Long-Term Pressure-Stage Comprehensive Planning of Natural Gas Networks

Michael Hübner and Hans-Jürgen Haubrich

Abstract Due to the forthcoming regulation schemes throughout Europe, new challenges for natural gas network operators arise. The pressure for realizing and operating cost-efficient network structures increases as the regulation is based on a comparison of different network operators with the network operator setting the minimal allowable costs. Optimization methods, which will also be applied by regulatory authorities as part of the analytical cost models for calculating the efficiency of natural gas networks, provide the opportunity to identify long-term cost-efficient network structures, so called reference networks.

Boundary conditions of natural gas networks, which concern the system's technical safety and thus need to be regarded during network planning, are given by the rules set by each country's technical assembly for natural gas supply. Degrees of freedom exist in alternative network structures, the number and degree of pressure stages and for the dimensioning of equipment. Therefore, optimization methods are required for solving the extensive optimization problem.

Especially heuristic optimization algorithms have proved to deliver an optimal performance for the determination of cost-efficient network structures. Their essential advantages over exact methods are a reduced computational effort, leading to computing times of typically few hours for real natural gas systems while simultaneous delivering several similar cost-efficient network structures. These advantages allow sensitivity analysis by a variation of boundary conditions and supply tasks on network structure and network costs and lead to a greater flexibility for the future network development.

Therefore, an optimization method for natural gas distribution networks based on Genetic Algorithms is proposed. The method is capable of calculating cost-efficient

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network structures with regard to all technical and economic boundary conditions and is also used by the German Federal Network Agency for calculating reference networks with minimum costs for given supply tasks. Exemplary applications demonstrate the method's capability and the advantages through applying this method for long-term planning of natural gas networks.

Keywords Combinatorial optimization • Distribution networks • Genetic algorithms • Minimal network costs • Natural gas • Network planning • Parallel optimization

1 Introduction and Motivation

The cost pressure on distribution companies has increased because of the upcoming regulatory framework in the European power and gas markets. Therefore, in particular gas network operators, who focused mainly on the compliance of the technical safety proposals by national technical and scientific associations for gas and water networks, need to reveal potentials for a cut down of costs in the field of network planning.

The reduction of directly controllable costs in the short-term, e.g. a decline in maintenance work or an abandonment of investments, provides a limited lowering of costs, if the high reliability and safety standards of existing networks should be maintained. Another option for lowering network costs is the operational optimization. The aim of this method is to supply all customers via the existing network at minimal costs with regard to contractual obligations [1, 2]. Nevertheless, due to the narrow time planning horizon, advancements in efficiency are constricted to short-term manipulable expense factors.

A sensible approach seems to be the refinement of the network planning process in order to determine efficient networks, which provide for an equivalent level of reliability and technical safety compared to the existing network and at the same time lower costs. Therefore, the application of a computer-based network-planning instrument for the objective determination of long-term cost-efficient networks is necessary. At present, there exists no instrument for the integrated planning of natural gas distribution networks with different pressure stages. Hence, the primary objective of this paper is to introduce the status quo of current developments of a computer-based technique for the integrated planning of natural gas distribution networks with variable pressure stages.

In case of the long-term planning of electrical networks, computer-based procedures are deployed that optimize the network structure as well as the dimensioning of necessary operating facilities with regard to the given supply task. All relevant technical and company internal planning criteria need to be considered. Numerous studies have proven the overall functionality of the aforementioned procedures for realistic planning tasks [3]. On the other hand, in the past, the planning of natural gas networks has been vastly driven by the company's success of acquiring new customers. Therefore, apparently the long-term strategy has depended on subjective expert knowledge of the planning engineers in charge [4].

The objectification of the network planning process by means of long-term cost-optimal networks (target networks) gains in importance against the background of the liberalization and regulation of the European power markets. Thus, the application of computer-aided optimization procedures is indispensable for natural gas networks.

2 Network Planning Process

Due to the complexity of the network planning process, it seems both necessary and beneficial to subdivide it into two separate planning stages [5], see also Fig. 1.

2.1 Long-Term Planning

Regarding a planning horizon of several decades, the existing network structure and operating facilities may be ignored. The long-term planning is based on the aforementioned assumption that is often referred to as Greenfield development. Therefore, the long-term planning will identify cost-efficient network structures neglecting the existing facilities.

2.2 Expansion Planning

The expansion planning determines cost-efficient systematic development strategies starting with the existing network structure and aiming at the identified

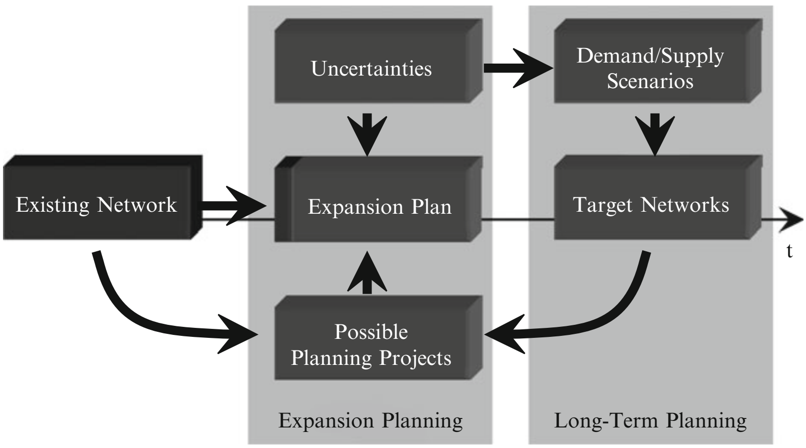

Fig. 1 Expansion and long-term planning

target networks based on the outcomes of the long-term planning [6]. Uncertainties concerning, e.g. load growth, changes in interest rates, etc., may be considered in this planning stage.

As the long-term planning resembles in many respects the determination of reference networks and is therefore attached with special consideration in the regulatory context, this article will focus exclusively on the long-term planning of natural gas networks.

2.3 Boundary Conditions and Degrees of Freedom

A complete description of the underlying degrees of freedom and boundary conditions of the network planning is fundamental to the development of efficient network structures. In the following, the main aspects of both will be presented. For a summary, see also Fig. 2. The supply task is defined by the geographical location of network customers as well as their demand and feed-in respectively. Topographic characteristics of the supply area restrict the degrees of freedom considering the choice of possible pipeline trenches and location of stations.

