Models, Calculation and Optimization of Gas Networks, Equipment and Contracts for Design, Operation, Booking and Accounting

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Abstract

There are proposed models of contracts, technological equipment and gas networks and methods of their optimization. The flow in network undergoes restrictions of contracts and equipment to be operated. The values of sources and sinks are provided by contracts. The contract models represent (sub-) networks. The simplest contracts represent either nodes or edges. Equipment is modeled by edges. More sophisticated equipment is represented by sub-networks. Examples of such equipment are multi-poles and compressor stations with many entries and exits. The edges can be of different types corresponding to equipment and contracts. On such edges, there are given systems of equation and inequalities simulating the contracts and equipment. On this base, the methods proposed that allow: calculation and control of contract values for booking on future days and for accounting of sales and purchases; simulation and optimization of design and of operation of gas networks. These models and methods are realized in software systems ACCORD and Graphicord. As numerical example, the industrial computations are presented.

Contents

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1 Introduction

In the paper, there are proposed contract models representing by (sub-) networks. These contract models are used for booking, accounting, and estimation of contract values, for operating of contracts, and for network optimization.

In addition, equipment is modeled by edges and sub-networks. The edges can be of different types. A type of an edge correspond to a type of equipment and contracts. On such edges, there are given systems of equation and inequalities simulating the operation of equipment and contracts. In case of gas network, an edge might have a type of a pipe, compressor, compressor station, control valve, shut-off valve, and so on.

The models of contracts and equipment construct a base for methods for balancing and optimization both of contracts and of gas networks for design, planning, control, operation, booking and accounting.

These models, methods and functions describing contracts and equipment are realized in the software systems ACCORD and Graphicord.. The software ACCORD has been developed as application of economic and operational steady state simulation and optimization of gas pipeline networks.

Any network topology and in principle almost any objectives are available. Minimization of fuel gas and purchased electricity, minimization of cost of purchased gas, injection and withdrawal optimization for storage facilities within the network, profit maximization with cost consideration are provided for any network. Both the quality and supply tracking are available. It makes possible to produce the cost tracking, to estimate and to establish the optimal selling prices. Compressors can be considered both with and without description of their operating ranges or characteristics.

ACCORD has graphical user interface and interface to the third party programs e.g. to the distributed control systems. The programs providing these types of interface construct a family named GRAPHICORD Suite. The software GRAPHICORD provides Graphical user interface, database support, interface with Geographic information system, interface to Distributed control systems as well as to the third party systems, call of the third party programs, flie management, scenario management, means to the search of information in the networks saved, etc. The interface to the third party programs has input and output in the form of text files. It allows to connect ACCORD with a graphic editor and with geographic information system to create a network; to receive initial values of supplies, demands, and gas parameters; to produce and present a graphic output.

Steady state optimization by ACCORD had been connected with programs that perform a dynamic simulation of gas networks.

ACCORD is integrated in the distributed control system such as GAMOS that consists of SCADA and various high level functions.

As numerical examples, the industrial computations are presented.

ACCORD is an abbreviation for Algorithmic and software Complex of Constructive nonlinear Optimization with Restriction on Discrete-Continuous network variables. It is intended for economic and operational steady state optimization of gas pipeline networks. There is no restriction on network topology in ACCORD.

The general objectives of optimization are:

- to plan the installation of a network;
- to optimize the routing of pipelines and location of equipment;
- to select pipe diameters;
- to specify facilities;
- to minimize the expenditure;
- to select supplies and demands;
- to optimize network operation, etc.

There are available in ACCORD such objective functions as:

- operational expenditure minimization;
- network flow maximization;
- set-point deviation minimization;
- profit maximization;
- minimization of weighted average cost of gas;
- specific transport cost minimization;
- injection and withdrawal optimization for storage facilities in pipeline network, etc.

There are available such searching variables as:

- pressure ratio of compressor stations;
- output pressure of control valves;
- equipment of compressor stations;
- flow values of user-chosen supplies and demands;
- pressure in a user-chosen node.

A network state is a distribution of flow and pressure. The feasible network state is received by ACCORD automatically as a result of optimization problem.

Both the quality and supply tracking are available. It makes possible to produce the cost tracking and to establish the optimal selling prices.

Compressors can be considered in ACCORD both with and without description of their operating ranges.

By computation of pressure drop, the modelling procedures are used which simulate the operating of technical equipment. Therefore computation of pressure drop can be sophisticated.

The problems solved in ACCORD are to find the optimal set-points for supplies, demands, and pressures and to make the optimal choice of equipment on compressor stations to optimize both operational transport costs and costs for purchased gas in order to optimize profit. In this class of problems the objective functions depend on both flow and pressure. Minimal cost and maximal flow problems are generalized. The typical problem consists in the optimal choice of:

- dependencies between flow and pressure from the given families;
- node intensities, i.e. values of supplies and demands;
- flow;
- pressure.

This is a class of problems belonging to the area of large scale nonlinear discrete-continuous optimization on general networks. The developed optimization method represents a branching multi-level computational process. It is based on nonlinear and integer programming and graph theory. Its main characteristic feature consists in obtaining of dominant solutions on network fragments.

ACCORD has an input and output interface in the form of text files. It allows to connect ACCORD with a graphic editor or geographic system to create a network; to receive initial values of supplies, demands, and gas parameters; to monitor the runs of optimization; to produce and present a graphic output.

Steady state optimization by ACCORD is connected with dynamic simulation programs such as SIMONE and GANESI and is integrated in the complex GAMOS that consists of SCADA and various high level functions. Due to his interface, ACCORD can be connected with any other simulation program and SCADA system to provide steady state optimization of gas networks with economic, business or operational objectives.

Industrial computations for gas pipeline network operation and planning are presented.

The paper consists of 6 significant sections and supplemented sections containg notations, figures, and tables.

Section 1 is an introduction while section 6 presents conclusions.

In section 2, mathematical model and problem formulation are presented.

In section 3, the developed methods of the continuous - discrete nonlinear optimization on networks are briefly described.

Section 4 contains some results of computational experience. For optimal operation, a gas network consisting of a central distributed ring with large - scale supply and transport pipelines containing ten - th compressor stations were optimized.

Section 5 presents the quality, supply and cost tracking computed by ACCORD in consequence of optimization. The graphic presentation of the tracking is made on a way between two nodes in a gas network.

Section 6 contains conclusions.

2 Models and problems

2.1 Analysis of models used in gas supply companies

Let us consider a set of models and functions which are widespread in gas transport, distribution and gas supply companies:

1) gas demand forecast for every client;

2) definition of set of gas suppliers and corresponding purchase quantities;

3) definition of gas injection and withdrawal quantities for every gas storage;

4) optimization of contracts for gas sale and purchase, including both gas exchange with adjacent companies and injection or withdrawal for different gas storage;

5) contract optimization with restrictions arising due to gas network;

6) gas price investigation, calculation and definition for sale and purchase for long and short term planning;

7) determination of sold and purchased gas quantities in order to prepare billing;

8) settlement and confirmation of accounts for sold and purchased gas for every supplier and consumer and for every client station;

9) SCADA functions both for sale and purchase and for gas network (SCADA is abbreviation for supervision, control and data acquisition);

10) supervision of actual contract fulfilment;

11) optimization of gas network state;

12) simulation and optimization of development of gas network.

The above functions allow to conclude that the following models play a central role:

1) contract;

2) contract partner: supplier, consumer, gas storage, etc.;

3) client station;

4) gas network;

5) flow network.

At present, these models have different development degrees.

The network modelling went through several development steps. It derives its sources from Kirchhoff. It follows the development periods of graph theory, flow networks, dynamic hydraulic simulation of networks, and network steady state optimization. It should be pointed out that models for network dynamic optimization are not developed yet so that they could be used industrially.

There are various contract models. They have a common feature that they are not connected with a model of gas network. It could seem that contract models are significantly simpler than network models. More detailed consideration shows this is not the case.

A contract model source is the contract text. To originate a model, the text must accept a formalization. Then a degree of detailed elaboration of the formalization depends on the function wherein the model is used. Hence a contract model depends on functions wherein the contract or contract restrictions are used. Therefore there is a contract model family corresponding to family of functions of planning, control, invoicing, etc.

