A Method to Aggregate Schemes of Gas Systems for an In-Depth Study of Their Expansion

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***Abstract* — There are about 30 natural gas production and transmission companies operating currently in the Russian Federation. The vast majority of them are interconnected and form the Unified Gas System. It includes gas production, processing, transmission, and underground storage facilities. Various problems in the gas system are solved relying on multilevel modeling and indicators of varying degrees of detail. This generates the need for and relevance of the development of methods for multilevel modeling and aggregation of gas systems. The paper presents an analysis of methodological approaches to the aggregation of schemes of gas systems and their facilities, which are currently available in the world. A method is proposed to aggregate gas systems, which encompasses a procedure for aggregating a real-world gas system, i.e., its representation as a calculated scheme of a smaller size. The study employs the methods of graph theory and aggregation procedures. The proposed method is illustrated by an example of a gas system covering three territorial entities, including 20 consumer nodes, 8 fields, and 14 compressor stations. The proposed methodology is applied to create a database for comprehensive studies of the Unified gas system expansion.**

***Index Terms*: aggregation, gas system, main gas pipelines, fields, gas consumers, calculated scheme, real-world system.**

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I. Introduction

The Unified gas system (UGS) of the Russian Federation is a complex, multi-line, extended system that integrates gas systems of the CIS, Eastern and Western Europe. It interacts with gas producers in Central Asia, and supplies gas to the countries of Northeast Asia. The UGS has a huge number of components and connections. It is virtually impossible to create an accurate model that adequately describes all UGS facilities (linear sections, main gas pipelines (MG), compressor stations (CS), gas compressor units (GCU), fields, underground gas storages, gas consumers, and others) in a comprehensive study of the system expansion. In this regard, the aggregation of a real-world gas system, i.e., its representation by a smaller calculated scheme, is of great importance. This is why this research is relevant.

The UGS of the Russian Federation is a unique natural monopoly structure. Given various factors and properties of the gas system, we can distinguish the following main levels of its investigation and mathematical modeling [1]:

1) A subsystem of a more general system of the energy sector (in general energy, economic, environmental and other intersectoral problems);

2) The industry as a whole, in technical and economic terms (natural monopoly);

3) A functionally integral system (for the cases of gas flow control in normal situations, for seasonal and emergency control) in the problems of planning and phased expansion, reconstruction and operation of gas systems, as well as in the analysis and synthesis of their reliability;

4) A set of production and technological facilities and subsystems (determination of parameters during their design for gas systems).

Aggregation of gas systems (GS) is relevant at all levels of the hierarchy, but especially at the first three. It includes the following steps: 1) building an aggregated calculated gas system scheme; 2) identifying aggregated technical and economic characteristics (TEC) of new and existing gas transmission and gas production companies (GTC and GPC), which also includes demand projection in the wholesale natural gas markets; and 3) aggregating the gas systems in quasi-dynamics by year of the calculation period. This paper focuses on the construction of an aggregated calculated scheme of a gas system.

The construction of an aggregated gas system is understood as the transformation of a real-world gas supply diagram into another, a simpler one, but corresponding to the original one with a certain accuracy, while maintaining the required properties of the primary system in the resulting scheme [2]. The resulting aggregated scheme, being simpler than the original one, is characterized by a smaller number of nodes and links, which facilitates the analysis and use of the results to generate the necessary solution.

II. Analysis of Methodological Approaches to Aggregation of Calculated Schemes of Gas Systems and Their Facilities

The increase and complication of gas systems in Russia and their integration into the UGS led to the need to create enlarged calculated schemes to comprehensively examine and identify the optimal path for their expansion.

Currently, there are various aggregated schemes of the UGS as a whole and its individual parts. These schemes differ because they are designed for different objectives, based on different initial information available, and intended for different levels of the hierarchy.

For example, the existing General plan for the Development of the Russian Gas Industry until 2030 [3] makes it possible to determine economically sound strategic directions for the development of the gas industry. It presents projections for the development of consumption, transport and production of natural gas in Russia as a whole and in the federal districts. Study [4] describes the stages of the general plan development. The first stage employs a systems approach to plan the development and reconstruction of the UGS; the second stage suggests fundamental technical solutions at the level of individual sections of the UGS. It also substantiates the need to consider a large number of expansion options. The study also accentuates that at present, medium- and long-term planning relies on an aggregated flow diagram, which was once adopted in an unnecessarily enlarged form because of the capabilities of computers.

