constraint on the increase in the capacity along edge (i, j) above d_{ij}; C_{ij} - price or specific costs of energy resource transportation along edge (i, j) within d_{ij}; A_{ij} - price or specific costs of energy resource transportation with respect to increase y_{ij}; N_j^+ - subset of edges incoming to node j; N_j^- - a subset of edges outgoing from node j; O - total source; S – total sink ; x_{ij} - value of the flow along edge (*i, j*), obtained by solving problem (1)–(4).

As a result of the solution of problem (5) - (9), we can form a list of those arcs of the graph, the capacity of which can and should be increased within 10%. Such an increase in the real gas transportation network will significantly reduce the gas deficit in consumers in the event of disruption of emergency situations at various sites. This will be achieved by using other workarounds on the network.

To answer the posed questions, special studies were conducted. These studies used the “ROG” software that was based on the tools intended for solving integer and mixed integer linear programming problems lp_solve [31].

5. The results of the research

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The research included the calculations that made it possible to identify the nodal compressor stations and crossing points of the gas trunkline corridors that are situated between the compressor stations whose disconnection can lead to the total potential gas shortage for consumers in a relative amount of 5 percent, i.e. this concerns Russia's gas transportation system facilities that represent critical facilities of the federal level. The database of gas part of software "ROG" includes information on:

- 378 nodes: 28 gas sources; 64 consumers (regions, individual industrial hubs); 24 underground gas storages (UGS); 266 major compressor stations and compressor stations at crossings of the main gas pipelines;
- 486 arcs representing main gas pipelines and their corridors connecting the above nodes with each other.

With the help of this software, multivariate calculations were carried out. Gas deficit was calculated in the event of disconnection of each gas pipeline intersection of all available in the network. There are 132 intersections in the model, including 85 nodal compressor stations at the sites of splitting and crossing of the gas trunklines and 47 crossings of the gas trunklines beyond the compressor stations (crossings of the pipeline sections).

With the use of the simulation mathematical model of the Russian gas industry (software "ROG"), calculations were made. Calculations were carried out on averaged information for average winter days of 2015. We were looking for critical facilities of the Russian gas transportation network. These are facilities that in the event of an accident at them will actually limit the production capacity of the system and generate the maximum gas deficit among consumers. It is possible to find such objects only when investigating the functioning of the maximally loaded network. In Russia, the gas transportation network is loaded to the maximum extent in the coldest period, usually on an average day of January. This was the case in the analyzed year 2015, which was practically identical to other neighboring years by characteristics. The calculations use data on the average daily gas consumption for all regions of Russia on an average day of January 2015, as well as data on gas output at the main compressor stations of Russian gas fields during this period. In this period, underground gas storage facilities also provide certain gas volumes to the gas pipeline network. Information on possible maximum gas withdrawals from UGS is also used in the model. In addition, the model uses information on the current throughput capacities of all sections of main gas pipelines and the unit costs of gas transportation in these areas. All this information was taken from the relevant sources of the Public Joint Stock Company "Gazprom" and used in software "ROG" to solve the problem of gas distribution in the network.

We will dwell on the calculation results in more detail.

5.1. The number of critical facilities of the gas transportation system and an example of meeting the needs of the gas in case of failure of the largest critical facilities before solving the problem of bottlenecks bypass.

In the first stage of the research we identified 33 facilities in the gas transportation system of Russia that qualified for inclusion in the list of critical facilities. These facilities include 25 nodal compressor stations at the sites of splitting and crossing of gas trunklines and their corridors and 8 crossings of the gas trunklines beyond compressor stations (crossings of pipeline sections). In the case where any of these facilities ceases to operate gas supply to consumers can be limited by 5–27 percent of the total gas flow in the network.

Table 1 shows the situation with satisfying the gas needs of domestic consumers and the countries that import Russian gas that can arise in the event of the disconnection of one of the critical intersections of the main gas pipelines. This intersection is located in the Urals Federal District. The volumes of gas deficit during the accidents at the intersection were determined for all consumers considered in the model, and then summed up by federal districts of Russia.

Table 1. Meeting gas demand in case of a gas pipelines intersection failure at one of nodal compressor station

Federal district, importers	Demand	Supply	Shortage	Satisfaction, %
	million cub.m/day			
Northwestern FD	130.5	124.4	6.1	95.3
Central FD	394.9	278.2	116.7	70.4
Southern FD	90.5	90.5	0.0	100
North-Caucasus FD	77.1	45.0	32.1	58.4
Volga FD	384.7	361.4	23.3	93.9
Ural FD	340.9	340.9	0.0	100
Siberian FD	45.7	45.7	0.0	100
Non-FSU countries	452.7	155.4	297.3	34.3
FSU countries	143.4	65.5	77.9	45.7
APR	13.8	13.8	0.0	100
Total	2074.0	1520.6	553.4	73.3

5.2. The final number of critical facilities of the gas transportation system and an example of meeting the needs of the gas in case of failure of the largest critical facilities after solving the problem of bottlenecks bypass.

The final list of critical facilities will be shorter than the initial one (33 facilities). This is related to the assessment of potential operation of the gas transportation system of Russia in the case of a short-term increase in the capacities of individual edges of the gas trunklines which is admissible under emergency conditions, i.e. it concerns the problem of bypassing the "bottlenecks" in the conditions of congested network or, in other words, in the conditions when the network operates at full capacity but this is not enough to fully meet the demand of consumers for natural gas. In the cases where after solving the problem of bypassing the "bottlenecks" the relative total gas shortage in the network declines to the values lower than 5 percent, the corresponding nodal compressor stations or crossings of the gas trunklines that were initially included in this list should be removed from it, since the system capabilities used during the emergency situation made it possible to sufficiently minimize the negative effect of the failure of this facility.