Questions arise, how these models are connected with each other; could they be connected formally and therefore automatically; do they accept a uniform representation. In the paper, there is proposed a contract model which represents an object consisting of:

- a graph;

- an ordered set of feasible intervals of gas parameters such as gas demand, pressure, calorific value;

- price calculation procedures corresponding usually to the above intervals of gas parameters;

- integral quantities of gas.

The contract paragraphs could be represented as elements attributed to edges of the contract graph, i.e. to the connections between contract partners.

In the simplest case, the contract graph consists of a node with which the feasible intervals of gas parameters and procedures for calculation of gas prices and transport expenses correspond.

Such a contract model causes different merits. It enables a simple, visualizable, structured and unified representation of contracts. It admits an automatic choice of degree of detailed elaboration of a contract model, i.e. auto-modelling due to automation of procedures of reduction or expansion (re-reduction) of contract graph.

A comparison of planning and invoicing functions allows to find a lot of similarities. In both cases, it handles with a gas distribution between the sources or targets correspondingly. But direction of time as well as of cumulative or decumulative operation is opposite by planning and invoicing.

It is sufficient to compare a planning function of definition of purchase quantities covering an expected demand with an invoicing function of distribution of gas quantities metered on a client station over the contracts and contract conditions.

By planning function such as demand coverage, the client demands are accumulated to define a total demand and to distribute demand through suppliers. The delivery ways from supplier to customer could be considered either implicitly by restrictions of maximal delivered gas quantities or explicitly by explicit representation of gas network structure. Time is directed forwards, in the future.

By invoicing, the metered gas quantities have to be distributed i.e. decumulated on a client station in accordance with contracts, contract partners and prices. For the most contracts, the gas flow ways from measurement places to contract partners could be considered explicitly by explicit representation of client station structure. The graph theory gives a suitable means for that. Time is directed backwards since information about the earlier purchased gas is processed.

Thus, the uniform modelling of pipelines, client stations and contracts by means of networks allows to represent their relations and producible operations explicitly, to visualize models, and it establishes a base for strict mathematical problem formulation.

2.2 Contract and client station models

2.2.1 Contract models for planning and control of gas networks and for invoicing.

The simplest representation of a contract is an object consisting of:

1) a node;
2) an interval of feasible demand;
3) an interval of feasible pressure;
4) values of demand and pressure;
5) a procedure for payment calculation.

A more complicated contract having an ordered set of feasible intervals of demand and pressure with corresponding procedures for invoicing shall be represented as a graph.

Such a model causes different merits. It enables a simple, visualizable, structural and unified representation of contracts.

The unified contract representation is used for the following purposes and by the following implementations:

- both for technical and economical objectives;
- for technical and contractual supervision of gas network in dispatcher center;
- for short and long term planning;
- by gas balancing for automation of checking and achievement of gas balance;
- by data acquisition from client stations, i.e. gas meter stations;
- by data preparation for settlement of accounts;

- to construct the data base of gas company.

2.2.2 Models of client and shut-off stations.

A client station is a gas meter station. It consists of:

- shutting-off devices;
- means providing measuring of gas flow, pressure, temperature, and other;
- valves;
- control valves;
- service pipes.

A shut-off station has the same structure as a client station. A difference is only that the flow meter and control valves are used rather seldom by shut-off stations. So the client and shut-off stations can be modelled in the same way.

A gas meter station has a technical structure plotting as a scheme. A scheme is represented as a graph. Model of a gas meter station shall be a graph.

Station modelling by graphs causes the same merits as contract modelling by graphs.

Hence graphs are used as models for gas networks, contracts, client and shut-off stations.

2.3 Network models

2.3.1 Network models for hydraulic simulation and optimization.

A network is modelled as a graph. Nodes and edges possess technical parameters. Pressure is considered explicitly. It is a nodal parameter. Restrictions are formulated in terms of both pressure and flow.

Technical equipment as pipeline sections, compressor stations, control valves and valves are represented by edges of the network. The complicated compressor stations can be represented by sub-graphs of the network.

Client and shut-off stations are represented by nodes of the network. The complicated client and shut-off stations can be represented by sub-graphs of the network. If a contract is connected with only one client station and this station is represented by a node of the network then the contract is represented by the same node too. More complicated contracts
can be represented as sub-graphs of the network.

By computation of pressure drop, the modelling procedures are used which simulate the operating of technical equipment. Therefore computation of pressure drop can be very sophisticated.

Exactly as in network operation, a pipeline capacity is represented implicitly. This means that pipeline capacities are given due to maximal and minimal pressure limits in nodes of network. Pressure limits arise owing to technical and contractual restrictions.

There are two types of hydraulic simulation: a dynamic simulation and a steady state simulation.

In the dynamic simulation, the partial differential equations are used to model hydraulic. The network parameters such as flow and pressure depend on time.

In the steady state simulation, the algebraic equations are used. The network parameters such as flow and pressure are taken at a certain moment or in average.

A network optimization based on the hydraulic simulation considers restrictions and objective functions which are formulated in terms of both pressure and flow. As a result of optimization, the feasible and optimal hydraulic state of the whole network must be found and simulated.

A network dynamic optimization, i.e. the network optimization based on the dynamic hydraulic simulation is not developed anywhere yet. A network steady state optimization, i.e. the network optimization based on the steady state hydraulic simulation is provided in Wingas by methods and software ACCORD developed there.

2.3.2 Using the optimization based on hydraulic simulation by planning.

For short term planning, the network steady state optimization by ACCORD is a useful tool. When planning for serial time periods, the network steady state optimization can be used. For this purpose it must run several times sequentially for sequential moments. Practically for long term planning it is possible rather often. But, for some cases, it can be expensive if not prohibited due to complexity of problem.

For example, a feasibility of the network state must be checked every year for an extremely cold winter and for a summer which follows after the extremely cold winter. Hence a planning for e.g. 25 years requires at least 50 feasibility checking of the network state. Every feasibility checking of the network state is reduced to the solution of a network optimization problem based on the steady state hydraulic simulation. It means that ACCORD must run 50 times. For complex networks represented in detail, it requires such user efforts that cannot be completed in a very short time.

2.4 Flow network models

A network is modelled as a graph. Edges dispose of flow. For nodes the value of demand or supply are considered. Simulation of operation of technical equipment is not used. Hydraulic simulation is not used either.

Pressure is considered implicitly. Restrictions are formulated in terms of maximal flow that is capacity for every edge. Pipeline capacities must be given as input data. Capacity is an idealization that is not met by network operation. Capacities simulate technical and contractual restrictions such as maximal and minimal pressure limits. A capacity models pressure limits only in an indirect way. Client stations and contracts are represented as nodes. If necessary, they can be represented as sub-graphs of the network.

To optimize gas network without hydraulic simulation, flow models are use such as in the minimal cost network flow problem.

Let $G = (V, E)$ be a network with a node set V and an edge set E. The minimal cost network flow problem consists in:

minimize $\sum_{(i,k)\in E} f_{ik}(q_{ik})$

subject to:

$\sum_j q_{ji} - \sum_k q_k = Q_i, \quad i \in V,$

$q_{ik}^{min} < q_{ik} < q_{ik}^{max}, \quad (i,k) \in E,$

where: q_{ik} is flow in arc (i,k); $f_{ik}(q_{ik})$ is cost of flow q_{ik} ; Q_i is supply or demand in node i .

The minimal cost network flow problem is much easier as a network optimization with hydraulic simulation. There are efficient methods delivering a solution of this problem.

For long term planning for serial time periods, it is worthwhile to use a minimal cost network flow problem as a compromise simplification. It must run several times sequentially for sequential moments for this purpose. Due to efficient solution methods, a planning for 25 years requiring 50 - 100 solutions of minimal cost network flow problem seems realistic.

The correct investigation of capacities can turn out as a weakest point in such a simplified approach. Here is useful a method for precise definition of pressure limits in a gas network. This method we have developed [10]. Normally by long term planning, the supplies and demands are considered as constant in every time period. Hence it is allowed to use the said method for sub-networks that are defined by connected subsets of nodes which include terminal nodes and nodes of compressor stations.

