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LNG Port Interconnection with the Natural Gas Distribution Network in Finland

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In northern countries, such as Finland, the heat and electricity consumption are strongly affected by seasonal conditions. Thus in the cold and dark winter season the consumption is higher than during the other periods of the year. This leads to a strong seasonal component in the demand of natural gas, which is mainly used by heat and power plants. The current study focuses on the natural gas pipeline in Finland and considers options of extending the pipeline to new cities and/or connecting it with future LNG terminals. The simulation of the gas pipeline is based on information about the present layout, outdoor temperatures and a rough estimate of the distribution of the consumption in the nodes. For a given pipe network and given demands, it provides information about the pressures, flow rates and compressor duties. Furthermore, using the model within an optimisation framework, the feasibility of extending the pipeline to new regions and/or connecting LNG sites with regasification facilities to the network can be studied. The task is formulated as an MINLP optimisation problem, where, e.g., the choice of suitable sites for new LNG terminals in Finland can be evaluated, considering the future development of the whole natural gas distribution network and the gas demand around it. This is a key issue to decrease the dependence on the present energy supply paths and to increase the capacity without pipeline investments in remote regions.

1. Introduction

Finland currently uses Russian natural gas delivered to Imatra through a double pipeline from Russian Svetogorsk. Gas is further distributed to the southern parts of the country to the customers that are mostly heat producers, power plants or large industries. In 2013 the natural gas consumption was about 33 TWh (Gasum, 2014). Recently, politicians in Finland and Estonia agreed upon a need for a new pipeline connection for liquefied natural gas. This decision would include also the construction of a new LNG terminal (YLE uutiset, 2014). The pipeline, expected to be built at the latest by 2019, will make it possible to increase the natural gas volume, allowing for new customers. An early study on optimisation of natural gas pipeline distribution using dynamic programming was presented by Wong and Larsson (1968). Dynamic programming was also used by Borraz-Sanchéz and Haugland (2011). De Wolf and Smeers (2000) introduced an extended simplex algorithm to solve this problem, while Cobos-Zaletta and Ríos-Mercado (2002) presented an MINLP formulation with the aim to minimise the fuel consumption in the compressor stations in a pipeline. Meta-heuristic approaches, such as the ant colony optimisation presented by Chebouba et al. (2009), have also been used to tackle this problem. The present study reflects the current public interest to decrease the dependence on the recent energy supply paths. Accordingly, the proposed MINLP model allows for additional supply and demand points and also the possibility to change mass flow directions in pipeline sections can be noted. The results provide information about the feasibility to expand the Finnish natural gas pipeline and operate it in alternative ways under fluctuating demand and supply scenarios.

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2. Mathematical model

Data on the current natural gas pipeline network in Finland, which are available on the webpages by the Finnish gas company Gasum Oy (2014a, 2014b), are used as a starting point. At present, there are three compression stations that maintain an adequate pressure level in the pipeline. Places that serve as major demand or potential supply points, as well as points before and after compressors were considered in the model, yielding 26 nodes in the network. In these nodes, the mass flow rate and pressure of the natural gas are calculated. In demand nodes where natural gas is not available (e.g., if the pipeline does not extend to the site or if the price of natural gas is not competitive) the local fuel demand is taken to be satisfied by an alternative fuel. In order to roughly describe the variations during the year, three time periods characterised by different outdoor temperature and, thus, different fuel demand were used. In order to reduce the number of decision variables, the binary variables expressing existence of a pipe, $y_{i,j,r}$, can be only selected in the case that the route between nodes i and j (with pipe diameter size r) is preselected as a possible connection $N_{i,j}$

$$y_{i,j,r} \leq N_{i,j} \ \forall i \in I \ \forall j \in J \ \forall r \in R \tag{1}$$

To include the existing natural gas pipeline in the model and reduce the number of binary variables, we impose the condition

$$y_{i,j,r} = 1 \quad \forall\, i \in I_{\text{exist}} \ \forall j \in J_{\text{exist}} \ \forall r \in R_{\text{exist}} \tag{2}$$