Technical restrictions are given by each operating facility's operating characteristics and safety requirements regarding both the system's safety and individual customer specifications. They primarily consist of maximum and minimum admissible connection pressures for every nodal point, maximum gas flow speeds in pipelines for a limitation of noise emissions and maximum volumetric flow rates in pressure regulators.

Company-internal planning guidelines that exceed technical minimum requirements correspond to a demanded retention capacity that is necessary for a safe operation especially in cases of critical network loadings. It may also be used,

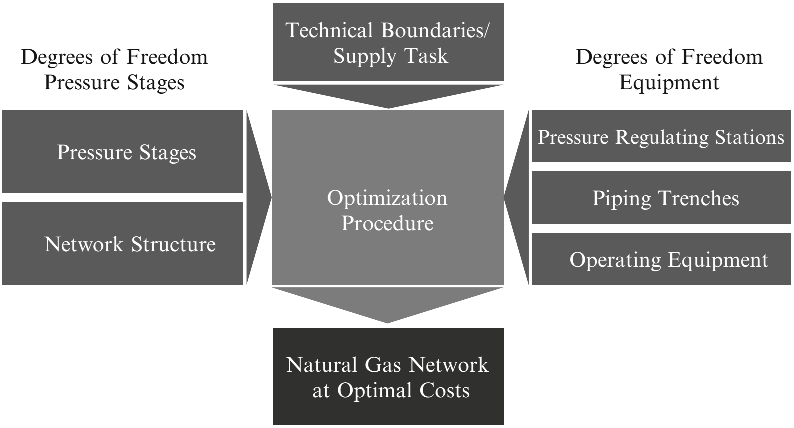

Fig. 2 Boundary conditions and degrees of freedom for network planning

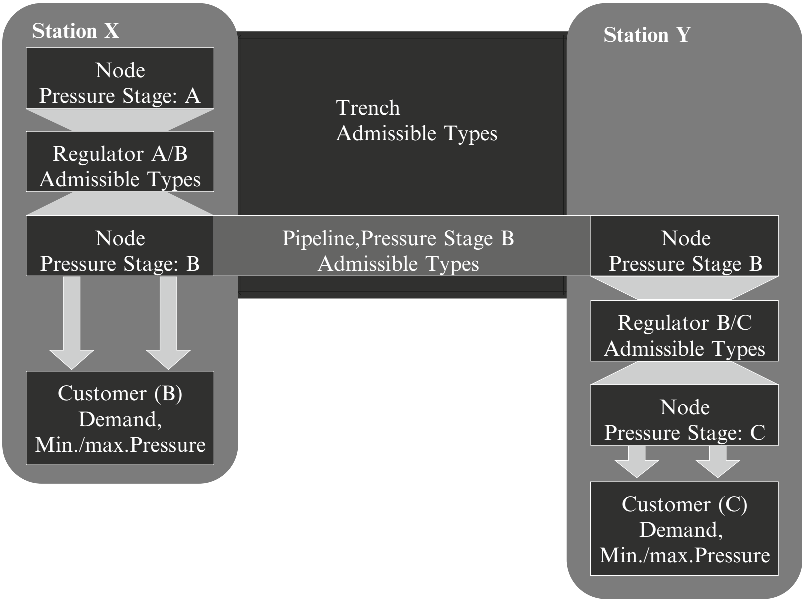

Fig. 3 Network model

especially in networks of high operating pressures, for an optimization of the gas acquisition strategy. Information on the calculation as well as dimensioning of retention capacities is published by the national technical and scientific organizations [7].

Degrees of freedom exist in the choice of different network structures, the number and degree of pressure stages and for the dimensioning of equipment. Figure 3 depicts the chosen network model that forms the basis for the proposed optimization approach. It is composed of stations and interconnecting trenches on the primary level. Stations are specified by their associated coordinates and likewise serve as geographical positioning reference of pressure regulators and network customers. Trenches may contain pipelines of different pressure stages in order to connect two stations.

2.4 System Model

The model allows for a definition of multiple pressure stages connected via pressure regulators within a station. Each node represents a pressure stage in each station. The closed analysis of possible dislocations of network customers between pressure stages as well as the fundamental determination of efficient vertical network configurations, realization and positioning of pressure regulators, is made possible by the presented network model.

As the pressure level of each pressure stage is depending on the location and discharge pressure of the used pressure regulators that is determined within the optimization procedure, the resulting operating pressure is an outcome of the optimization. Therefore, it is possible to determine the optimal combination of pressure stages objectively. Nodes are used to offer both an assignment of operating equipment to dedicated pressure levels and furthermore a junction of pipelines as well as pressure regulators. Trenches are composed of a combination of pipelines with potentially differing technical properties and pressure stage assignments.

3 Methodology

Methods for a solution of combinatorial optimization problems can be divided into exact and heuristic proceedings [8]. Approaches with a mathematically verified optimality for a given objective target are ranked among the group of exact methods. The group of heuristic methods incorporates proceedings that feature a systematic search adapted to the problem statement.

3.1 Exact Methods

All relevant exact optimization proceedings are based on the iterative resolution and modification of a relaxation – broken down simplified problem – with a solution set containing all solutions of the initial problem. The branch-and-bound search and the cutting plane method apply a relaxation into a linear optimization problem and disregard all integrity requirements in the first instance. Since in principle, a greater number of solutions are accepted in the relaxation than in the initial problem, the optimal value of the relaxed problem is at least as good as the optimal value for the initial problem, hence providing an upper or lower bound. The value of each admissible integral solution defines just as well a boundary for the optimal solution of the initial problem as per definition. The comparison of both upper and lower boundary yields the maximum distance between a found solution and the optimum one, even though it is unknown.

3.2 Heuristic Methods

Heuristic methods are recognized as approaches to identify reasonable and admissible solutions to a problem statement and help map real decision problems mathematically. They proceed according to specific rules for solution finding or advancements that shall exploit the given model structure effectively while simultaneously lowering the time necessary for computing. Heuristic methods come into operation in situations where exact methods are inapplicable to real life planning problems because of their immoderate need for computing power.

Local search algorithms generally start with an admissible solution of the problem, which has been identified either stochastically or by applying approximation algorithms. Transitions between adjacent solutions in the solution space are initiated in each step of the process. The neighborhood consists of all solutions that can be derived from the actual solution by a once-only execution of a transition directive. Pure local search algorithms end as soon as no further superior adjacent solution exists. The best-achieved solution represents, for the chosen neighborhood, the local optimum. Its objective function value may be considerably lower than the objective function value of the global optimum.