2.5 Mathematical model and problem formulation

Let be given a connected undirected network $G = (V, E)$ with a set of nodes V and a set of edges E. Let q_{ik} be the flow in the edge (i,k) and Q_i the supply or demand called intensity of node i, which satisfies the next conservation law:

$$\sum_k q_k + Q_i = 0, \qquad (1)$$

$$q_{ik} = -q_{ki}, \quad i,k \in V, \quad (i,k) \in E. \qquad (2)$$

The necessary and sufficient optimality conditions for the minimum cost network flow problems with linear or nonlinear objective functions are well known [3], [11]. They include the connection between pressures p_i, p_k and flow q_{ik} in the form of equality and inequality system between the pressure differences and the left and right derivatives of the cost at the flow.

These equalities represent the rules how equipment works, i.e. Ohm law, Bernoulli law etc. To generalize equipment models and to give a possibility to select the equipment, we suppose that there are given the families of functional dependencies between flow and pressures:

$$f_{d_{ik}}(p_i, p_k, q_{ik}, c_{ik}) = 0, \quad (i,k) \in E, \tag{3}$$

$$d_{ik} \in \{1, ..., N_{ik}\}. \tag{4}$$

Here c_{ik} is a vector of continuous parameters (coefficients), and d_{ik} is a discrete parameter on the edge (i,k). We suppose that there are given the limitations Q_i^-, Q_i^+, p_i^-, p_i^+, c_{ik}^-, c_{ik}^+ :

$$Q_i^- \leq Q_i \leq Q_i^+, \quad i \in V, \tag{5}$$

$$p_i^- \leq p_i \leq p_i^+, \quad i \in V, \tag{6}$$

$$c_{ik}^- \leq c_{ik} \leq c_{ik}^+, \quad (i,k) \in E, \tag{7}$$

and the other restrictions can be represented by inequalities with given a_{ik}^-, a_{ik}^+ for the vector-functions $a_{ik}(p_i, p_k, q_{ik}, c_{ik}, d_{ik})$ which have to be calculated:

$$a_{ik}^- \leq a_{ik}(p_i, p_k, q_{ik}, c_{ik}, d_{ik}) \leq a_{ik}^+, \quad (i,k) \in E. \tag{8}$$

The considered objective function depends both on flow qik and on pressures p_i, p_k, intensities Q_i, continuous c_{ik} and discrete parameters d_{ik} . Then the problem is:

$$minimize \quad F = \sum_{ik} F_{ik}^{(1)}(p_i, p_k, q_{ik}, c_{ik}, d_{ik}) + \sum_i F_i^{(2)}(p_i, Q_i) \tag{9}$$

$$\text{subject to (1)-(8).} \tag{10}$$

We may interpret (7) as restrictions on the power, temperature, dissipation and other characteristics of the equipment that is represented by the edge (i,k). The set of available values of discrete parameters d_{ik} in (4) means that the family of functions $f_{d_{ik}}$ can act on the edge (i,k), and we have to select the best function $f_{d_{ik}}$ for an equation (3). Thus, we have to select such equation (3), which is the best for the objective function (9). We may interpret this as a selection of the most profitable equipment which is installed or can be installed on the place (i,k).

The continuous parameters c_{ik} in (3) can be interpreted as parameters that smoothly regulate the work of equipment dik in bounds (7).

The inequalities (5) and the dependence of objective function on intensities Q_i mean that the most profitable values of supplies and demands have to be chosen.

Without concentration on the conditions of existence and uniqueness of the solution and on the proving of convergence to it, we describe the methods that work in practice and bring the solution of the formulated problem in the general case.

2.6 Merits and demerits of different optimization problems

2.6.1 The network optimization based on hydraulic simulation.

Advantages:

1) The network optimization with hydraulic simulation could be useful for both operational and economic optimization;

2) The very broad range of technological restrictions can be considered;

3) The broad range of objective functions can be considered, multi-objective problem can be modelled;

4) Steady state network simulation is provided;

5) Pressure is considered explicitly. Restrictions and objective functions are formulated in terms of both pressure and flow;

6) Exactly as in network operation, capacity of pipelines are represented implicitly. This means that pipeline capacities are given due to maximal and minimal pressure limits in nodes of network. Pressure limits arise owing to technical and contractual restrictions;

7) In comparison with optimization based only on flow models, the network optimization based on hydraulic simulation has a high technical reliability and exactness of results.

Demerits:

1) Complication of models and methods;

2) In comparison with optimization based only on flow models, the network optimization based on hydraulic simulation usually needs more computational time and more efforts of user to get final results.

2.6.2 The network optimization based only on flow models.

Merits:

1) Simplicity of models;

2) In comparison with network optimization based on hydraulic simulation, the optimization based only on flow models usually needs not so much computational time and less efforts of user to get final results

Demerits:

1) Pressure is considered implicitly;

2) Pipeline capacities must be given as input data. They simulate technical and contractual restrictions such as maximal and minimal pressure limits only indirectly;

3) The optimization based only on flow models has rather low technical reliability of results.

3 Method of continuous - discrete nonlinear optimization on a network

The formulated problem (1) - (9) is a problem of a search for a conditional extreme for a function with continuous - discrete parameters of optimization. According to the mixing character of variables, the combination of the continuous and discrete optimization methods is used to solve the problem. The graph theory, integer programming, nonlinear programming with and without constraints and the methods of solving the nonlinear systems of equations and inequality are the basis of the offered method. Its main characteristic feature consists in obtaining dominant solutions for fragments of the network.

The discrete variable is e.g. the structure of a compressor station, i.e. how much compressors have to be in operation and what scheme of their connection has to be used there. To manage the discrete variables, there are at least two methods in ACCORD. The first one is a special modification of branch-and-bound method. Another procedure for searching an integer-feasible solution is connected with a possibility to check whether there is a realization of equation $t_{jk} = p_j - p_k$ in the equation family (3). The complementary variable t_{jk} will be penalized if it cannot be represented by one of equations (3).

The difference between this method and the branch-and-bound approach is clear for the cases of pure discrete problems on a tree. Such class of problems means that the network has no cycles and there are no continuous variables at all. Then the second method can fall in a local optimum. To avoid it, a restart can be useful. For the same problem on a tree, the branch- and-bound method can be very efficient. It brings a global optimum as a solution. However, for a network with complicated topology the branch-and-bound method could be expensive if not prohibited. This is valid especially for the networks with a lot of cycles. Then the second procedure consisting of searching the discrete variables d_{jk} by penalizing non-realizable continuous complementary variable t_{jk} is available there.

In practice, the method avoids the local optima.

4 Numerical example and experience: optimal operation of a gas network

The graph of a tested gas network is presented on Fig. 1. The network consists of a central distributed ring with large - scale supply and transport pipelines. Every edge is either a pipeline section or a compressor station. The input data for nodes are given in Table 1, for pipeline sections in Table 2, for compressor stations in Table 3.

As a first approximation for pressure drop on a pipeline, there is used the simple formula for pressure drop on an aligned pipeline section

$$P_i^2 - P_e^2 = k_D l q_{ie}^2 sign\left(q_{ie}\right), \tag{11}$$

where: P_i , P_e - pressures respectively in inlet node i and outlet ("exit") node e, [bar]; q_{ie} - flow rate [Mm^3/d], i.e. gas flow volume per day reduced to the standard temperature $T = 273K$ and pressure $P = 1.013$ bar; l - pipeline length, [km]; k_D - coefficient defined by formula

$$k_D = R_a d_a^2 10^{-1} \lambda z G T / \left\{ E^2 (\pi/4) \left(\sum D_i^{5/2} \right)^2 \right\}, \tag{12}$$

where: E - efficiency factor that is a relation between real and theoretical flow such that $E < 1$ and $E = 0.92$ for average operating conditions; $R_a = 287$ J/kgK - gas constant for air, $d_a = 1.293$ kg/m^3 - air normal density; λ - hydraulic resistance coefficient defined e.g. after Colebrook - White formula [12], p. 286, [1]; z - average gas compressibility, [1]; G - gas specific density on air (for air, $G_{air} = 1$); T - average gas temperature, $[K]$; D_i - inside diameter of the i-th parallel pipe, $[m]$; here [1] means a dimensionless value.

. Finally, for pressure drop on (unaligned) pipelines, the more complicated formula [12] is used.