The length $l_{i,j}$ of the permitted pipes that can built should not be longer than a maximum length $l_{\max,}$, i.e.,

$$y_{i,j,r} \cdot l_{ij} \leq l_{\max} \quad \forall i \in I\,,\ \forall j \in J\,, \forall r \in R \tag{3}$$

A constraint limiting the number of parallel pipes of type r to maximally k is also imposed

$$\sum_r y_{i,j,r} \leq k \quad \forall i \in I\,, \forall j \in J\,, \forall r \in R \tag{4}$$

The mass flow between any two nodes i and j is equal to the sum of the mass flows through all pipes from i to j in time period e

$$m_{i,j,e} = \sum_r m_{i,j,r,e} \quad \forall\, i \ \forall\, j \ \ i \neq j\,, \forall r \in R \tag{5}$$

To allow for a mass flow in both directions, two new binary variables $a_{i,j,r}$ and $b_{i,j,r}$ are introduced. The direction of the flow is restricted, so that only one direction in a pipe is allowed a time

$$a_{i,j,r} + b_{i,j,r} = y_{i,j,r} \quad \forall\, i\,, \forall\, j\,, i \neq j\,, \forall r \in \mathrm{R} \tag{6}$$

Furthermore, there is no mass flow between two nodes if no flow direction is appointed

$$m_{i,j,r,e} \leq M \cdot \left(a_{i,j,r} + b_{i,j,r}\right) \quad \forall\, i\,, \forall\, j\ i \neq j,\ \forall r \tag{7}$$

The mass flows of gas, $m_{i,j}$, between the nodes is calculated from a mass balance equation

$$\sum_j m_{i,j,e} + O_{i,e} = \sum_j m_{j,i,e} + S_{i,e} \quad \forall\, i\ , \forall\, j\ \ i \neq j \tag{8}$$

where O_i and S_i are the outflow and supply, respectively, at node i. The supply to the node is limited by the maximum capacity of the node to supply gas to the network

$$S_{i,e} \leq S_{\max,i} \quad \forall\, i \in I\,, \forall\, e \in E \tag{9}$$

To secure that the whole energy demand, D, at a node is covered either by the supply of natural gas or by an alternative fuel of a type ft, or their combination, an energy balance is used

$$O_{i,e} \cdot H_{\text{NG}} + \sum_{ft} m_{i,ft,e} \cdot H_{ft} \geq D_{i,e} \quad \forall\, i \in I\,, \forall\, e \in E\,, \forall\, ft \in FT \tag{10}$$

where H is the higher heating value of the fuel. The alternative fuel of type ft is supplied to a node i in period e only if the (binary variable) $f_{i,ft} = 1$

$$m_{i,ft,e} \leq M \cdot f_{\text{i,ft}} \quad \forall\, i \in I\,, \forall\, e \in E\,, \forall\, ft \in FT \tag{11}$$

where M is a large positive constant. To deliver the desired amount of natural gas to each node we need an adequate pressure. It is assumed that the pressure in the Russian Svetogorsk, before coming to Finland, is 35 bar and the cost for this compression is not included. Furthermore, the pressure, $p_{i,e}$ is bounded at each node by minimum and maximum values, so the pressure is kept in the pressure range permitted for the pipes and for compressor suction and discharge respectively.