There is an approach to the construction of enlarged calculated schemes, which is based on an expert method. According to this method, the main gas transport corridors are marked on the map of the Russian Federation and the main intersections of gas flows are marked following the opinion of a decision maker or a group of experts [5]. Such a scheme is too enlarged and does not sufficiently reveal the nature of gas supply to some regions and constituent entities of the Russian Federation (small entities are discarded), meanwhile accuracy is lost.

Although, in the world, there is no analogue to the UGS of Russia, which is a unique large-scale system, still researchers from other countries conduct the studies on the expansion of large gas systems [6–9]. For example, they consider gas systems of different European countries, where gas supplies from the UGS of the Russian Federation are also taken into account [10–12]. The expansion of gas systems is modeled in gas models. Papers [13, 14] provide a review and comparison of gas models developed in different countries.

The main downsides of such models are as follows: gas production and liquefaction are linked into one production; it is assumed that the country has a single gas producer, i.e., aggregated source nodes are characterized by aggregate cost and performance; the real market is segmented along the boundaries of the network companies, while in the models, the network has no clear boundaries; only few models can take into account gas storage.

Some models consider networks of varying degrees of aggregation (countries, cities, territories) [15]. When calculating gas transfers between countries, gas exporting countries are designated as source-nodes, and one country can be designated by one or more source-nodes. Similarly, importing countries can be designated by one or more consumer-nodes on the scheme. Source-nodes and consumer-nodes are interconnected by gas transport arcs. Such networks require the aggregated performance to be determined, however, these calculations are not described. According to [14], the lack of transparency in obtaining an aggregated network is a common modeling problem.

Authors of [16] propose iterative aggregation, which involves examining the features of the system, statistical data, and, on this basis, building mathematical models that describe the development and functioning of the system. Further, the main indicators of the system are determined, their weight coefficients are set to calculate the aggregated characteristics. A heuristic algorithm is also proposed for iterative aggregation, which suggests that the weight coefficients are given by experts, not by a fixed number, but by a range. The use of this method is complicated due to the impossibility of collecting a huge amount of detailed initial information on the system, and due to the existence of a large number of random factors that cannot be taken into account and described.

In [5, 17], approaches to the aggregation of indicators from the lower level of the hierarchy to a higher one are described. An attempt is also made to switch from expert aggregation to formal mathematical modeling (the method of convolutions of particular values of indicators is used).

Gas exports are calculated based on an analysis of global trends in the development of gas systems and an assessment of the gas market situation following the materials given in the general plan for the development of the gas industry. Retrospective information is collected for each country consuming Russian gas, including purchase volumes and information on long-term contracts for the sale of gas to these countries. Based on this information, export volumes are projected. The average gas export values are detailed and distributed among the nodes of the calculated scheme in accordance with the capacity of the export corridors.

New natural gas consumer-nodes "appear" in the calculated gas supply scheme when considering prospective hydrocarbon markets for the constituent entities of the Russian Federation. The studies examine the feasibility and efficiency of investment projects for the development of natural gas resources, rationale for the long-term goals for the development of industry, agriculture, and for the improvement of the welfare of the people.

World's scientific and practical experience shows that the issue of aggregation of gas systems is neither sufficiently studied nor systematized. There is no algorithmic description of the methods for aggregating the gas system scheme. The following aspects of aggregating the system components are poorly investigated:

– Demand for natural gas is most often projected to be overall for the country or a district;

– Aggregated source nodes are represented in the scheme by large fields, disregarding small fields and independent gas producers;

– Aggregation of the main gas pipelines identifies the main gas transmission corridors, which have a single-line representation with a total throughput capacity. Other main gas pipelines are often ignored.

The scientific novelty of this work is related to a gas system aggregation method including an algorithm for building a model calculated scheme of a gas system to the level of entities, which allows formalizing this process.

III. A Method of Aggregating the Gas Supply Calculated Scheme

A method is proposed to aggregate the gas system to the level of the entities of the Russian Federation but not to the level of the federal district (as in the General Plan), which allows clarifying and detailing information on gas consumption, transmission and production to a lower level.

Gas system is considered at three levels: 1) main gas pipelines, fields, underground gas storages; 2) gas transmission and gas production companies (GTCs and GPCs); 3) Unified gas system of the Russian Federation. Solving the problems of the optimal gas system expansion, we firstly analyze technical and economic characteristics of the lower level components (main gas pipelines, fields), then use these data to determine the characteristics of GTCs and GPCs, and consider the entire UGS, determining the optimal flows, gas transmission directions and cost. In reverse order, the obtained data is checked for the agreement with the lower levels. If discrepancies occur, the next cycle of calculations is performed until a solution acceptable for all levels is found.