In the past, a multitude of meta strategies have been developed to overcome the aforementioned problem of local optimality. The combination of local and global search techniques summarized in abstract meta strategies are used to enhance advancement heuristics by navigating to promising solution spaces in order to avoid local optima. For solving combinatorial optimization problems, applied problem solving models of specific adaption mechanisms in natural systems are being applied cumulatively. Common ground of the developed adaption analogies is, besides their origin from the study of natural phenomena, the principle as to converge to a problem's solution by manipulating potential solution candidates, assess each manipulation and in conclusion extract new solution candidates based on the previous assessment.

3.3 Selection of Optimization Procedure

A guarantee for optimality, mathematically proven, is the essential advantage of exact methods. Although the branch and bound algorithm as well as all thereof derived variants exhibit a considerably improved run-time characteristic in contrast to alternative exact methods for combinatorial optimization, only problems with restricted extent can be solved [9–12]. The handling of extensive problems accrued from real life applications is rarely possible with justifiable computing power because the number of integer variables is exponentially increasing the complexity. Considering the aforementioned network model and the resulting degrees of freedom, computer-based optimization methods are required for solving the extensive optimization problem.

Heuristic optimization algorithms have proved to deliver an optimal performance for the determination of cost-efficient network structures [13–16]. Their essential advantages are a reduced computational effort leading to computing times of typically few hours for realistic natural gas systems while simultaneously delivering several similar cost-efficient network structures. These advantages allow sensitivity analysis by a variation of boundary conditions and supply tasks on network structure and network costs and lead to a greater flexibility for the future network development. In contrast to exact algorithms, heuristic algorithms yield no guarantee for optimality. Nevertheless, numerous studies indicate that the difference between these nearly optimal results and the absolute optimum is typically below 1% [3] and therefore negligible for realistic problem formulations. Genetic algorithms are, especially for combinatorial optimization problems, widely adopted heuristic optimization approach that will be applied for the introduced optimization problem. They refer to the natural evolution of animals over multiple generations. They additionally offer the possibility to exploit their population based design with a parallel execution to achieve further computing time reductions [17].

3.4 Optimization Procedure

In the following, the newly developed optimization procedure will be described in detail. For that purpose, the heuristic optimization approach will be explained in general before the necessary specific adaption to the problem of natural gas network planning will be introduced.

3.4.1 Genetic Algorithms

The nomenclature of genetic algorithms is based on the evolution theory and population genetics. The main elements that will be used frequently in the following algorithms are specified in Table 1.

At the bottom of genetic algorithms is the idea, likewise based on the evolution theory, that a population made up of many individuals is generated stochastically and of these individuals who conform best to a dedicated quality criterion, i.e. have a high fitness value, are selected. The properties of the selected individuals that are encoded in each genestring are afterwards recombined and stochastically altered with the help of the genetic operators selection, crossover and mutation, in order to generate a population for a new generation. This procedure will be repeated many times for each newly generated population until an optimal conformance with the problem structure is reached.

A schematic illustration of the process sequence of genetic algorithms is shown in Fig. 4. At the beginning of the procedure, an adequate and problem-adapted coding scheme has to be chosen, defining the composition of genestrings. A single gene with a generally arbitrary number range will map each decision variable of the underlying problem. These genes act as distinct identification objects of the

Table 1 Terms of genetic algorithms

Term	Explanation
Individual	Potential problem solution
Population	Set of potential problem solutions
Fitness	Objective function subject
Generation	Iteration
Gene	Variable of decision
Genestring	Encoding of problem statement

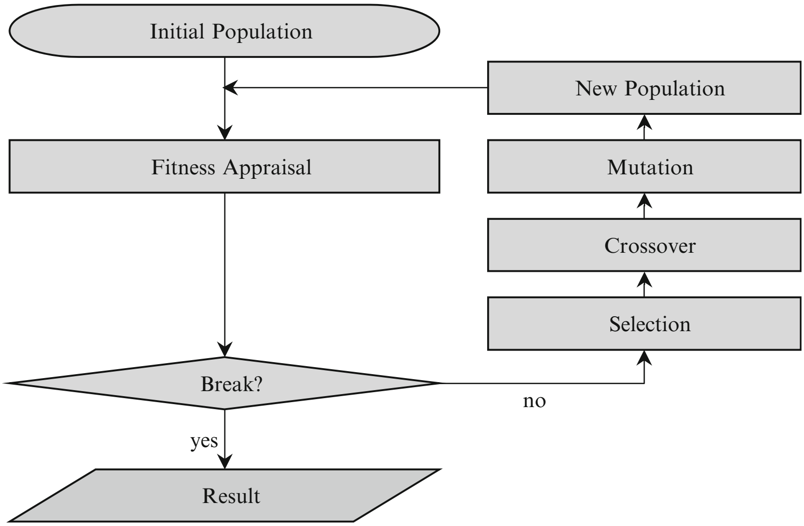

Fig. 4 Process sequence of genetic algorithms

decision variables and therefore make a decoding of the problem for a validation and assessment of the individual possible. Subsequently, an upfront-predefined number of individuals will be chosen from the search space stochastically or in combination with already known solutions. These individuals compose the initial population of the procedure.

Afterwards, the quality of all individuals within the present population will be assessed with the help of a fitness function. The fitness function includes all relevant parameters as investment cost input and technical specifications so that a concrete roundup of each individual's quality is possible. The termination criterion will be checked at the end of every generation. For example, a termination criterion may be a maximum number of iterations or a stagnant convergence over several iterations. If no termination criterion is met, new individuals are created by means of genetic operators that constitute the new population. Selection, crossover, and mutation are counted among the genetic operators. Figure 5 shows an exemplary application to illustrate the general approach of genetic operators.