$$p_{\min} \le p_{i,e} \le p_{\max} \quad \forall i,\ \forall e \tag{12}$$

Furthermore, the pressure levels required at (some) nodes have to be attained. For example in nodes, where the natural gas is used in gas turbines, the pressure should be higher than some minimum required pressure:

$$p_{i,e} \ge p_{\mathrm{dem},i} \quad \forall i\ ,\ \forall e \tag{13}$$

The pressure at each node can be calculated with the help of the pressure drop equation for compressible flow, which has to be solved considering pipe diameter d_r, gas density ρ and the friction factor ζ. For the sake of simplicity the friction factor assumed to be constant. The pressure loss is not calculated between compressor suction and discharge, where a pressure increase is expected. In writing the model equations, the flow direction in the pipes should be considered. The nonlinear constraints of Eq.(14a,b) are active if the gas flows from i to j ($p_i > p_j$), while Eq.(14c,d) apply if the flow goes in the opposite direction ($p_j > p_i$)

$$p_{j,e}^2 \le p_{i,e}^2 - p_{i,e} \cdot \zeta \cdot \frac{l_{i,j}}{d_r} \cdot \rho_{i,e} \cdot \left(\frac{m_{i,j,r,e}}{\frac{1}{4} \rho_{i,e} \cdot \pi \cdot d_r^2} \right)^2 + \left(1 - a_{i,j,r}\right) \cdot M \tag{14a}$$

$$p_{j,e}^2 \le p_{i,e}^2 - p_{i,e} \cdot \zeta \cdot \frac{l_{i,j}}{d_r} \cdot \rho_{i,e} \cdot \left(\frac{m_{i,j,r,e}}{\frac{1}{4} \rho_{i,e} \cdot \pi \cdot d_r^2} \right)^2 - \left(1 - a_{i,j,r}\right) \cdot M \tag{14b}$$

$$p_{i,e}^2 \le p_{j,e}^2 - p_{j,e} \cdot \zeta \cdot \frac{l_{j,i}}{d_r} \cdot \rho_{j,e} \cdot \left(\frac{m_{j,i,r,e}}{\frac{1}{4} \rho_{j,e} \cdot \pi \cdot d_r^2} \right)^2 + \left(1 - b_{i,j,r}\right) \cdot M \tag{14c}$$

$$p_{i,e}^2 \le p_{j,e}^2 - p_{j,e} \cdot \zeta \cdot \frac{l_{j,i}}{d_r} \cdot \rho_{j,e} \cdot \left(\frac{m_{j,i,r,e}}{\frac{1}{4} \rho_{j,e} \cdot \pi \cdot d_r^2} \right)^2 - \left(1 - b_{i,j,r}\right) \cdot M \tag{14d}$$

$$\forall j \in J_{\mathrm{pass}}, J_{\mathrm{suct}} = J_{\mathrm{rec}}\ , \forall i \in I_{\mathrm{pass}}, I_{\mathrm{disch}} = I_{\mathrm{send}}\ , \qquad \forall r\ , i_{\mathrm{send}} \ne j_{\mathrm{rec}} \mid l_{i_{\mathrm{send}}, j_{\mathrm{rec}}} > 0$$

The densities are estimated by the ideal gas law

$$\rho_{i,e} = \frac{p_{i,e} \cdot M_{\mathrm{NG}}}{R_g \cdot T_{\mathrm{amb},e}} \quad \forall i \in I\ ; \qquad \rho_{j,e} = \frac{p_{j,e} \cdot M_{\mathrm{NG}}}{R_g \cdot T_{\mathrm{amb},e}} \quad \forall j \in J \tag{15}$$

where R_g is the gas constant, M_{NG} the molar mass of natural gas and $T_{amb,e}$ the ambient temperature during period e, assuming that the gas in the pipe reaches the outside temperature.

The information about the pressure at each node yields the required compression pressure ratio between the discharge and suction pressure, which allows for estimating the cost of compression. It is assumed that the gas is cooled down after each compression step to the ambient temperature. The temperature after an ideal compression stage, $\tilde{T}$, is first solved, again accounting for the possibility of a reverse flow in the pipe

$$\tilde{T}_{i,j,e} \ge T_{\mathrm{amb},e} \cdot \left(\frac{p_{j,e}}{p_{i,e}} \right)^{\frac{R_g}{M_{\mathrm{NG}} \cdot c_p}} - \left(1 - a_{i,j,r}\right) \cdot M \quad \forall i \in I_{\mathrm{suct}}\ , \forall j \in J_{\mathrm{disch}}\ , \forall e \in E \mid l_{i_{\mathrm{suct}}, j_{\mathrm{disch}}} \le 0 \tag{16a}$$