The simulation of a compressor station cannot be reduced to a formula like it has been made for a pipeline section. However, as a result of the simulating algorithm, the exhaust pressure P_e can be computed as a function of inlet pressure P_i , flow rate q_{ie} , gas characteristics, and operating equipment of compressor station a_{ie} and d_{ie} :

$$p_e = f_{ei}(P_i, q_{ie}, T_i, ..., a_{ie}, d_{ie}), \tag{13}$$

where a_{ie} are continuous characteristics of equipment and d_{ie} are discrete characteristics, i.e. compressor types and connection schemes of compressors.

For our example, two problems have been solved:

1) Reproduction of initial operating conditions by means of optimization with criterion of minimal deviation from set points;

2) Minimization of expenditure in the power expression.

It was required to support the set points of pressure in nodes of pipeline joints. For this purpose, the narrow intervals of feasible pressure were taken in these nodes. These intervals are presented in Table 1. The intervals in other nodes are equal (0; 56 bar). The node 48 is taken as a root with the root pressure $P_{48} = 55$ bar.

The value $E = 0.9$ of efficiency factor has been used in formula (12) for most of the pipeline sections. Efficiencies of other pipeline sections were varied to reach the feasible pressure area and to reproduce the initial operating conditions (column "k_D initial" of Table 2). On compressor stations, the reproduction of initial operating conditions has been provided by using efficiency factor E and with schemes of connection of equipment which are presented in Table 3 in the columns "Efficiency factor" and "Initial schemes" respectively. For compressor, efficiency E is a relation between real and theoretical productivity like it is for pipeline section. With the help of it, the real characteristics of compressors are taken into account.

In a lot of practical implementations the simplified sub-optimal way can be sufficient. It consists of dividing the initial discrete-continuous problem to the pure discrete problem on a spanning tree with computed flow and to the prefix and postfix network continuous problems which could be solved interactively. However, we solved the full optimization problem for the test network.

In the central distributed ring two chords have been distinguished: the pipeline sections 29 = (14, 17) and 35 = (22, 24). The pressure errors in nodes 17 and 24 are corresponding to flows in these chords. The found flows and the pressure errors are:

$q_{14,17} = 22.654$ Mm^3/d, $dP_{17} = 0.01$ bar.
$q_{24,22} = 5.906$ Mm^3/d, $dP_{24} = 0.33$ bar.

The optimal connection of equipment on compressor stations has been found. The results are presented in Table 3 in the column "Optimal schemes". The power expenditure is reduced from 260.765 MW to 234.432 MW that means 11.2 % decreasing.

From the presented data we can see that the solution of the optimization problem enables to find the feasible operating network conditions and to reduce the transport expenditure by 11.2 % as a result of selection of optimal equipment on the compressor stations No. 1, 6, 12 and 18.

5 Quality, supply, and cost tracking

We present the quality, supply and cost tracking computed by ACCORD in consequence of optimization (Fig. 2 - 5). The graphic presentation of the tracking is made on a way between two nodes in a pipeline network. To choice a way, user clicks on 2 nodes - on its origin and terminus. If the way between these nodes is unique, it will be selected by ACCORD. Otherwise it should be necessary to click on one or a few additional nodes.

Each of Figure 2 - 5 consists of two diagrams. The upper one shows the parameters distributed along the way: in Fig. 2a, there are distance from origin in km as axis x, pressure as axis y1 , and flow as axis y2 . Below (Fig. 2b) the parameters concerning nodes are shown: there are supplies and demands situated on the selected way and flows in the pipelines branched off the way. On Fig. 3a, supply tracking is shown, while quality tracking as gas calorific value is shown in Fig. 3b. The computed data presented in Figs. 2 and 3 are basis for the supply cost tracking presented in Fig. 4. We can see how the money for purchased gas is flowing along the pipeline per supply and in total, and how much the normalized costs of purchased gas and the addendum per supply for every consumer are. The operating expenses are depending on fuel costs. The flows of operating expenses and fix (investment) cost are shown in Fig. 5a. As a result, the normalized costs per consumer are presented in Fig. 5b.

6 Conclusions

The optimization methods and program ACCORD are developed for network optimization. There are used steady state models of equipment. The equipment such as pipelines, compressor stations, controlled valves, valves, etc. are represented by the edges of the network. Supplies and demands, inlets and outlets of equipment are represented by the nodes of the network. The economic and operational problems solved in ACCORD are formulated as continuous, discrete and discrete-continuous optimization on general network with given family of functional connections between flow and pressure. The continuous variables can be acted both in nodes and edges. Pressures, flow and parameters of simulating models are examples of them. The discrete parameters correspond to edges. Examples of them are internal structure of edges and types of simulating models of edges, i. e. of concrete functional dependencies between flow and pressure. The optimal equipment to operate can be selected. The generalizing of the discrete characteristic of nodes such as "the node is source (sink)" is possible.

During optimization, the methods adapt themselves to the concrete network and the features of both object function and variables.

There is proposed a model of contracts having a set of feasible intervals of demand and pressure with corresponding procedures for payment calculation. Every contract is represented as a graph. Such a model causes different merits. It enables a simple, visualizable, structural and unified representation of contracts.

For short term planning, the steady state optimization of gas network is a useful tool. For long term planning for serial time periods, it is worthwhile to use the minimal cost network flow problem as a compromise simplification. The correct investigation of capacities can turn out as a weakest point in such a simplified approach. Here a method [10] is useful; which we developed for precise definition of pressure margin in gas networks.

Steady state optimization by ACCORD is connected with dynamic simulation programs such as SIMONE and GANESI and is integrated in the complex GAMOS that consists of SCADA and various high level functions. ACCORD possesses a clear and simple interface in the form of text files. Due to this interface, ACCORD can be connected with any other simulation program and SCADA system to provide steady state optimization of gas networks with economic, business or operational objectives.

7 Notation

Letters

A = area or cross section, $[m^2]$
$A_k = \frac{k-1}{k}$, $[-]$
$A_n = \frac{n-1}{n}$, $[-]$
a = speed of sound, $[m/s]$
b = outlet width of impeller, $[m]$
C = conversion factor , $[-]$
D = outlet diameter of impeller, $[m]$
E = efficiency, $[-]$
H = mass-specific enthalpy, $[kJ/kg]$
H_p = specific polytropic work of compression i.e. specific polytropic head, $[kJ/kg]$
k = isentropic exponent, $[-]$
m' = mass flow, $[kg/s]$
Ma = Mach number, $[-]$
Mix = gas composition as a list of components, [%]
n = polytropic exponent i.e. polytropic volume exponent, $[-]$
N = speed of rotation, $[1/s]$ (sometimes $[rps/rpm]$)
P = absolute pressure, $[bar]$
R, R_g = specific gas constant, $[J/(kg \cdot K)]$
R_0 = universal gas constant, $[J/(kmol \cdot K)]$
Re = Reynolds number, $[-]$
S = pressure ratio, $[-]$
T = absolute temperature, $[K]$
u = velocity; linear tip speed, referred to D of impeller, $[m/s]$
v = velocity, $[m/s]$
V = volume, $[m^3]$
$V' = \dot{V}$ = volume flow, $[m^3/s]$
W = power, $[W]$
Y = specific work of compression i.e. specific head, $[kJ/kg]$
Z = compressibility factor, $[-]$
μ = molar mass, $[kg/kmol]$
ν = kinematic viscosity, $[m^2/s]$
ρ = density, $[kg/m^3]$
φ = flow coefficient, $[-]$
ψ = head coefficient i.e. process work coefficient, $[-]$

Indexes

1 = inlet
2 = outlet
a = actual i.e. operating point of compressor
e = expected value read from manufacturer characteristics
c - converted point i.e. result of conversion of operating point of compressor to the reference gas and the reference inlet conditions

n = standard state i.e. standard condition for temperature and pressure (STP)

p = polytropic

r - the reference gas composition and the reference state i.e. the reference condition for temperature and pressure (RTP)