The genetic operator selection is chosen to arrange a gene pool from individuals of a population. All individuals are considered with a probability according to their fitness values. Therefore, well-adapted individuals receive a higher share in the gene pool than individuals with a poor fitness value do. Thus, the main functions of selection operators within genetic algorithms are:

- Selection of individuals participating in the crossover
- Selection of a predefined number of individuals that form a successive population from a set of individuals
- Selection of a predefined number of individuals from the set of individuals resulting from a crossover that shall be further regarded

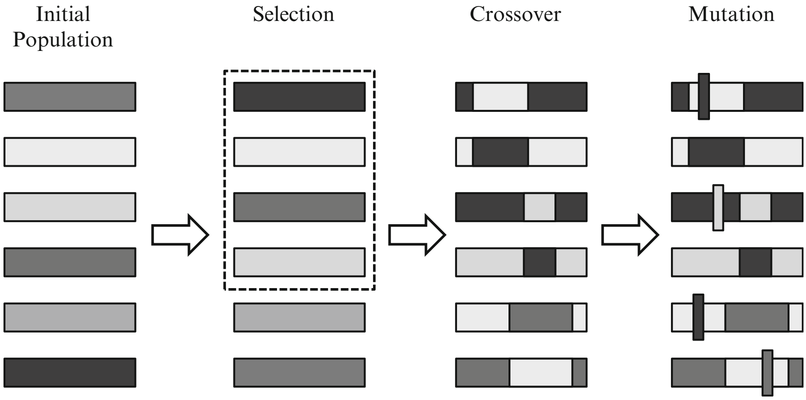

Fig. 5 Exemplary application of genetic operators

Following the selection, at least two individuals are extracted from the gene pool and recombined with a definable crossover operator to form new individuals. The main goal of this recombination is ideally to transfer the positive attributes of the different parent individuals so that the succession unifies these attributes.

The concept of a genetic operator mutation has been introduced to genetic algorithms in order to replicate the naturally occurring stochastical modification of genes. For this purpose, individuals from the actual population will be selected and their genestrings altered at sparse positions. In comparison to the crossover operator, the mutation operator should be applied the more infrequent the more advanced the genetic algorithms get as otherwise individuals in the near of a potential optimum will be altered too excessively. Depending on the chosen mutation function, one ore more genes of a genestring will be mutated.

Finally, the population generated by the genetic operators and tested for the termination criterion will replace the actual population. The genetic algorithm does not necessarily need to replace the old population entirely but can also take over the best individuals from the old population. If no termination criterion is fulfilled, all genetic operators will be applied to the new population. Otherwise, a predefined number of the best individuals will be exported.

3.4.2 Application to the Planning of Natural Gas Networks

A fundamental advantage of genetic algorithms is they are in large part problem-independent frameworks that allow for an application different formulated problems. The approach simultaneously offers a great flexibility to consider problem specific requirements. Essential adaptions are in particular:

- Used encoding
- Definition of a fitness function

Table 2 Representation of decision variables

	Network level	Pressure regulator	Trench
Range	1–ℓ	0–m	0–n
Representation	Realization and choice of structural parameter	Realization and choice of operating resource category	Realization and choice of operating resource category

The encoding is determined by the individual approach's implementation and defines the meaning of each decision variable. All degrees of freedom, such as the choice of operating equipment for pressure regulators and pipelines, are ranked among the decision variables. For the planning of natural gas systems, only integer values are acceptable for decision variables.

Table 2 depicts the chosen gene encoding for the degrees of freedom for pressure stages, pressure regulators, and trenches. The encoding for trenches contains both the surface works and all possible pipelines that may be installed on the trench with specification of type and pressure stages.

Basis for the appraisal of an individual (the fitness function) is the economic evaluation of each decision variable so that predominantly cost-efficient network concepts with a consequentially high fitness value will be brought forward. Additionally, violations of technical minimum requirements that are uncorrectable with repair functions may be considered via a penalty function. The penalty function makes sure that network concepts with malfunctions receive a lower fitness value.

Optimization Procedure

An overview of the applied optimization procedure is illustrated in Fig. 6. First, possible optimization variables consisting of usable trenches, pressure regulating stations and types of operating facilities are assembled. They enter the optimization procedure in combination with the given boundary conditions.

Of the closed optimization core, a multitude of different possible network concepts is drafted stochastically within each iteration. First, each network concept will be analyzed regarding its technical feasibility. If any boundaries are violated, a multitude of repair functions are applied in order to transfer the draft into the admissible solution space. Local search algorithms improve the network structure with limited changes and thus support a faster convergence towards optimal network structures.

In the next step, network costs for each concept will be determined and attributed to the corresponding concept as a quality rating. All concepts will be arranged according to their quality in order to compose a new genetic pool for the stochastic generation of new network concepts. The best network concepts will be transferred unchanged into the new population. Thereby, the already achieved level of quality will likewise be transferred combined with completely new concepts. Genetic operators, e.g., selection, crossover, and mutation, will be applied on the whole population. If no significant advancement in quality is perceived the iterative process will be aborted and the best network structure will be exported.

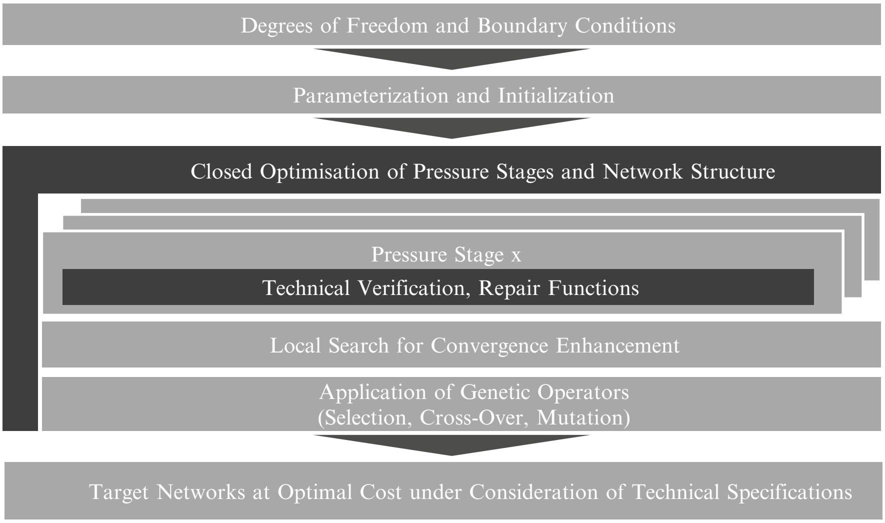

Fig. 6 Optimization procedure scheme

Technical Assessment

The compliance with all required technical minimum requirements is checked in a two-stage process. If a violation is detected, the repair functions are used to recover a state without these violations. The first step comprises structural inspections that in essence target the security of supply. Afterwards, all operational constraints are checked by calculating nodal pressures and all thereof derived values like gas velocities. Based on this flow calculation, technically admissible and sensible planning alternatives in the neighborhood of the network structure under consideration are analyzed.