$$\tilde{T}_{i,j,e} \ge T_{\mathrm{amb},e} \cdot \left(\frac{p_{i,e}}{p_{j,e}} \right)^{\frac{R_g}{M_{\mathrm{NG}} \cdot c_p}} - \left(1 - b_{i,j,r}\right) \cdot M \quad \forall i \in I_{\mathrm{suct}}\ , \forall j \in J_{\mathrm{disch}}\ , \forall e \in E \mid l_{i_{\mathrm{suct}}, j_{\mathrm{disch}}} \le 0 \tag{16b}$$

The real temperature after the compression is then obtained considering the efficiency factor, η_{ad}, of the compressor

$$T_{i,j,e} = T_{\mathrm{amb},e} + \frac{\tilde{T}_{i,j,e} - T_{\mathrm{amb},e}}{\eta_{\mathrm{ad}}} \quad \forall i \in I_{\mathrm{suct}}\ , \forall j \in J_{\mathrm{disch}}\ , \forall e \in E \mid l_{i_{\mathrm{suct}}, j_{\mathrm{disch}}} \le 0 \tag{17}$$

The cost of compression in a given period e is now

$$C_{i,e} = t_e \cdot C_{\mathrm{pow}} \cdot c_p \cdot m_{i,j,e} \cdot \left(T_{i,j,e} - T_{\mathrm{amb},e}\right) \quad \forall i \in I_{\mathrm{suct}}\ , \forall j \in J_{\mathrm{disch}}\ , \forall e \in E \mid l_{i_{\mathrm{suct}}, j_{\mathrm{disch}}} \le 0 \tag{18}$$

where C_{pow} is the cost of power and t_e is the time of operation.

For the compression of the natural gas supplied to the network from a source along the pipeline, e.g., the injection of regasified natural gas, it is assumed that the gas is compressed from atmospheric pressure to the required pressure over multiple N_{comp} stages. The ideal and subsequent real temperatures are

$$\tilde{T}_{i,e} = T_{\mathrm{amb},e} \cdot \left(\frac{p_{i,e}}{1\ \mathrm{bar}} \right)^{\frac{R_g}{N_{\mathrm{comp}} M_{\mathrm{NG}} \cdot c_p}}\ ; \qquad T_{i,e} = T_{\mathrm{amb},e} + \frac{\tilde{T}_{i,e} - T_{\mathrm{amb},e}}{\eta_{\mathrm{ad}}} \quad \forall i \in I_{\mathrm{supply}}\ , \forall e \in E \tag{19}$$

The cost of compression at a supply node in a given period e is

$$C_{i,e} = C_{\mathrm{pow}} \cdot t_e \cdot c_p \cdot N_{\mathrm{comp}} \cdot S_{i,e} \cdot \left(T_{i,e} - T_{\mathrm{amb},e}\right) \quad \forall i \in I_{\mathrm{supply}}\ , \forall e \in E \tag{20}$$

Another term is the fuel cost, including the cost of natural gas supplied from Russia, cost of natural gas injected into the pipeline in Finland, and the cost of the alternative fuel needed to cover the demand not satisfied by natural gas.

In addition to this, the investment cost of new pipeline connections, discounted with the interest rate of u over K years, was considered

$$C_{\text{pipe}} = \frac{\sum_i \sum_j \sum_r l_{i,j} C_r \, y_{i,j,r}}{(1+u)^K} \qquad \forall i \in I_{\text{new}}, \forall j \in J_{\text{new}},\ r \in R, \forall e \in E \tag{21}$$

where the unit price of pipe of diameter size *r* is C_r.