The gas system is represented as a directed graph and is considered as a set of three subsystems: gas sources, main transmission networks and consumers. Source facilities include all facilities that deliver gas to the main transmission network: complex gas treatment plants, gas chemical complexes and underground gas storage facilities (UGSFs), if at the considered time point the UGSF is working for gas extraction. The main gas transmission facilities consist of sections of the main gas pipelines, including the linear part and compressor stations located on it. Consumers include consumer groups that take gas from main gas pipelines and UGSFs, if the time under consideration coincides with the period of gas injection into them.

The construction of the gas system model network graph is based on the following principles:

the network configuration reflects the directions of the main gas transmission systems, the location of large gas transmission interconnectors, the points of connecting the main gas pipelines of source facilities to consumers;

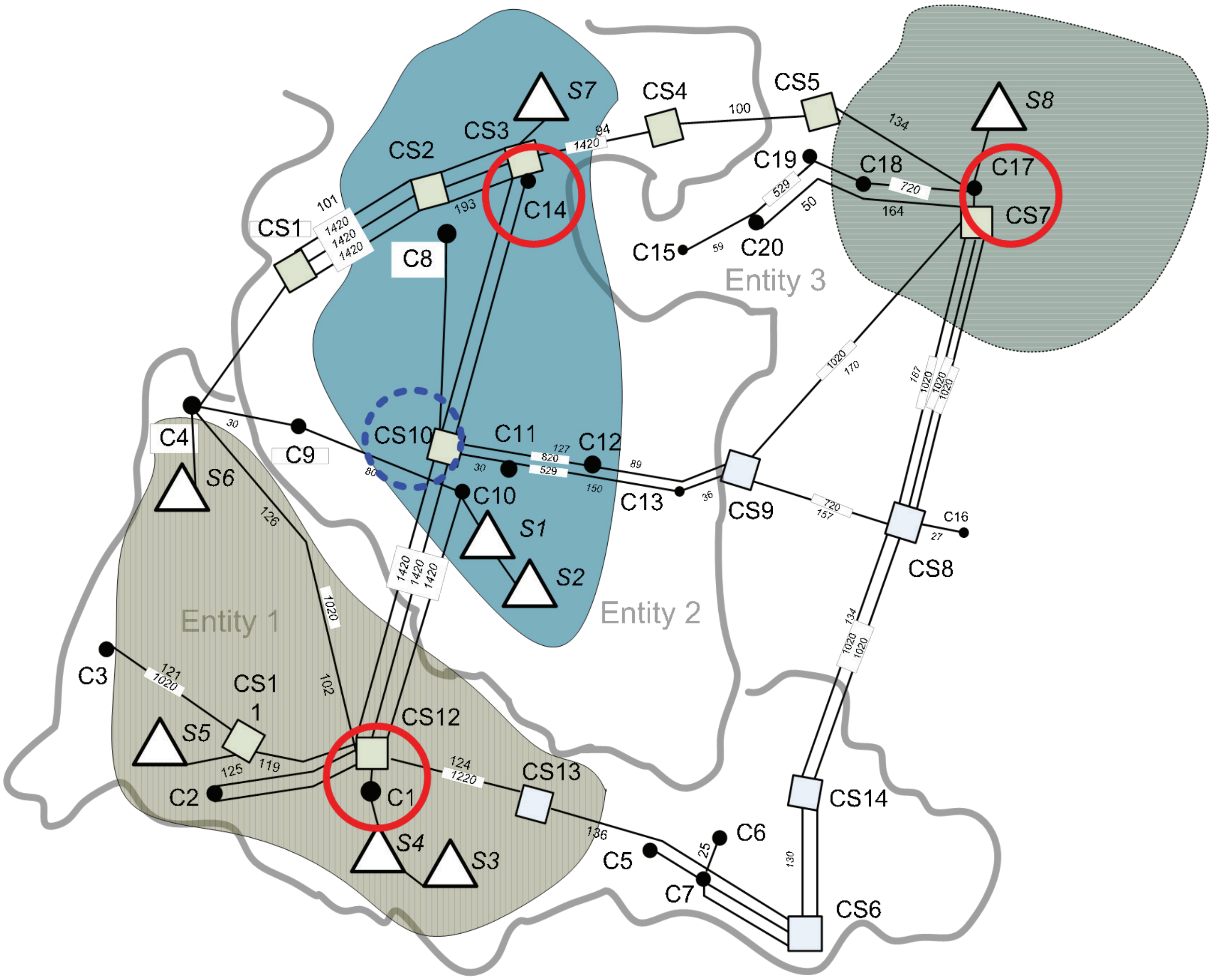
network nodes include the points of connecting gas transmission mains to the production, storage, and consumption facilities, as well as branching points of gas flows (at the locations of nodal CSs); the sections of main gas pipelines located between two network nodes stand for branches of the model network;

technical and economic indicators of the aggregated network components are obtained by summing or averaging the corresponding indicators of the detailed scheme components