Operational Assessment

Substantial operational requirements for the planning of natural gas networks are limits for flow velocities in pipelines, flow rates in pipelines and through pressure regulators and as obligatory limit maximum and minimum pressure levels for all nodes. The compliance of these limits is likewise checked with the results of a flow calculation.

Required maximum flow rates are depending on the type of each used pressure regulator. If the actual flow rate exceeds the maximum admissible value, a potentially more expensive pressure regulator with broader limits or a pressure regulator with a lower outlet pressure may be inserted. Should the aforementioned possibility be unfeasible, pressure regulators at different positions within the pressure stage may be amplified to relieve the pressure regulator under consideration.

In principle, it is possible to give a minimum and maximum pressure limit for every network node. In the majority of cases, such stipulations suffice for nodes connecting network customers or storages. In the case of a violation of pressure limits in the flow calculation, adjacent pipelines in the direction of pressure regulators will be amplified in order to increase the node's pressure.

Similarly, violations of maximum flow velocities can be intercepted with an increase of the pipeline diameter of the section under consideration. As high flow velocities coincide with high-pressure gradients due to undersized pipeline diameters, the examination of minimum pressure limits will have a positive impact on the compliance of maximum flow velocities.

Local Search for Convergence Improvement

The stochastic components of genetic algorithms and the starting population that in general has been generated without consideration of any constraints cause the individuals in the beginning generations to be far from the searched optimum. The violations of boundary conditions due to the aforementioned stochastics furthermore demand the use of repair functions that in either case lead to a worsening of the fitness value. Therefore, it seems advisable to conduct cost-reducing structural refinements in the form of a local search that does not change the fundamental structural character of a network significantly.

Because of marginal efforts for technical and economic evaluations of network concepts, a great part of the surrounding solution space of each solution can be examined easily. If a solution possibility with a higher fitness than the initial solution can be found, a transfer to this solution will be carried out. Possible solution changeovers include modifications of operating equipment or the dismantling of several – from technical point of view not necessary – equipment.

For that purpose, a network concept from a restricted neighborhood of the actual concept is chosen with the help of two heuristics. An obvious approach is based upon inspection of exceptionally low loaded operating equipment. For instance, diameters of pipelines with low flow velocities are reduced and pressure regulator types are adjusted to the real flow rate. A second heuristic, based on sensitivity matrices, considers the impact of single structural changes on the residual network. Having preferred equipment with low sensitivity coefficients, the network will be adapted adequately with a minimum number of structural changes and with a minimum operational influence.

The immediate verification of the technical characteristics for all solution transitions provides information on its suitability and possibly its economic advancement. Each new solution, summing up all carried out transitions, will be included in the population and technically and economically evaluated. This approach allows for a systematic search for structural changes to improve the convergence characteristics of the genetic algorithm.

4 Exemplary Results

In this chapter, the approach's performance and functionality will be demonstrated with the help of an exemplary application for a real supply area. For that purpose, a medium-scale urban supply task will be optimized with regard to pressure stage composition, network structure design, dimensioning of operating equipment, and compliance with state-of-the-art technology requirements. Initially, the system under investigation will be described and the already existing natural gas network assessed from a technical as well as economic point of view. The findings will provide a standard of comparison for the optimized cost-efficient network structures. A survey of all necessary degrees of freedom and boundary conditions will be subsequently defined.

In the following section, the results of a pressure stage comprehensive network optimization for the considered area will be presented as well as technical and economical assessments. The integrated optimization of pressure stages, network structures, and operating equipment is a fundamental innovation in the field of network planning. Furthermore, the convergence characteristic of the genetic algorithm will be explored with the use of a sensitivity analysis. Finally, prospects for a significant reduction of computing time by the use of a parallel execution of the genetic algorithm on multiple processors shall be analyzed.

4.1 Data Models

The considered supply area (see Fig. 7) exhibits a predominant urban character. The total area is approximately 100 km^2 in size. Two connection points to the overlaying 16 bar regional distribution grid provide the opportunity to feed natural gas into the supply area. With a number of 30,000 inhabitants, the total power output adds up to 150.8 MW. A share of 68% of the power output falls upon the low-pressure household customers and the remaining output falls upon business customers in the medium pressure stage. In a prognosis for a long-range planning horizon, stagnation on today's level of the demand situation has been determined (cp. Table 4). Because of the general decline of demand for natural gas due to a replacement of natural gas for alternative energy sources and a reducing population, a scenario of a halving of the total demand will be analyzed additionally.

Three potential pressure stages will be considered for the exemplary results: one high-pressure stage operated at four bar (HP4), one medium-pressure stage (MP), and one low-pressure stage (LP).

4.1.1 Boundary Conditions and Degrees of Freedom

The degrees of freedom are composed as follows:

- The existing network features three pressure stages with the low and medium pressure stage predominantly used for the supply of network customers. Due to

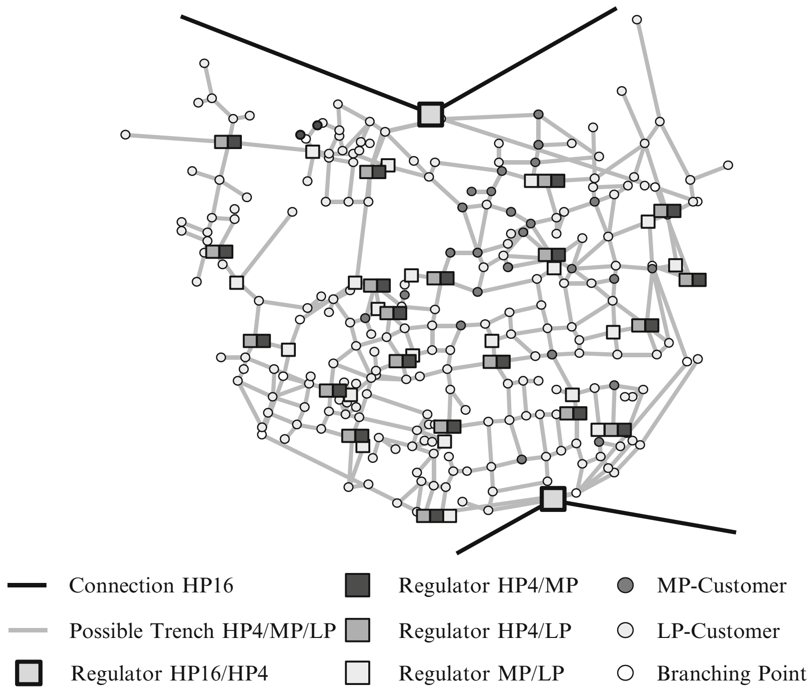

Fig. 7 Network for exemplary investigation

the small geographical dimension of the supply area, the number of pressure stages will be limited to these three pressure stages.

