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Probabilistic modelling of security of supply in gas networks and evaluation of new infrastructure

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A B S T R A C T

The paper presents a probabilistic model to study security of supply in a gas network. The model is based on Monte-Carlo simulations with graph theory, and is implemented in the software tool ProGasNet. The software allows studying gas networks in various aspects including identification of weakest links and nodes, vulnerability analysis, bottleneck analysis, evaluation of new infrastructure etc. In this paper ProGasNet is applied to a benchmark network based on a real EU gas transmission network of several countries with the purpose of evaluating the security of supply effects of new infrastructure, either under construction, recently completed or under planning. The probabilistic model enables quantitative evaluations by comparing the reliability of gas supply in each consuming node of the network.

1. Introduction

A number of energy supply disruptions due to economic, political or technical reasons highlight the need to study energy infrastructure networks from the security of supply point of view. After supply disruption in January 2009 due to the Russia-Ukraine dispute, the European Commission reacted by issuing Regulation 994/2010 on security of gas supply [1], which requires the EU Member States to fulfil a number of requirements, including risk assessment, preventive action plan and emergency action plan, installation of cross border reverse flow capabilities, and supply and infrastructure standards, including the N-1 criterion. These and other measures proved to be important for the gas network resilience in the subsequent smaller supply disruptions (e.g. Libyan war in 2011, cold snap in early 2012). As energy security remains on the top priority list of the European Commission, several actions are planned including revision of the Regulation [1], funding construction of new infrastructure, adoption of energy security strategy and finally creation of Energy Union.

A gas transmission network can be understood as a critical infrastructure, an issue that has been recently addressed by various initiatives from research institutions and governments worldwide. The European Commission has taken the initiative to organise a network consisting of research and technology organisations within the European Union with interests and capabilities in critical infrastructure protection [2]. Interdependencies between critical infrastructures make the analysis complicated and challenging, but the topic has attracted a growing number of researchers [3–5]. For energy infrastructures the most interesting interdependence is between gas and electricity networks, as discussed in the benchmark study presented in [6].

Reliability, risk and security of supply analyses of energy infrastructure networks present a number of challenges as many network analysis algorithms (optimal distribution of capacity, rerouting of flows etc.) originally developed for telecommunication networks are not directly applicable to gas transmission networks. Detailed analysis of large networked systems is being addressed by a growing number of researchers. From the computational point of view, large network analysis is very demanding; however increased power of modern computers makes complex studies feasible.

A detailed review of the state of the art in the field of network reliability analysis is reported in [7] in which computational complexity, exact algorithms, analytic bounds and Monte Carlo (MC) methods are presented. Availability evaluation of gas transportation is analysed in [8]. Reliability and vulnerability analysis of networks with application to power system is shown in [9]. Reliability of multi-state flow networks has been recently analysed in [10].

The paper [11] focuses on developing a simulation model for the analysis of transmission pipeline network with detailed characteristics of compressor stations. The simulation model is used to create a system that simulates the network with different configurations to get pressure and flow parameters.

The authors analyse gas networks with inclined pipes [12]. The resulting set of fluid flow governing equations is highly non-linear. The authors introduce a novel linear-pressure analogue method,

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which is compared with the Newton–Raphson nodal method. The proposed solution methodology retains most advantages of the Newton-nodal method while removing the need for initial guesses and eliminating the need for expensive Jacobian formulations and associated derivative calculations.

Cost-related objectives for gas transmission pipelines network design and planning are analysed in [13]. In this task, the type, location, and installation schedule of major physical components of a network including pipelines and compressor stations are assumed. The authors propose an integrated non-linear optimisation model for this problem.

Taking as examples the power and gas transmission systems in Harris County, Texas, USA, optimum interface designs under random and hurricane hazards are discussed in [14]. To model the gas pipeline operation, the maximum flow algorithm is used. The paper goes beyond previous studies focused only on connectivity.

The book [15] addresses a gap in current network research by developing the theory, algorithms and applications related to repairable flow networks and networks with disturbed flows. According to the author, the potential application of repairable flow networks reaches across many large and complex systems, including active power networks, telecommunication networks, oil and gas production networks, transportation networks, water supply networks, emergency evacuation networks, and supply networks.