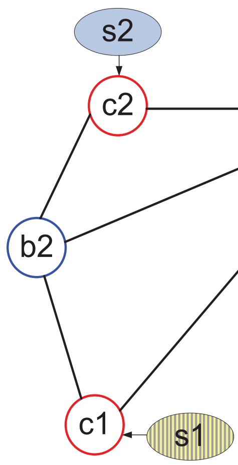
The nodes to be investigated include a region, an autonomous republic, and a territory with focus on large industrial consumers (if necessary).

The initial data used in the study are:

- ***for sources***: maximum annual gas production at all fields and gas producing companies in general, operating costs and gas loss at the GTCs. Information used is from the Main Directorate of Natural Resources of the Ministry of Natural Resources of the Russian Federation and the JSC "Gazprom;"
- ***for UGS gas mains***: diameters, the number of lines, lengths, connection points of all compressor stations, operating costs and the share of gas losses of the gas transmission company (auxiliary gas consumption and leaks). UGS maps and collected statistical information used are from JSC "Gazprom;"
- ***for consumers***: projections of future gas demand for constituent entities of the Russian Federation, various industries, gas exporting countries, which are obtained by studying with the models of the energy sector of the Russian Federation, and the data from the General Plan for the development of the gas industry and other sectors of the economy.
- Let us consider an algorithm for scheme aggregation by using a conventional example of a gas system consisting of three territorial entities (for example, entities of the Russian Federation), including twenty



(a)



(b)

Fig. 1. Schemes of a conventional gas system: (a) detailed scheme of the gas system, C – consumer nodes; CS – compressor stations; S – source nodes; (b) aggregated gas system scheme, c – consumer nodes; s – source nodes; b – branching nodes.

consumer nodes (C1, C2, ..., C20) and eight fields (S1, S2, ..., S8), Fig. 1a.

1. Identification of adjacent nodes.

The proposed conventional scheme is an undirected graph.

Adjacent nodes are nodes connected to each other by one or more arcs. For example, CS10 is connected to C8, CS3, C11, C12, C10, and CS12 (6 adjacent nodes). Thus, the branching nodes in the presented scheme are CS3, CS7, CS8, CS9, CS10, CS12, C4, and CS11. In the aggregated scheme, for each entity, we take one main branching node, from which gas pipelines with the highest total throughput capacity (CS7, CS10, CS12) run.

We identify the branching nodes, i.e., the nodal components of the scheme (most often CS), with at least three adjacent nodes.

2. Identification of aggregated consumer nodes and branching nodes.

The aggregation of the detailed gas scheme in this case is proposed to the level of the constituent entities of the Russian Federation, which will act as consumer nodes.

In each entity, a node with the maximum demand is identified. If the entity has two or more nodes with the same maximum demand, then the node closest to the main branching node is selected.

In our example, the largest consumers are C1 – in entity 1, C14 – in entity 2, and C17 – in entity 3. We place the aggregated consumer nodes at the nearest branching nodes with which they are connected by the gas main: C14 ≡ CS3, C17 ≡ CS 7, C10 ≡ CS10, C1 ≡ CS12, and designate them as consumers on the aggregated scheme. In entity 2, the branching node CS10 does not coincide with the maximum consumer node C14 ≡ CS3. In this case, both nodes are marked on the aggregated scheme, one as a consumer node, the other as a branching node designated as b2. Such a node is necessary to correctly indicate the main gas flows on the scheme. The total demand of the entity is summed up to be the demand of the consumer node, and the demand of the branching node is assumed to be zero.

Each consumer (entity) is a collection of all consumer nodes included in it. Thus, the first consumer entity (c1) includes the demand of seven consumer nodes: C1, C2, ..., C7; c2 – (C8–C14), c3 – (C15–C20).

The nodes in the detailed scheme (Fig. 1a) are numbered in an end-to-end manner for clarity, while the nodes in the formulas proposed below to obtain the technical and economic characteristics of the aggregated scheme are numbered by entity.