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The results obtained by solving the problem of bypassing the “bottlenecks” ((5)–(9)) for the presented example of a gas trunkline crossing failure at a major compressor station are presented in Table 2.

Table 2. Meeting gas demand in case of a gas pipelines intersection failure at a nodal compressor station when solving the problem of bypassing the “bottlenecks”

Federal district, importers	Demand	Supply	Shortage	Satisfied, %
	million cub.m/day			
Northwestern FD	130.5	124.4	6.1	95.3
Central FD	394.9	311.6	83.3	78.9
Southern FD	90.5	90.5	0.0	100
North-Caucasus FD	77.1	53.5	23.5	69.5
Volga FD	384.7	379.3	5.4	98.6
Ural FD	340.9	340.9	0.0	100
Siberian FD	45.7	45.7	0.0	100
Non-FSU countries	452.7	166.9	285.8	36.9
FSU countries	143.4	66.1	77.3	46.1
APR	13.8	13.8	0.0	100
Total	2074.0	1592.7	481.4	76.8

Table 2 shows that by solving the problem of bypassing the “bottlenecks” the gas shortage in Central FD can be reduced by more than 8 percent, in North Caucasus FD – by 11 percent and in Volga FD - almost by 5 percent. The total shortage of Russian gas for its importers (excluding APR) can be reduced by 2%.On the whole, the gas shortage for consumers throughout the network can be reduced by 3.5%.
The said gas shortage can be reduced by increasing gas supply within 10 percent along the pipelines:

- from the compressor station “Aganskaya” and the compressor station “Vyngapurovskaya” to the compressor station “Bogandinskaya” (the gas trunkline “Urengoi – Chelyabinsk – Petrovsk 1,2”);
- from the compressor station “Pangody” to the compressor stations “Kazym” and “N.Kazym” (along all the gas trunklines in this corridor).

As a result of solving the problem of bypassing the “bottlenecks”, 9 nodal compressor stations and 4 crossings of the gas trunklines outside the compressor stations were excluded from the list, since the relative gas shortage in the network made up less than 5 percent owing to a short-term increase in its capacity. Thus, at present 20 facilities have to remain on the list of critical facilities of the gas transportation system of Russia.

5.3. Sections of main gas pipelines for increasing bandwidth

The authors carried out multi-iterative model studies. A search was made for possible ways of minimizing the negative consequences when switching off critical facilities of the Russian gas transportation network. These studies were carried out for all 33 intersections of trunk gas pipelines initially included in the list of critical facilities of

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the Russian gas transportation network. As a result of the research, about 90 sections of main gas pipelines were found. Increasing their capacity would reduce the gas deficit in cases of disconnection of relevant critical facilities.

As a result of the research, it was noted that some sections of the gas pipelines where the capacity is to be increased are repeated when different intersections are disconnected. First of all, financing of measures to increase throughput should be directed to those sections of the main gas pipelines that are most often encountered in various accident scenarios. As a result of the research, the relevant sections of the main gas pipelines were found. These sections in 80% of the analyzed situations were identified as bottlenecks, the capacity of which must be increased. Below is a list of such sections of main gas pipelines with the indication of real names of compressor stations and affiliation to real main gas pipelines:

- from the compressor station “Peregrebnoye” and the compressor station “Sosvinskaya” to the compressor station “Vuktyl” (the gas trunk lines «SRTO – Torzhok”, “Urengoi – Gryazovets – Torzhok”);
- from the compressor station “Taezhnaya to the compressor station “N.Ivdel” (all the gas trunklines in this corridor);
- from the compressor station “Aganskaya” and the compressor station “Vyngapurovskaya” to the compressor station “Bogandinskaya” (the gas trunkline “Urengoi – Chelyabinsk – Petrovsk 1,2”);
- from the compressor station “Pangody” to the compressor stations “Kazym” and “N.Kazym” (all the gas trunklines in this corridor);
- from the compressor station “Ukhta” to the compressor station “Gryazovets” (all the gas trunklines in this corridor);
- from the compressor station “Vyngapurovskaya” to the compressor station “Priobskaya” (the gas trunkline “Urengoi – Chelyabinsk – Petrovsk 1,2”)

The analysis allows us to state that at these specific sections of the main gas pipelines, it is necessary to carry out the corresponding technical modernization and increase their throughputs within 10%. Such priority measures will allow the most simple and comparatively economical way to minimize the negative consequences from emergency situations at critical sites of the Russian gas transmission network in 80% of the possible cases.

Conclusion

The case study of Russia’s gas transportation system demonstrates an example of identifying the critical facilities in the gas industry. Undoubtedly, the choice of such critical facilities does not belittle the importance of providing reliable continuous operation of all the other facilities in the gas transportation system, since all of them are necessary for reliable gas supply to consumers and sometimes vitally important for certain consumers. The aim of the research was to solve the problem of prioritizing the measures to ensure the maximum operability of the system under emergency conditions, which was effectively demonstrated.

The research procedure adopted in the article was tested by numerous model calculations. In all cases, the solution of the problem of bypassing bottlenecks in the event of an accident in the gas transportation network made it possible to significantly reduce gas deficit for consumers. The possibilities for a short-term pressure increase in some parts of the gas pipeline network are real and it is important to find out where they need to be implemented in a specific emergency situation. The proposed approach realizes these possibilities. Real critical objects of the system are determined in the calculations and their list is refined in all cases after numerous model calculations. All the results obtained in the article are confirmed by model calculations and can be implemented in practice in the real gas transportation network of Russia.

The proposed approach to identifying critical objects of a complex branched network which can be applied to any complex technical infrastructure. An approach to the definition of invariant measures can also be applied to minimize the negative consequences of failures of critical objects of this infrastructure.

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