8 Figures

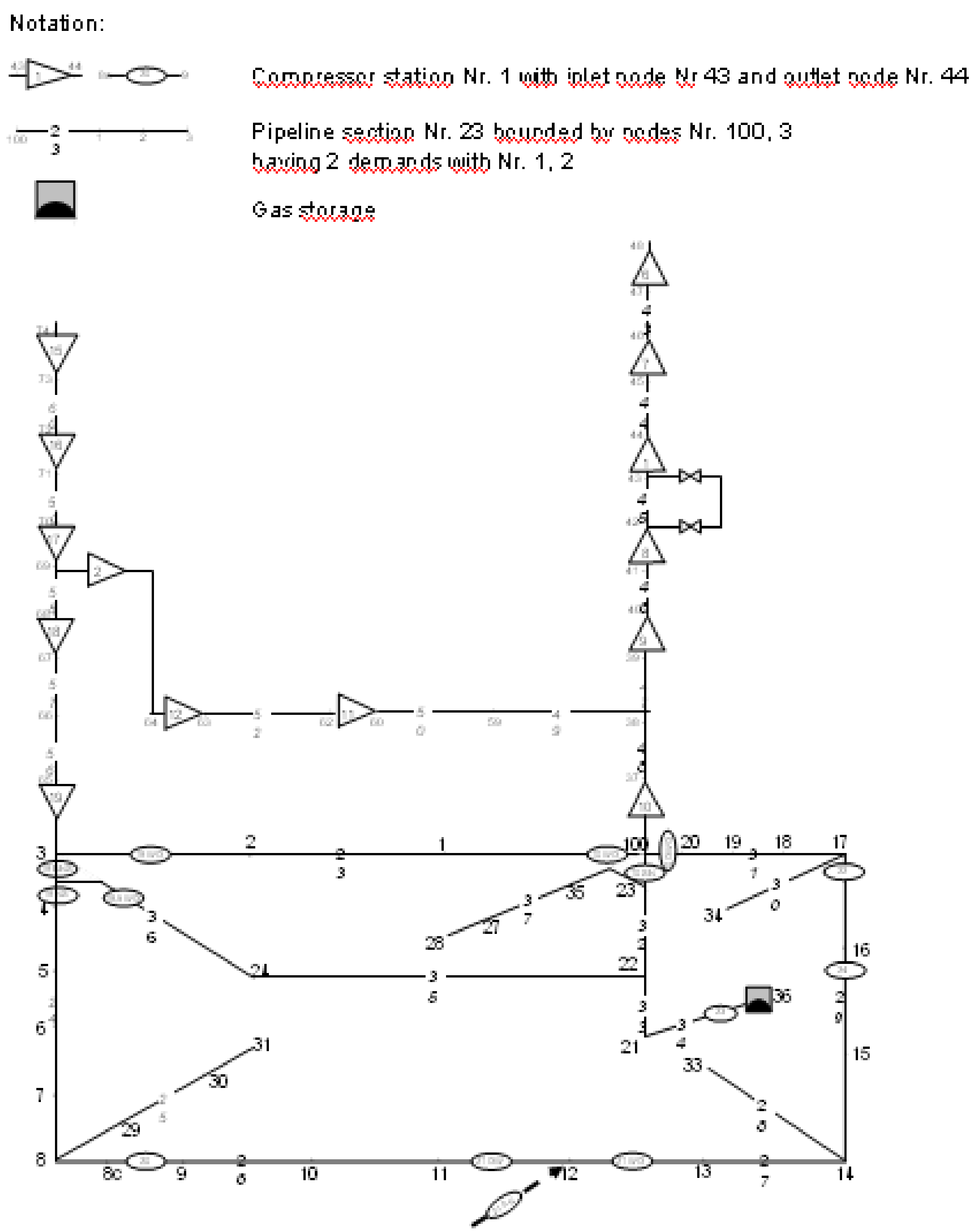
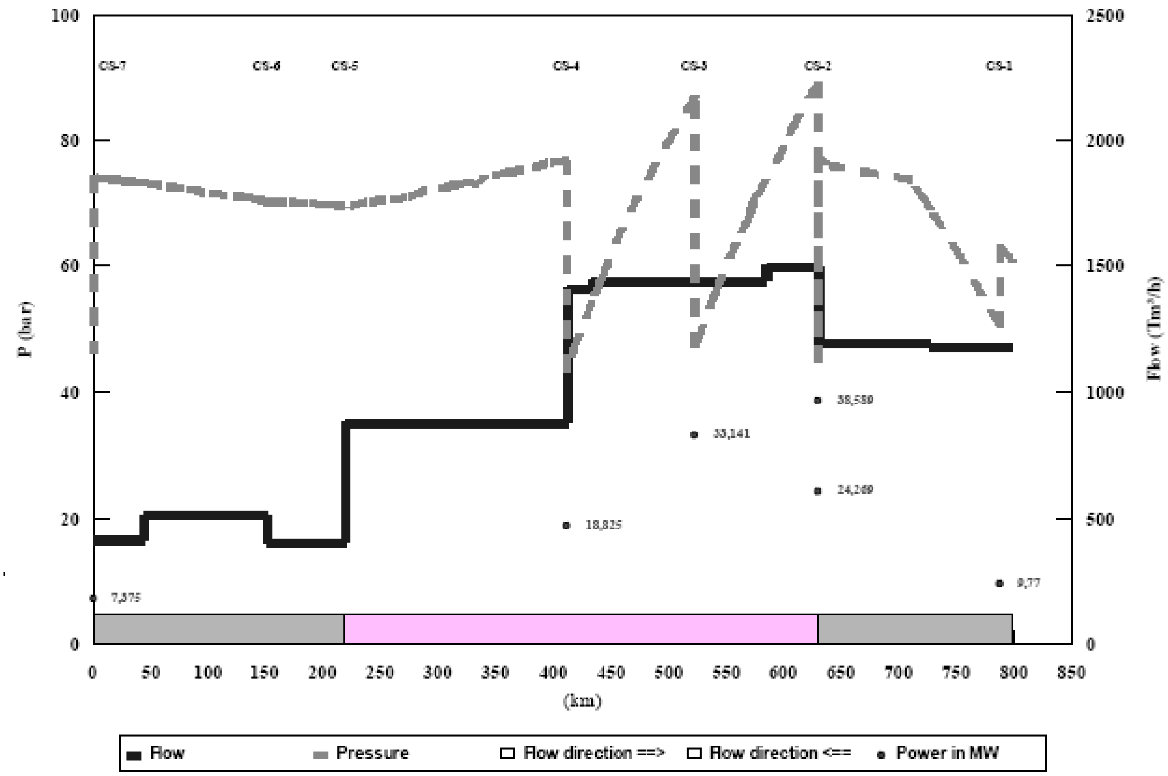
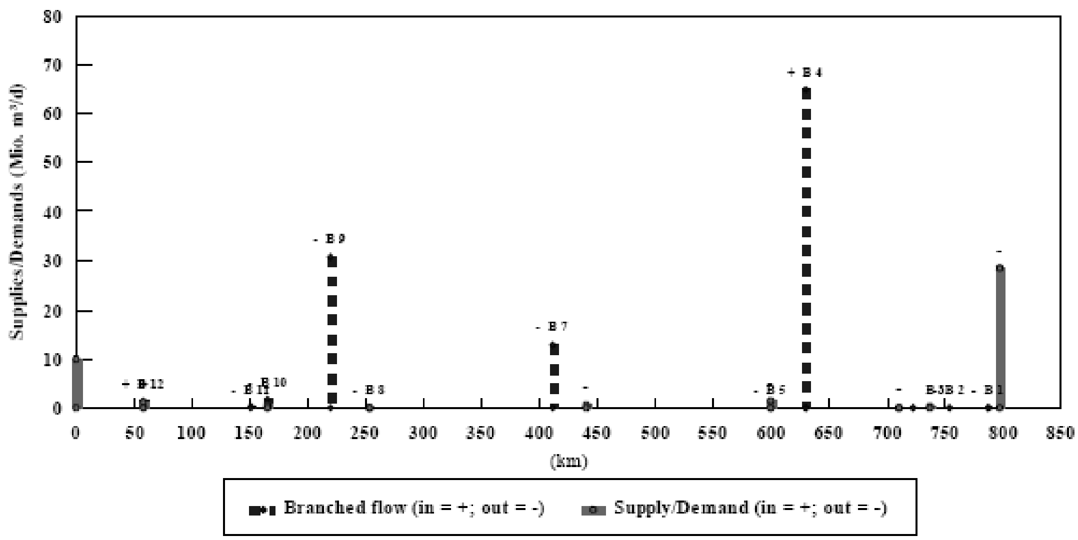


Figure 1: A gas pipeline network



a) A representation related to Pipeline: Distribution of flow, pressure, and compressor power