- Each combination of pipelines of all possible pressure stages may be placed in every trench connecting two stations.
- The positioning of pressure regulators will be restricted to adequate areas according to the place requirements (see Fig. 7). Overall, the optimization procedure may choose from 64 pressure regulators connecting the three pressure stages.
- Additionally, there are two possible transfer stations connecting to the overlaying 16 bar transmission network that bypasses the urban area (see Fig. 7).
- In accordance to the planning practice, the number of selectable equipment categories will be limited. For instance, pipeline types may be chosen from six categories representing diameters between DN 80 and DN 500 (cp. Table 3).

Furthermore, the following technical requirements are considered:

- Customers are located in the low and medium-pressure stage. The assignment of connection points is evident in Fig. 7.
- The requirements concerning the pressure level in each pressure stage result from maximum infeed pressure and minimum pressure at customer as well as pressure regulator connections (cp. Table 4).

Table 3 Possible equipment categories

	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6
Regulator	$p_d = 4$ bar	$p_d = 0.8$ bar	$p_d = 0.05$ bar			
Pipeline	DN 80	DN 100	DN 150	DN 300	DN 400	DN 500
Trench	One pipeline	Two pipelines	Three pipelines			

Table 4 Supply area properties

	HP4	MP	LP
Discharge power [MW]	0	48.4	102.4
Feed-in pressure [bar]	4	0.8	0.05
Minimum pressure [bar]	1.6	0.2	0.03
Number of possible regulators	2	22	42

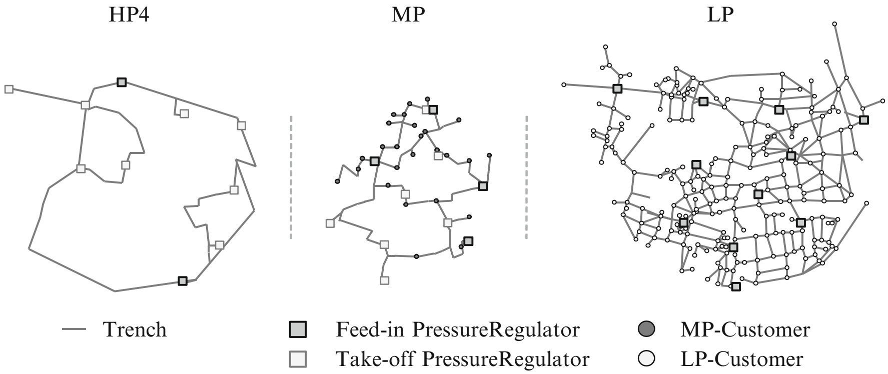

Fig. 8 Structure of existing network

- In order to restrict noise disturbances for residents in the urban area, the flow velocity will be limited to 20 m/s.
- The distributed natural gas is a H-gas with caloric value of 11.3 kWh/m_N^3 and a medium temperature of 5°C for the relevant peak load case.

4.1.2 Existing Network

Figure 8 illustrates the pressure stage design as well as the network structure for each pressure stage of the existing network, featuring two connection points with the overlaying 16 bar high-pressure network along with distributing the natural gas over three pressure stages to the end customers. While the high pressure stage (HP4) exhibits a wide-meshed network structure, the medium and low pressure stages (MP and LP) exhibit a fine-meshed network structure.

Besides the absolute minimum pressures, Table 4 equally provides bandwidths of the admissible pressure within each pressure stage as the zone between the feed-in pressure and the minimum outlet pressure for customers or pressure

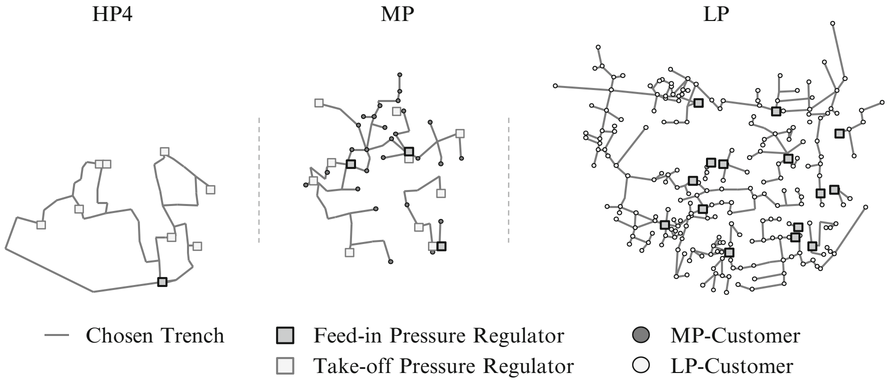

Fig. 9 Target network for a stagnating demand

regulators feeding lower pressure stages. In the existing network, the resulting total bandwidths are utilized only to a low extent indicating that taking into account the technical requirements, a substantial reduction of overall pipeline length and equipment dimensioning could be achieved.

In Fig. 11, the annual network costs of the existing networks (differentiated between investment and operating costs) for pressure regulators, pipelines, and trenches are depicted for each pressure stage. The total annual network costs aggregate to 3.2 Mio. € for an interest rate of 9.5% and are mainly influenced by the necessity to connect household and business customers to the medium and low pressure stage respectively leading to big pipeline lengths in these stages.

4.2 Determination of Long-Term Cost-Efficient Networks

In the following, long-term cost-efficient networks (also referred to as target networks) for the given supply task will be determined with the use of the proposed optimization approach. The results will exhibit optimal functional segmentations in pressure stages and optimal network structures – with an integrated dimensioning of operating equipments – for each used pressure stage. Figure 9 (scenario stagnating demand) and Fig. 10 (scenario halved demand) give an overview of both obtained target networks for the projected demand scenarios.

Both target networks have a significantly different network structure, especially in the low pressure stage, compared to the existing network but also among one another. The pipeline length in both target networks has been considerably reduced (stagnating demand: −17 km, halved demand: −24 km with a total of 79 km in the existing network). Furthermore, the pipelines in the target networks are on average of smaller dimension. The low-pressure stage is, adjusted to the connection points of end customers, wider meshed than the existing network leading to the formation of island networks. Island networks can be found in the medium pressure stage as well.