The objective to be minimised is now

$$\min C_{\text{tot}} = C_{\text{pipe}} + \sum_e (C_{\text{fuel},e} + \sum_i C_{i,e}) \tag{22}$$

This MINLP problem was solved with the AIMMS software suitable to solve MINLP problems, similarly to general purpose optimization package GAMS described by Lam et al. (2011). AIMMS employs the outer approximation algorithm including the CPLEX 12.6 solver for MIP sub-problem and MINOS solver for the NLP sub-problem. Time required is about 3,800 s.

3. Case study results

The mathematical model was used to optimise the Finnish natural gas pipeline network. The year was divided into three periods: winter (121 d, average temperature 272 K), autumn + spring (122 d, 288.5 K) and summer (122 d, 290.5 K).The energy demand estimates during the three periods were based on the information about the daily consumptions averages in 2009 - 2011 supplied by Gasum Oy. The demand in each node is a result of a proportional distribution of the total consumption, which is approximated with a linear function of the ambient temperature. The values u=0.05 and K=30 y. The results of the optimisation of the MINLP model provide information about the optimal compression of the natural gas, whether or not pipelines should be built to new consumers and the position of LNG terminal(s) connected to the pipeline. In order to illustrate the features of the model, a case is presented where the influence of the regasified LNG price is studied. The price of the Russian natural gas is assumed to be 0.11 €/kg. The price of the alternative fuel delivered to each node in the case the demand cannot be covered by natural gas in the network was assumed to be 0.25 €/kg for heating oil and 0.24 €/kg for coal, while the power needed for compression was priced 67 €/MWh.

The model was tested with LNG prices of 0.15 €/kg and 0.25 €/kg to illustrate the sensitivity of the results. With reference to Figure 1, three possible places for LNG injection were considered: Tolkkinen (node 18), Inkoo (node 25) and Turku Pansio (node 26). The maximum possible injection into the network at these nodes was set to 20 kg/s of regasified LNG. Information about the pipe diameter is given in Table 1 and the demand in the nodes in Table 2. In the case of the lower price of LNG, terminals in Tolkkinen, Turku and Inkoo are connected to the pipeline. Tolkkinen is also connected to the compressor in Mäntsälä, as can be seen in Figure 1. However, the additional supply of regasified NG is still not able to cover the high energy demand in Period 1, so alternative fuel (heating oil) has to be supplied to nodes 20, 21 and 22. The objective function value for this case is 43 M€.

Increasing the price of LNG to 0.25 €/kg does not have a significant influence on the structure of the pipeline network: Tolkkinen, Turku and Inkoo are still connected to the pipeline by a pipe of 0.5 m diameter. Inkoo, Tolkkinen and Turku supply the maximum of 20 kg/s in Period 1 and Period 2 to the NG network, Turku supplies a small amount in Period 3 to the local customers. But now is more favourable to supply higher amount of alternative fuel to nodes 20, 21 and 22. The optimum objective function value is now 47 M€.