Figure 2: Pressure, flow, and the compressor power over the selected path of the considered gas network



b) A representation related to Nodes: Distribution of supplies, demands, and flow in off-branched pipelines

Figure 3: Supplies, demands, and flow in the off-branched egdes over the selected path of the considered gas network

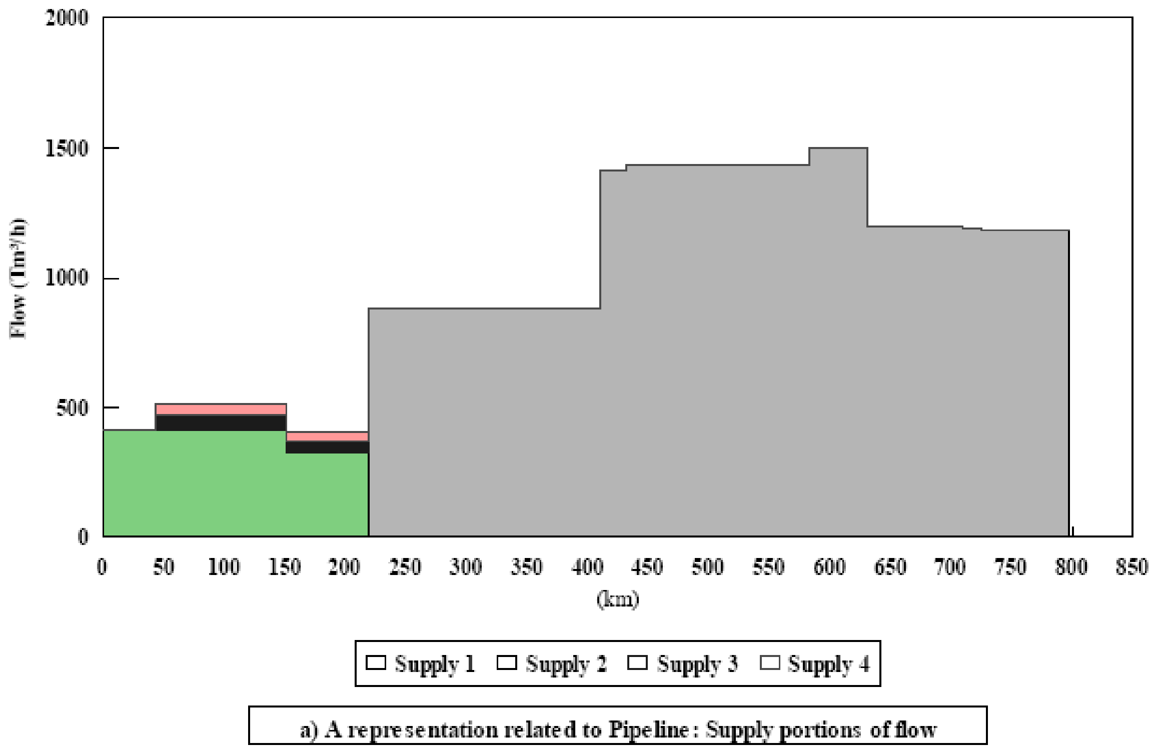


Figure 4: Supply portions in Tracking of supplies, gas composition, thermodynamic properties, and quality parameters of the flow over the selected path of the considered gas network

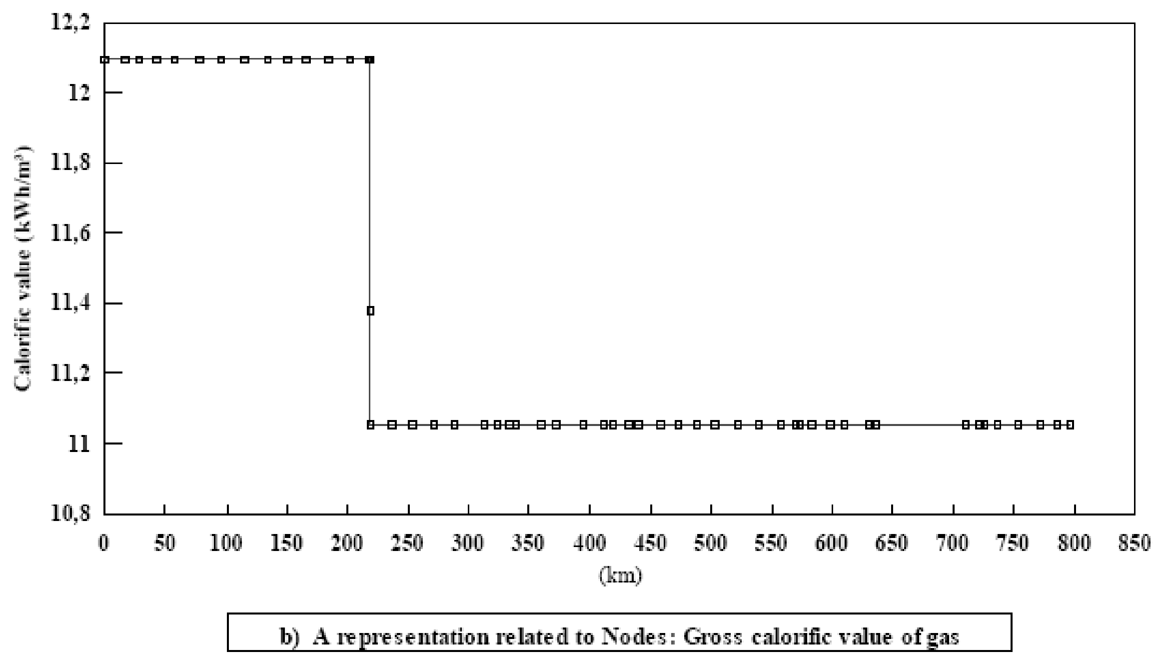


Figure 5: Heating value in Tracking of supplies, gas composition, thermodynamic properties, and quality parameters of the flow over the selected path of the considered gas network

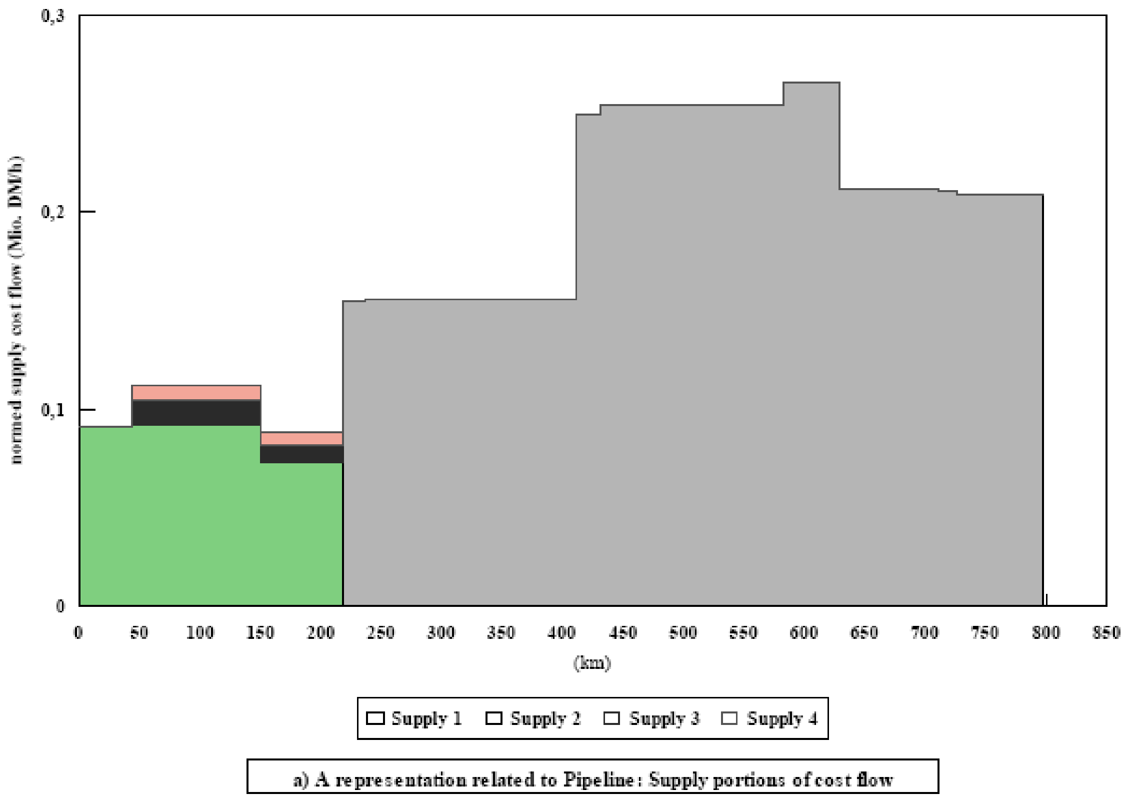


Figure 6: Costs of supplies in costs of flow as a part of Tracking of supplies, gas composition, thermodynamic properties, and quality parameters of the flow over the selected path of the considered gas network