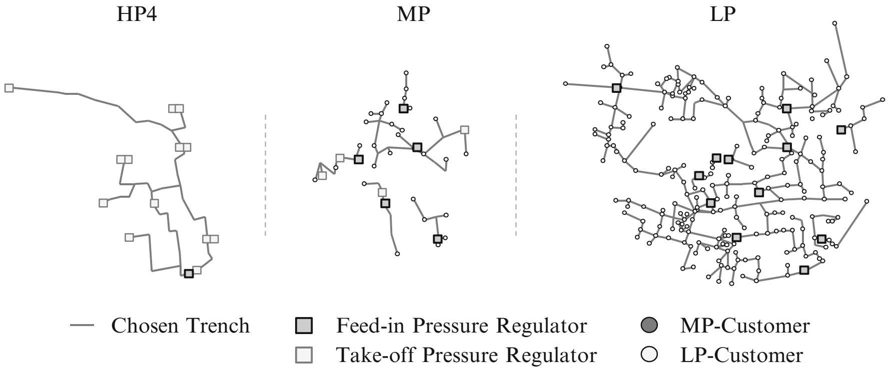

Fig. 10 Target network for a halved demand

The target network for the scenario halved demand exhibits less isolated networks in comparison to the target network for scenario of stagnating demand. This is due to a decreased need for pressure regulators. Furthermore, all target networks have significantly lower annual pipeline costs compared to the existing network. On the other hand, costs for pressure regulators are only slightly reduced. At the same time, the results demonstrate that the existing network is over dimensioned for the fulfillment of the supply task.

The following results are achieved:

- Positions of pressure regulators for a connection of two pressure stages are, due to the integrated optimization approach, optimally adjusted. This yields drastically reduced costs for pipelines with simultaneously maintaining a nearly equal number of pressure regulators.
- The northern pressure regulator feeding in from the 16 bar grid is not necessary for an economic connection of the considered network area.
- With exception of the medium-pressure stage in the scenario halved demand, the nodal pressures in all pressure stages max out the admissible bandwidth of pressures. Consequently, both target networks do not possess spare transfer capacities beyond the peak demand case.
- The medium-pressure stage in the scenario halved demand is used almost exclusively for the supply of network customers. Therefore, an investigation on altered pressure connections of medium and low-pressure customers seems sensible and has been included in the economic evaluation.

4.2.1 Evaluation of the Pressure Stage Comprehensive Optimization

Figure 11 illustrates the comparison of all executed evaluations and the existing network in terms of annual investment and operating costs.

The majority of annual network costs of the existing as well as of the target networks fall upon the distribution level of household customers. In contrast to the

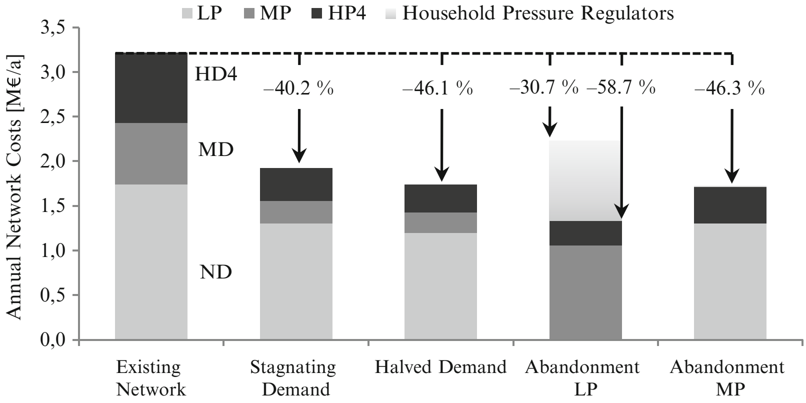

Fig. 11 Comparison of annual network costs

low-pressure stage that is mainly influenced by the given points of supply, advanced degrees of freedom exist in overlaying pressure stages leading to significant differences in their costs. The medium and high-pressure stage may take over different functionalities such as a wide-ranging transportation or localized supply of natural gas.

The theoretical cost cutting potential of all target networks are in-between 30,7% with an abandonment of the low-pressure stage and the assumption that each then required household pressure regulator will incur expenses of a further 500€ and 58,7% if the expenses for household pressure regulators are neglected. Because of the low number of medium-pressure customers, additional expenses for pressure regulators are neglectable concerning the target network with an abandonment of the medium-pressure stage. The optimal annual network costs in the scenario halved demand are reduced just slightly by approximately 6% compared with the scenario stagnating demand.

If the target networks for a reduced demand are analyzed it is obvious that the expenses for three pressure stages is almost equal to the expenses with regard to an abandonment of the medium-pressure stage. Nevertheless, three pressure stages offer major flexibilities for a deviation from the projected demand. An increase of the connection pressure for household customers to medium-pressure leads to considerably increased expenses due to the necessary household pressure regulators. As the results have shown, the proposed optimization procedure is capable of identifying inefficiencies in the existing network and recommends measures for correction.

4.3 Appraisal of the Optimization Procedure

Genetic algorithms offer a multitude of possibilities to parameterize, with each having an influence on the convergence characteristic to a greater or lesser extent

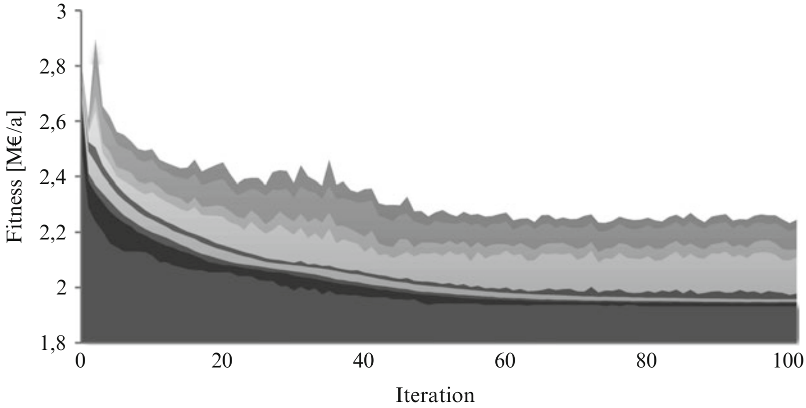

Fig. 12 Convergence characteristic

and consequently on the computing time. The iteration number and population size have a direct influence on the computing time as well as the quality of the achievable results. The iteration number specifies how many populations are generated and evaluated. With choosing a higher iteration number, in general, a greater part of the solution space will be explored. In order to analyze the influence of the iteration number in detail, an exemplary optimization for the identification of the cost-efficient network structure for the already described planning task is executed.