The natural gas needs of an aggregated consumer are obtained from the condition of equality of needs for the original and aggregated schemes. In general, the need of the *j*-th entity Q_j^C and the total demand in the system Q_Σ^C are determined as follows:

$$Q_j^C = \sum_{i=1}^{I_j} Q_{ij}^C ,\ j = \overline{1,J} ,$$

$$Q_\Sigma^C = \sum_{j=1}^{J} Q_j^C ,$$

where *j* is a number of entity of the RF, $j = \overline{1,J}$, J is the number of entities; *i* is a number of consumer node of the initial scheme, which refers to the *j*-th entity; $i = \overline{1,I_j}$, I_j is the number of consumers in entity *j*.

3. Aggregation of source consumers with respect to gas production companies.

In the aggregated scheme, the source is a gas production company that can operate several fields located in one entity. The operation areas of GPCs in Fig. 1a are shown with hatching areas. We designate each GPC as an aggregated source node (s1, s2, s3) connected to the consumer node of the entity where the GPC is located. The production in the aggregated entity is the total production of the GPC fields. For convenience, the numbering of source nodes coincides with the numbering of entities. In this algorithm, the scheme is aggregated to the level of entities. If it is necessary to introduce a new gas field into the calculated scheme, and there is uncertainty to which source node it should refer to, it is important that the aggregated source node include sources from one entity. If it covers two or more entities, then the gas flows along the arcs of the aggregated scheme will be very different from the real-world ones.

$$Q_j^S = \sum_{k=1}^{K_j} Q_{kj}^S ,\ j = \overline{1,J} ,$$

$$Q_\Sigma^S = \sum_{j=1}^{J} Q_j^S ,$$

where *k* is a number of source node of the initial scheme, which refers to the *j*-th entity; $k = \overline{1,K_j}$, K_j is the number of sources in entity *j*.

4. Aggregation of main gas pipelines.

In the aggregated scheme, multi-line main gas pipelines are represented as single-line ones. The aggregated arc of the graph between two nodes is characterized by the total capacity of gas pipelines at the boundary between two entities and the length of all gas pipelines going from one node to another. For example, the throughput capacity of arc c1–c3 will be equal to the throughput capacity of section CS8–CS14, Fig. 1a. If a branching node is introduced in the entity in addition to the consumer node, then additional aggregated arcs are specified for the other entities. For example, the throughput capacity of the additional arc b2–c3 is equal to the throughput capacity of the section CS10–CS9.

Many methods exclude gas pipelines through which gas does not flow from one entity to another (such as CS12–C2, CS10–C8, etc.) when aggregating the scheme. As a result, the costs allocated to such gas pipelines may be lost. To prevent this, we distribute the unconsidered lengths along the arcs coming from the entity proportionally to the capacities of these arcs. Thus, the length of the aggregated