This paper presents a probabilistic model to study security of supply in a gas network. The model is based on Monte-Carlo simulations with graph theory, and is implemented in the software tool ProGasNet. This paper also presents a development process and application study of the ProGasNet software tool to the European gas transmission network for the analysis of security of supply. The ProGasNet software is currently under development. The purpose is to develop a mathematical model of a flow network that could be used for many different purposes including reliability of supply at each consuming node, vulnerability analysis, bottleneck analysis, time-dependent gas storage analysis [29] or evaluation of new infrastructure, either real or virtual. The JRC report [16] presents the validation results of two approaches implemented for relatively simple benchmark network systems: Monte-Carlo (MC) reliability simulation and fault tree (FT) analysis, see also [30]. The results of test cases indicate the potential of both methods for network reliability analysis and the need for further research [17].

The purpose of the paper is to

- Develop a Monte-Carlo simulation algorithm for stochastic network model with a priority supply pattern (Section 2).
- To introduce a probabilistic approach for modelling of key gas transmission network components (Section 3).
- To define a real-world EU gas transmission network (Section 4) under selected disruption case studies (Section 5).
- And finally, to present results of numerical experiments in terms of security of supply at each consuming node, which can be used also for vulnerability ranking of disruption case studies (Section 6.1. Quantification of gas supply), redundancy analysis of gas sources (Section 6.2. Quantification of redundancy of gas sources), and evaluation of new infrastructure, either real or virtual (Section 6.3. Quantification of probabilistic effects of a new gas infrastructure).

The presented Monte-Carlo simulation technique for stochastic network model with a priority supply pattern represents a general approach, which can be used for security of supply modelling of various transportation networks (crude oil, water).

2. Monte-Carlo simulation technique for stochastic network model

2.1. Maximum flow algorithm

An important characteristic of a network is its capacity to carry flow. What, given capacities on the arcs, is the maximum flow that can be sent between any two nodes? The resolution of this so called Maximum Flow (MF) problem describes the optimal use of line capacities and establishes a reference point against which to compare other ways of using the network [18].

The mathematical description of the MF problem is a standard problem in graph theory [19]. The aim of the Maximum flow algorithm is to maximise the value of flow passing from the source node s to the sink node t given the two following constrains:

- Conservation of flows: the sum of the flows entering a node must equal the sum of the flows exiting a node, except for the source node and the sink node.
- Capacity: the flow of an edge is non-negative and cannot exceed its capacity.

The Maximum flow problem can be solved by various approaches, for example by linear programming or with the Ford–Fulkerson algorithm, which finds directed paths from the source node to the sink node with available capacity on edges in this path. In the algorithm, this path-searching process is repeated until no additional flow can be added to this directed path.

The case of multiple sources and sinks, involving several source nodes $s_1, s_2,\dots, s_k$ and several sink nodes $t_1, t_2,\dots, t_r$ and where the flow from any source can be sent to any sink, is known as Multiple Sources and Sinks problem, and can be straightforwardly converted into a one-source and one-sink problem [20]: Let us introduce a supersource s (virtual source node) with edges (of unlimited capacity) directed from this supersourse s to all source nodes $s_1, s_2,\dots, s_k$. Furthermore, let us introduce a supersink t (virtual sink node) with edges (also of unlimited capacity) directed from all sink nodes $t_1, t_2,\dots, t_r$ to the supersink t. Then the problem of maximising the total value of the flow from all sources is then the same as that of maximising the value of the flow from s to t.

2.2. Modelling of stochastic networks

In this subsection we present a Monte-Carlo simulation based algorithm for stochastic flow networks with priority supply patterns based on the distance from the source node: In order to concurrently model both reliability and capacity constraints of the gas transmission network, we use a stochastic network representation, where each node and edge of the flow network can randomly fail, according to a given probabilistic model of the network component. These component failures in the network are modelled using the Monte-Carlo simulation technique.

The algorithm has these inputs:

- The capacity matrix C that provides information about capacity constraints of the network elements including input source nodes, demand nodes and information about connected pipeline capacities (for example per day).
- The length matrix L that provides information about length of the edges between nodes (expressed for example in km). As the used geographical length is a symmetric relation, in order to save the computer memory, only an upper (or lower) triangular part of matrix L is necessary to store.

The output of the algorithm is an optimal flow matrix F satisfying for each Monte-Carlo step the Maximum flow algorithm