Figure 12 depicts the bandwidth of individuals' fitness values evolving with increasing iterations with a population of 1,000 individuals.

As shown in the diagram, it is apparent that due to the pure stochastic nature of the generation scheme at the beginning of the optimization and therefore high distance to the optimum, very fast advancements in the solution quality are achieved. After approximately 50 iterations, only minor improvements are necessary for the present case. The required number of iterations mainly depends on the number of degrees of freedom of each planning task. Application of the optimization procedure on different real supply tasks demonstrated that typically an iteration number in the same magnitude as the degrees of freedom provide good solutions even for huge problems. By using additional supporting local search algorithms, the iteration number can be decreased relative to comparable genetic algorithms without local search.

The population size specifies how many different individuals have to be created and evaluated during a single iteration of the genetic algorithm. An increasing population size leads to a greater diversity amongst the individuals and helps in preventing a premature convergence to local minima. For a detailed evaluation of this correlation, population sizes between 50 and 2,000 for 100 iterations are chosen. Figure 13 illustrates the resulting means and standard deviations of the annual network costs of the most cost-efficient network structures after 100 iterations for the specified population sizes. With an increasing population size,

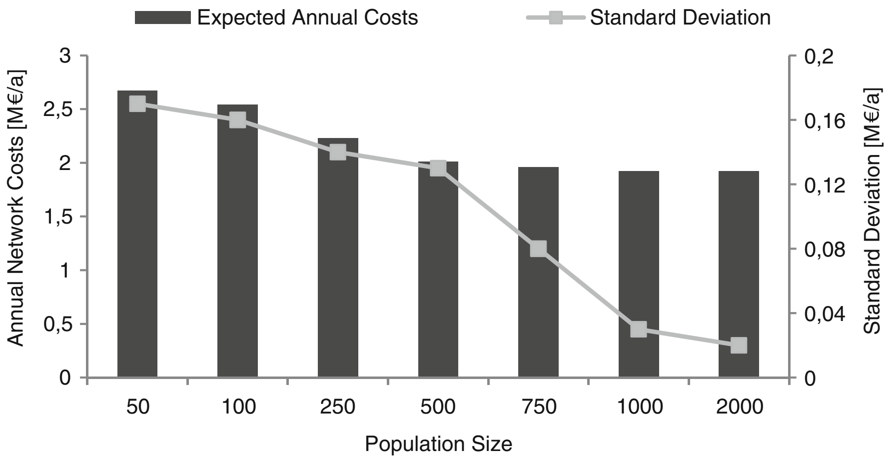

Fig. 13 Influence of population size on the solution quality

an initial drastic reduction of the annual network costs is achieved, but eventually converging to a nearly global optimum.

4.3.1 Parallel Optimization

A major issue of the demonstrated optimization procedure for practical planning tasks is the increasing computing time in consequence of size and complexity of the optimization problem. Hence, possibilities for accelerating the genetic algorithm with the use of parallel programming are analyzed. Genetic algorithms are particularly suitable for parallelization due to their design [18].

Creation, assessment, and selection of individuals during the genetic algorithm require the majority of all computing time. An adequate parallelization approach is the segmentation of each population's fitness assessment process. High computing time benefits are expected because of the time-consuming evaluation of the merit function, including a large number of flow calculations, for the planning of natural gas networks [17]. For the chosen parallelization approach, a primary process administrates the population and assigns further processes with the assessment of one individual each. Hence, the process flow remains unaltered in comparison to a sequential genetic algorithm, but high computational benefits can still be achieved (see also Fig. 14).

The parallel computation on multiple processors yields considerable computing time benefits in comparison to a sequential computation. However, the speedup – meaning the relative computing time benefit relating to the serial computation – does not ascent linearly, but converges with a rising number of processors. This results from higher coordination efforts towards the communication of all processes and their differing run-times. As the coordination effort is

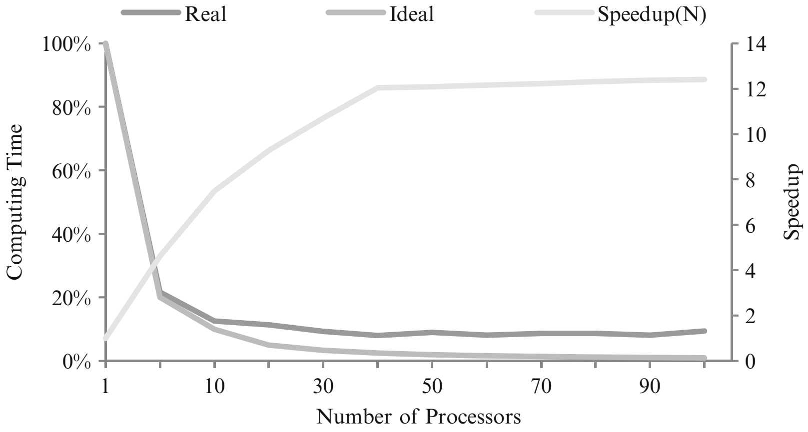

Fig. 14 Computing time benefits by parallelization

directly dependent on the population size, the number of utilized processors has to be adapted accordingly.

5 Conclusions

Due to the forthcoming regulation schemes throughout Europe, new challenges for natural gas network operators arise. In the past natural gas networks have been planned without the specification of long-term objectives and therefore often exhibit oversized dimensioning of the underlying network structure as well as the utilized operating facilities. This in consequence leads to corresponding higher network costs.

Computer-aided optimization procedures provide important assistance for the retrieval of potentials for future cost reductions. While the development and application of such optimization procedures for the planning of electricity networks is widely adopted and state-of-the-art, the planning of natural gas networks has previously been accomplished by predominantly experience-based example investigations and thus without the necessary objective future orientation.

The presented approach enables the long-term planning of natural gas networks under consideration of all relevant technical and furthermore company internal guidelines. It yields multiple alternatives as well as cost-efficient network structures with considerable low computational time.

With the aid of sensitivity analyses, possible effects of varying boundary conditions on structure and costs of cost-efficient networks may be quantified. These sensitivity analyses allow for a fundamental determination of optimal planning principles and are therefore able to explain minimal network costs for a given set of boundary conditions.

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