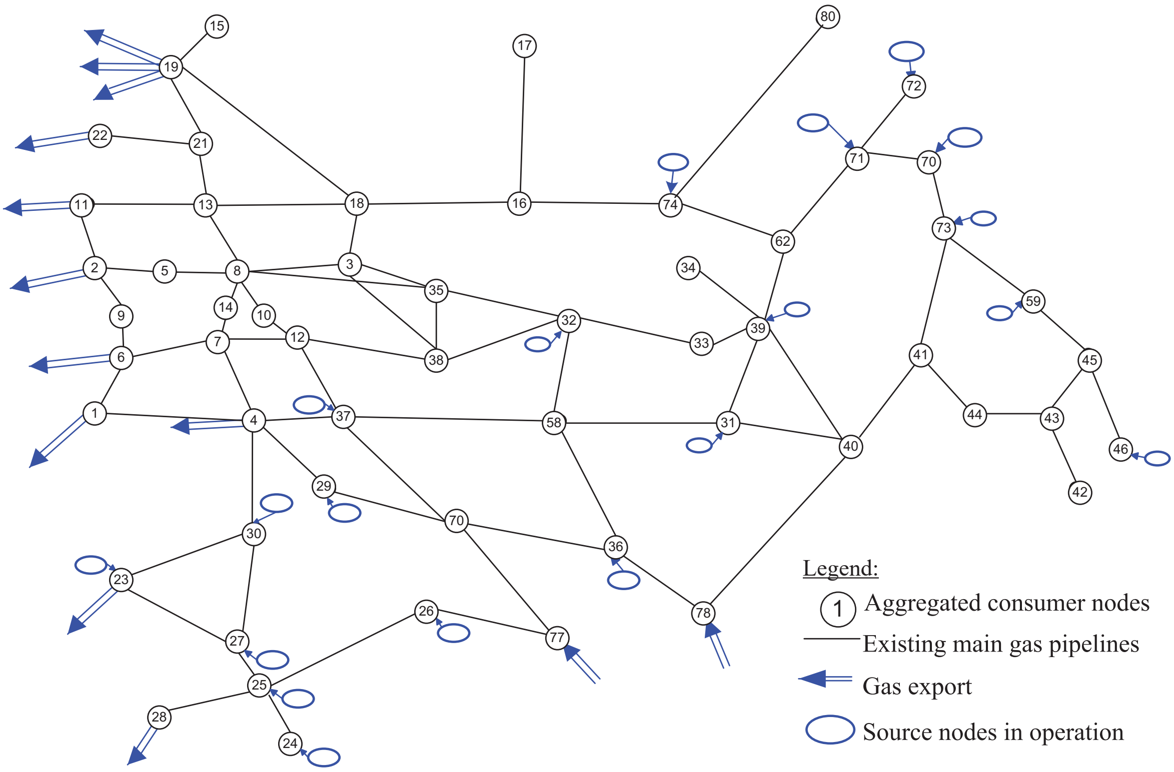


Fig. 2. Aggregated calculated scheme of the gas system of the Russian Federation.

arc, (1), is determined by summing the lengths of the gas pipelines running from the main consumer node of the original scheme of one entity to the consumer node of a neighboring entity or to a branching node, if it exists in the entity (term 1), and the lengths of all excluded gas pipelines located in the entity, including gas pipelines running from sources, in proportion to the throughput capacity of this arc (term 2):

$$L_{j-j'} = \sum_{m^B=1}^{M^B} \sum_{m=1}^{M} L_m \cdot n_m + L_j^{ex}, \qquad (1),$$

$$j \neq j';\ j=\overline{1,J};\ j'=\overline{1,J};\ n_m=\overline{1,N_m}$$

where j, j' are consumption or branching nodes of the aggregated scheme; $m^{\hat{A}} = \overline{1,M^B}$; M^B is the number of main gas pipeline branches at the boundary of the entities; $m=\overline{1,M}$; M is the number of sections between the compressor stations of the detailed scheme; L_m is the length of the m-th section; $n_m = \overline{1,N_m}$; N_m is the number of lines on the m-th section; L_j^{ex} is the lengths of unconsidered gas pipelines in entity j of the detailed scheme.

According to the above method, the scheme of each gas transmission company is aggregated.

5. Integration of aggregated schemes into one along the boundaries of the gas transmission company area.

The final step of building the calculated scheme is "gluing" all aggregated schemes into one (when considering the unified gas system). "Gluing" is performed along the boundaries of the operation areas of gas transmission companies. For example, a complex multi-line unified gas system is represented by an aggregated calculated scheme (Fig. 2).

6. Construction of a redundant scheme.

The existing large-scale projects of gas transmission systems under design or implementation are superimposed on the existing aggregated gas system scheme. Additionally, links corresponding to projects and scientific developments, carried out in research and design organizations, by year of planned periods, are placed on the calculated scheme. Thus, a redundant aggregated calculated scheme reflecting the stages of gas system expansion is provided for the time horizon under study (Fig. 3).

The proposed gas system scheme aggregation method is verified by a conventional example (Fig. 1). Calculations for various options (lack of gas at source nodes, bottlenecks along arcs, and others) indicate that, with the aggregation principles observed, the resulting calculated scheme clearly reflects gas flows among the entities.

Analysis of calculations for the detailed and aggregated schemes has shown that the gas needs of all consumers is 100% satisfied. In the detailed scheme, the reserve equal to 2.96 billion m^3/year remained only in field S8 (with the highest production price). In the aggregated scheme, there is a reserve of 2.98 billion m^3/year in S3, which includes S8 (calculation error was 0.7%). In the detailed scheme, the amount of gas transmitted from node 1 to node is 21.99 billion m^3/year, in the aggregated