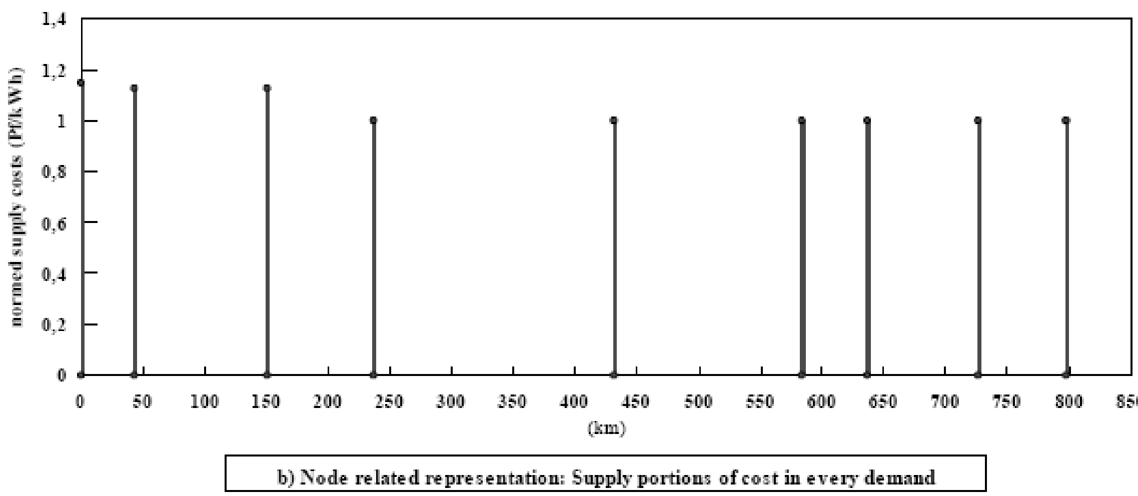


Figure 7: Tracking of the normed operating expenses: Costs of supplies in costs of demands as a part of Tracking of supplies, gas composition, thermodynamic properties, and quality parameters of the flow over the selected path of the considered gas network

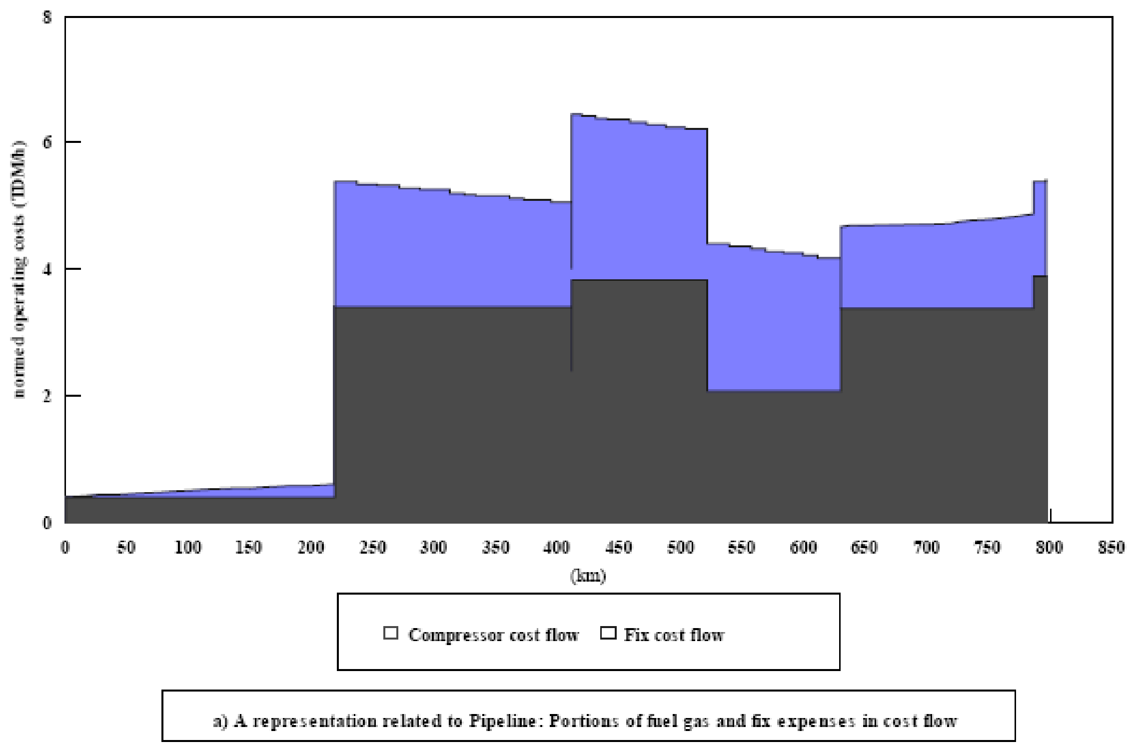


Figure 8: Costs of fuel gas, electro energy, and fix expenses in costs of flow as a part of Tracking of supplies, gas composition, thermodynamic properties, and quality parameters of the flow over the selected path of the considered gas network

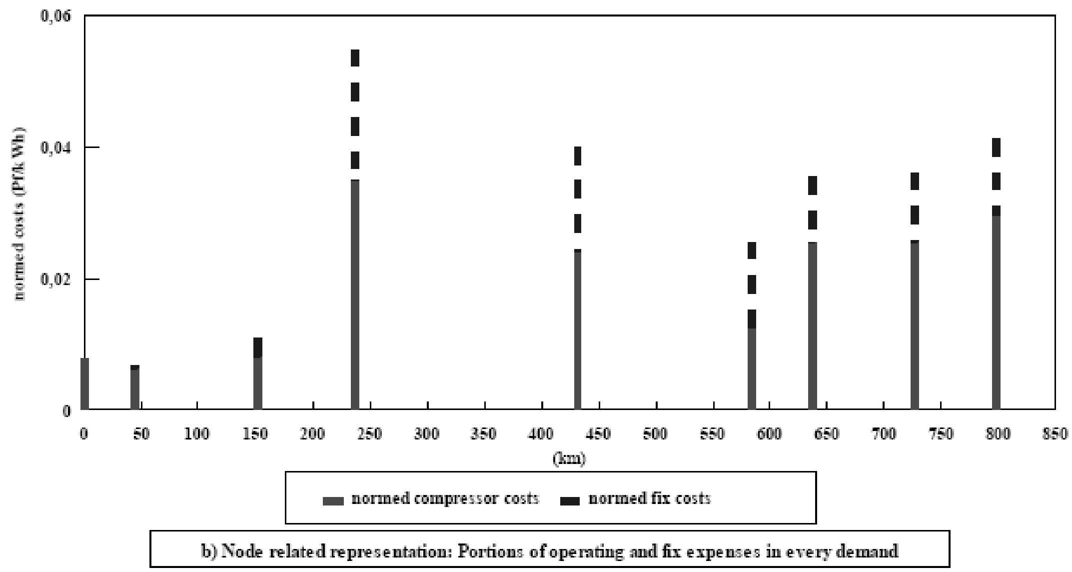


Figure 9: Transport and fix expenses: Costs of fuel gas, electro energy, and fix expenses in costs of demands as a part of Tracking of supplies, gas composition, thermodynamic properties, and quality parameters of the flow over the selected path of the considered gas network