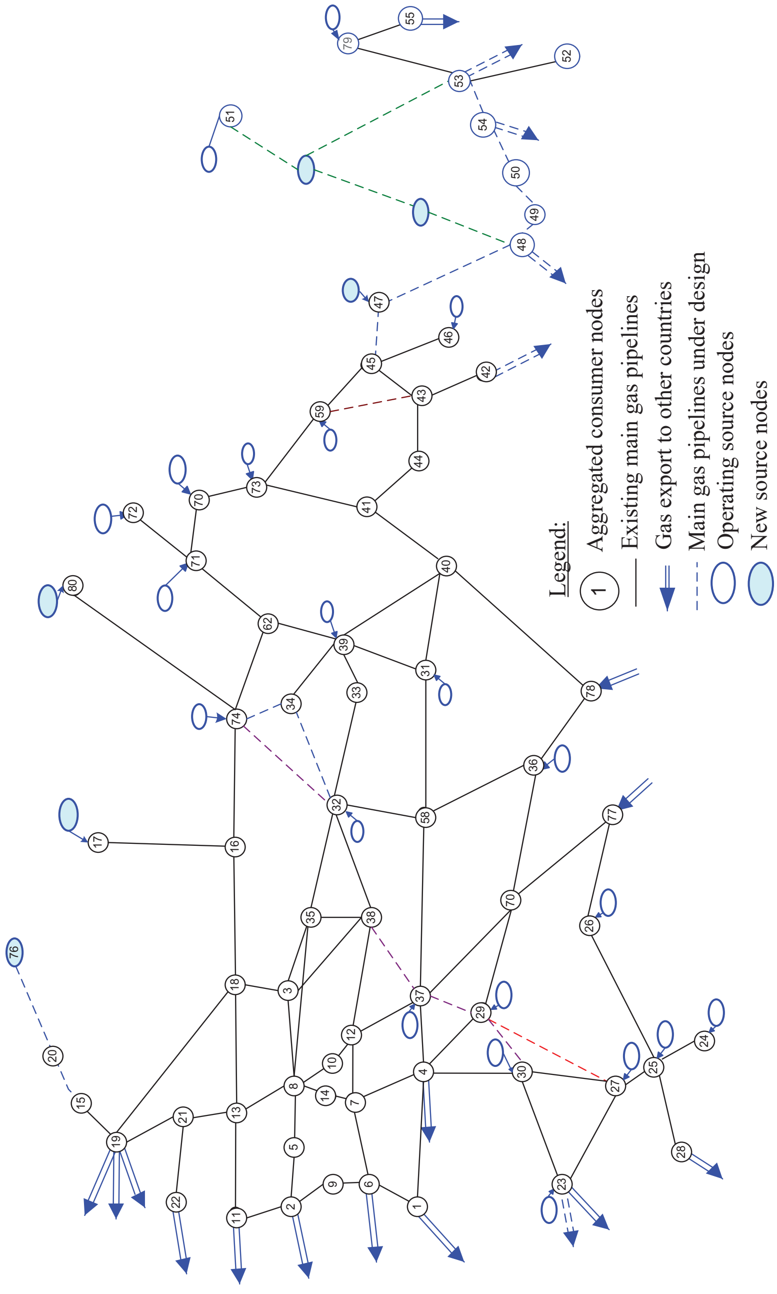
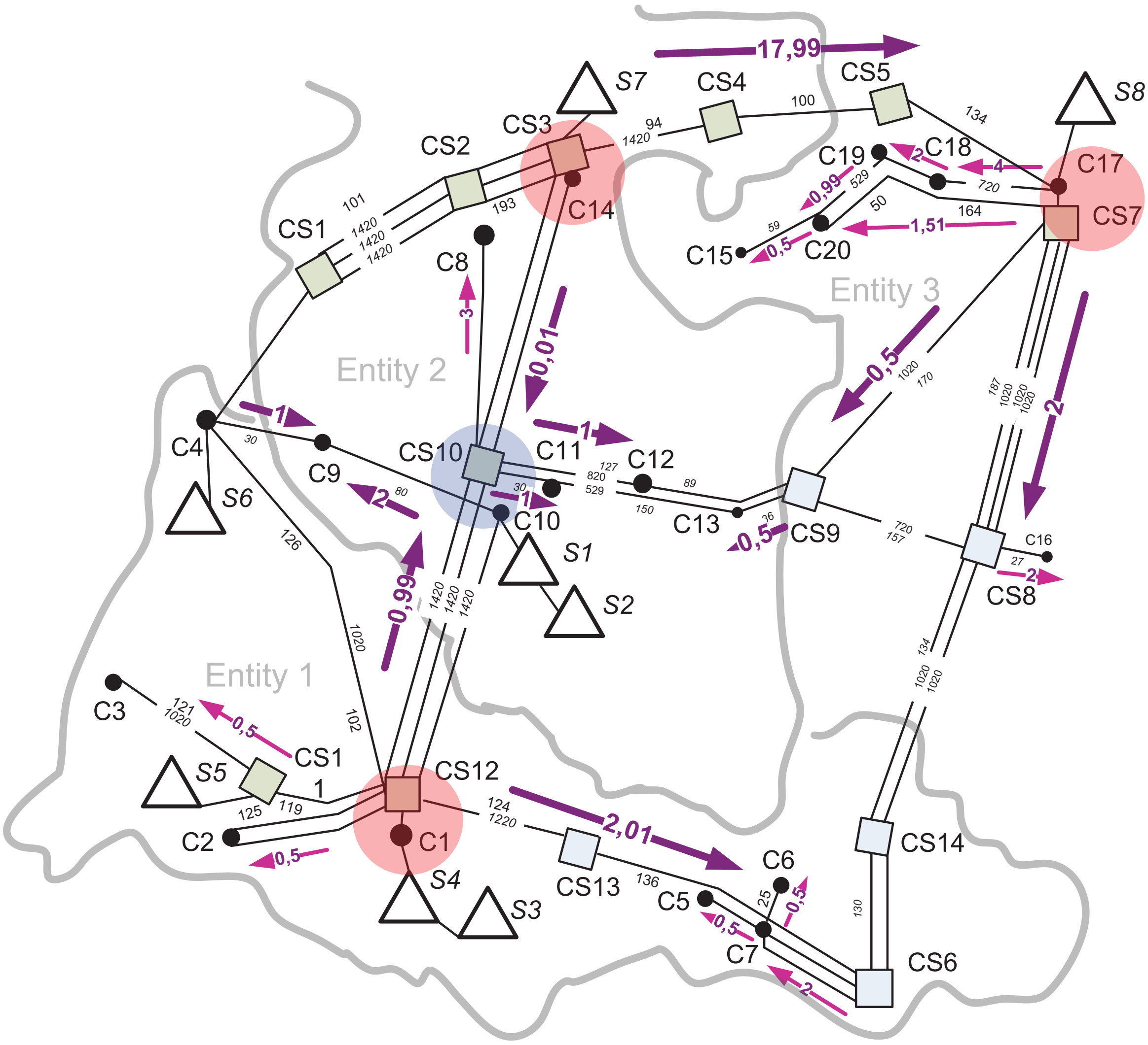