9 Tables

Table 1. Sub-table 1.1. Data in end-nodes of the gas network

Cons. No	Node	+, if supply	Supply or Demand, Mm3/d	P bar	Pmin bar	Pmax bar
1	**100**		2.3	41	40	42
2	**3**		3.55	46	45	47
3	**8**		1.9			56
4	**12**	+	43.4			56
5	**21**		9.83			56
6	**22**		46.07			56
7	**24**		8.14			56
8	**28**		12.06			56
9	**31**					56
10	**33**					56
11	**34**		10.76			56
12	**36**	+	13.5			56
13	**37**			41	40	42
14	**38**			40	38	40.5
15	**39**			28.3	27	29
16	**40**		11.3	33.4	29	34
17	**41**	+	19.9	31.3		56
18	**42**		1.6	42.5		56
19	**43**		0.1	37.5		56
20	**44**		10.1	37.5		56

Table 1. Sub-table 1.2. Data in end-nodes of the gas network

Cons. No.	**Node**	**+, if supply**	**Supply or Demand,**	**P**	**Pmin**	**Pmax**
			Mm3/d	**bar**	**bar**	**bar**
21	**45**		0.1	33.5		56
22	**46**		7.4	41.1		56
23	**47**	+	65.2	37.4		56
24	**48**		77.4	55		56
25	**59**		16.3	43		56
26	**60**		5.7	47.7		56
27	**62**			33.7		56
28	**63**			49.6		56
29	**64**	+	35.4	38.4		56
30	**65**			33.9		56
31	**67**		0.4	51		56
32	**68**		0.4	34.3		56
33	**69**		0.2	53.4		56
34	**70**		2.6	36.4		56
35	**71**		0.4	52.5		56
36	**72**		0.2	35.2		56
37	**73**		0.2	52.5		56
38	**74**	+	84.5	41	30	40

Table 2. Sub-table 2.1. Data of pipeline sections of the gas network

1 No	2 Section	3 End-nodes	4 L Sub-section	5 Inter-. mediate Node	6 Intermediate Demand	7 Ko initial	8 Ko result	9 ΔKo
	–	–	km	–	Mm3/d	–	–	%
1	**23**	100 – 3	36 25 38	1 2	0.5 2.5	0.083258	0.005263	-93.7%
2	**24**	3 – 8	28 23 19 16 21	4 5 6 7	0.6 1 2 3.9	0.011032	0.011032	–
3	**25**	8 – 31	9 14 8	29 30	1.2	0.011032	0.011032	–
4	**26**	8 – 12	28 13 31 1	9 10 11	2.7 1 1.2	0.83258	0.715182	-14.1%
5	**27**	12 – 14	9 38	13	0.3	0.005899	0.005899	–

Table 2. Sub-table 2.2. Data of pipeline sections of the gas network

1 No	2 Sec- tion	3 End- nodes	4 L Sub- sec- tion	5 Inter-. medi- ate Node	6 Inter- medi- ate Demand	7 Ko initial	8 Ko result	9 ΔKo
	–	–	km	–	Mm3/d	–	–	%
6	**28**	14 – 33	28 5	32	2.1	0.083258	0.083258	–
7	**29**	14 – 17	9 15 18	15 16	3.8 1.4	0.005899	0.005899	–
8	**30**	17 – 34	16			0.16232	0.16232	–
9	**31**	17 – 100	7 22 35 38	18 19 20	0.07 0.07 0.05	0.083258	0.083258	–
10	**32**	100 – 22	68 11	23	4.3	0.792462	0.792462	–

Table 2. Sub-table 2.3. Data of pipeline sections of the gas network

1 No	2 Section	3 End-nodes	4 L Sub-section	5 Inter-. mediate Node	6 Intermediate Demand	7 Ko initial	8 Ko result	9 ΔKo
	–	–	km	–	Mm3/d	–	–	%
11	**33**	22 – 21	6			0.792462	0.792462	–
12	**34**	21 – 36	75			0.872981	0.872981	–
13	**35**	22 – 24	12			0.16232	0.16232	–
14	**36**	24 – 3	106.3			0.027284	0.027284	–
15	**37**	100 – 28	13 80	35 27	1.2 3	0.083258	0.083258	–
16	**43**	47 – 46	12				0.00673	
17	**44**	44 – 45	100			0.00673	0.00673	–
18	**45**	42 – 43	100			0.311	0.311	–
19	**46**	40 – 41	100			0.0102	0.011	7.8%
20	**47**	38 – 39	100			0.00448	0.0166	270.5%

Table 2. Sub-table 2.4. Data of pipeline sections of the gas network

1 No	2 Section	3 End-nodes	4 L Sub-section	5 Inter-. mediate Node	6 Inter-mediate Demand	7 Ko initial	8 Ko result	9 ΔKo
	–	–	km	–	Mm3/d	–	–	%
21	**48**	38 – 37	100			0.00918	0.00262	-71.5%
22	**49**	59 – 38	100			0.00282	0.00282	–
23	**50**	60 – 59	100			0.00483	0.00483	–
24	**52**	63 – 62	100			0.00786	0.00786	–
25	**56**	66 – 65	100			0.00037	0.00037	–
26	**57**	67 – 66	100			0.00189	0.00189	–
27	**58**	69 – 68	100			0.00255	0.00255	–
28	**59**	71 – 70	100			0.00204	0.00204	–
29	**60**	73 – 72	100			0.0213	0.0213	–
30	**86**	61 – 64	462.08			0.01636	0.01636	–

Table 3. Sub-table 3.1. Data of compressor stations belonging to the subsystem No. 1 of the considered gas network

1 No	2 Compressor Station No	3 Efficiency of Station	4 T gas inlet	5 Shops Number	6 Type of Machines Drivers	7 Power of Compressors	8 Number of Machines Total	9 Machine Configuration Initial	10 Machine Configuration Optimal	11 Change	12 Benefit, Δ machines
			C			MW					
1	**6**	0.69	13	3	turbine	4	8	3 x 2	3 x 1	changed	−3
					turbine	6	3	1 x 2	1 x 1	changed	−1
					electro	4	8	3 x 2	2 x 1	changed	−4
2	**7**	0.91	9	3	turbine	4	5	2 x 1	2 x 1		
					electro	4	8				
					turbine	5	3				
3	**1**	0.91	8	1	electro	4	16	–	2 x 1	changed	+2
4	**8**	0.91	11	2	electro	4	8	1 x 2	1 x 2		
					turbine	4	5	2 x 2	2 x 2		
5	**9**	0.91	2	2	electro	4	7	2 x 1	–	changed	−2
					electro	4.5	5				
6	**10**	0.91	3	1	electro	4	8				

Table 3. Sub-table 3.2. Data of compressor stations belonging to the subsystem No. 2 of the considered gas network

1 No	2 Compressor Station No	3 Efficiency of Station	4 T gas inlet	5 Shops Number	6 Type of Machines Drivers	7 Power of Compressors	8 Number of Machines Total	9 Machine Configuration Initial	10 Machine Configuration Optimal	11 Change	12 Benefit, Δ machines
			C			MW					
7	**11**	0.98	13	1	electro	4	7	3 x 2	3 x 1	changed	−3
8	**12**	0.98	13	1	electro	4	7	3 x 1	3 x 1		

Table 3. Sub-table 3.3. Data of compressor stations belonging to the sub-system No. 3 of the considered gas network

1 No	2 Compressor Station No	3 Efficiency of Station	4 T gas inlet	5 Shops Number	6 Type of Machines Drivers	7 Power of Compressors	8 Number of Machines Total	9 Machine Configuration Initial	10 Machine Configuration Optimal	11 Change	12 Benefit, Δ machines
			C			MW					
9	**15**	0.91	16	2	electro	4	10	4 x 2	4 x 2		
					turbine	10	3	1 x 2	1 x 2		
10	**16**	0.83	20	2	turbine	10	6	2 x 2	2 x 2		
					turbine	6	6	2 x 2	2 x 2		
11	**17**	0.83	14	2	turbine	10	3	1 x 2	1 x 2		
					electro	4	10	4 x 2	4 x 2		
12	**18**	0.8	9	2	turbine	6	6	2 x 2	3 x 2	changed	+2
					electro	4	10	4 x 2	2 x 2	changed	−4
13	**19**	0.98	6	2	turbine	5	5	2 x 2	2 x 2		
					turbine	6	6	2 x 2	2 x 2		

Table 4. Benefits in the energy expended on compressor stations of the gas network

1 Initial Total Compressor Power	2 Optimal Total Compressor Power	3 Savings in Compressor Power	4 Benefits Δmachines
MW	MW	%	–
260.8	234.4	-11.2%	-13

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