Fig. 3. Redundant aggregated calculated scheme of the gas system of the Russian Federation, 2030.



(a)

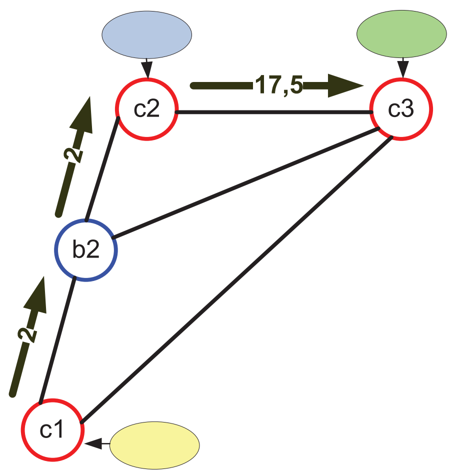


Fig. 4. Flow distribution in the detailed (a) and aggregated (b) schemes.

scheme – 2 billion m^3 / year (0.5%). In the detailed scheme, gas transmitted from node 2 to node 3 amounts to 17.99 – 0.5 = 17.49 billion m^3/year, in the aggregate scheme – 17.5 billion m^3/year (0.06%).

Thus, the maximum difference or calculation error between the calculated indicators, in particular, gas flows and production volumes of the detailed (Fig. 4a) and aggregated (Fig. 4b) schemes is about 1% (Fig. 4a, b) [18]. The difference comes from rounding off the data.

The proposed method was applied to create an information base for multi-level modeling of the gas system expansion in Russia until 2030; analyze the current state of the Russian gas industry with a focus on gas production, transportation and the demand for gas in different industries; aggregate the scheme of Russia's gas system (Fig. 3); identify the technical and economic characteristics of its facilities; and to investigate the prospects for the gas supply development in the constituent entities of the Russian Federation [1].

IV. Conclusion

1. The paper proposes a method for aggregating a real-world gas system, i.e., its representation by a simpler calculated scheme characterized by a smaller number of nodes and connections, which facilitates the analysis and use of the results to generate the necessary solutions. The aggregation approach is based on the consistent simplification of gas transmission and gas production companies and their integration into a single calculated scheme.
2. The proposed method for aggregating the scheme of the gas system factors in small fields, independent gas producers, and minor gas mains both among entities and within them.
3. The verification of the method presented in the paper has shown that the main characteristics (gas production and consumption volumes, wholesale prices) are in a fairly close and comparable range with actual indicators.
4. The research was carried out under State Assignment Project (no. FWEU-2021-0002) of the Fundamental Research Program of the Russian Federation for 2021-2030.

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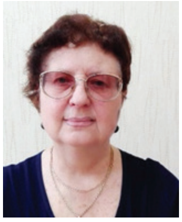

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