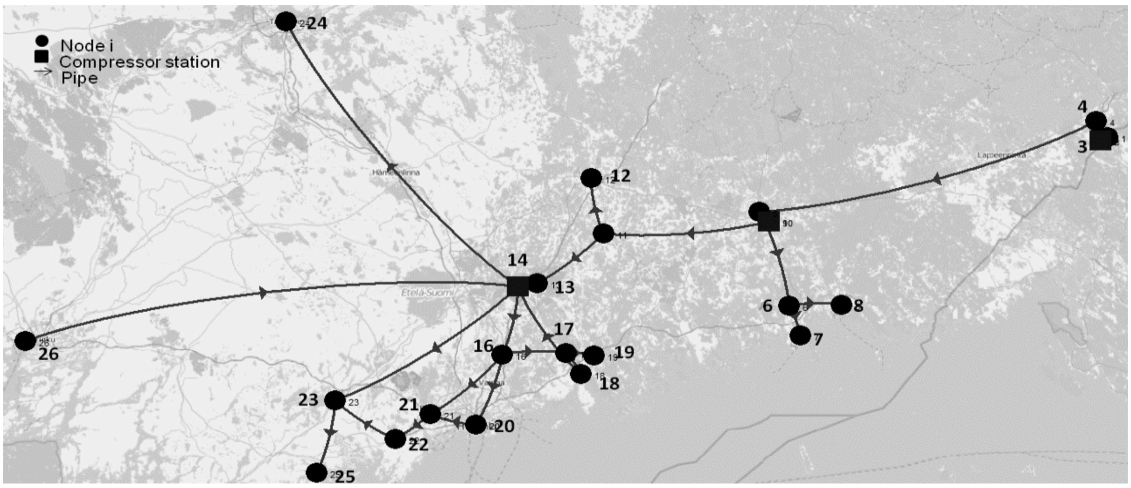

Figure 1: Pipeline network with LNG price 0.25 €/kg and fuel price 0.6 €/kg oil, 0.6 €/coal (background map source: © OpenStreetMap contributors)

However, the supply changes in the case where the price of alternative fuel is increased to 0.6 €/kg for both fuels while the LNG price is kept on the higher level of 0.25 €/kg. It is now favourable to supply natural gas instead of the costly alternative fuel. Tolkkinen and Inkoo are connected with pipes (*d* = 0.5 m), and Tolkkinen is connected to the compressor in Mäntsälä (node 14). The terminal in Turku is connected and supplies in Periods 1 and 2 the maximum of 20 kg/s, from which part is supplied to the other nodes in the network through a pipe (*d* = 0.5 m). The amount of the alternative fuel that has to be delivered only to Kerava(16), Porvoo (node 19) and Helsinki (20) in Periods 1 and 2 decreases to 20 kg/s. The objective function value is now 89 M€.

Table 1: Pipeline size type r, diameter and cost per meter

r	Diameter [m]	Cost [€/m]
I	0.5	571.4
II	0.5	571.4
III	0.6	685.7
IV	0.6	685.7
V	0.7	800
VI	0.7	800
VII	0.8	914.3
VIII	0.8	914.3

Table 2: Energy demand in the nodes

Node i	City Name	Period 1 [MW]	Period 2 [MW]	Period 3 [MW]
1	Svetogorsk	0.0	0.0	0.0
2	Imatra Suction	0.0	0.0	0.0
3	Imatra Discharge	0.0	0.0	0.0
4	Imatra	358.9	293.4	102.8
5	Kouvola	358.9	293.4	102.8
6	Kotka-Hamina intersect.	0.0	0.0	0.0
7	Kotka	358.9	293.4	102.8
8	Hamina	358.9	293.4	102.8
9	Kouvola Suction	0.0	0.0	0.0
10	Kouvola Discharge	0.0	0.0	0.0
11	Orimattila	179.4	110.0	51.4
12	Lahti	358.9	293.4	102.8
13	Mäntsälä	179.4	146.7	51.4
14	Mäntsälä Suction	0.0	0.0	0.0
15	Mäntsälä Discharge	0.0	0.0	0.0
16	Kerava	327.8	219.3	85.2
17	Porvoo-Tolkkinen intersect.	0.0	0.0	0.0
18	Tolkkinen LNG	0.0	0.0	0.0
19	Porvoo	1,311.1	877.1	340.8
20	Helsinki	3,933.2	2,631.2	1,022.4
21	Espoo	1,966.6	1,315.6	511.2
22	Kirkkonummi	327.8	219.3	85.2
23	Lohja	717.8	586.9	205.6
24	Tampere	2,551.0	1,696.7	574.4
25	Inkoo LNG Terminal	0.0	0.0	0.0
26	Turku Pansio	439.1	352.6	125.8

4. Conclusions

A model of the Finnish natural gas pipeline has been developed and optimized by MINLP. The cost related to the natural gas distribution is minimized, considering new pipeline extensions, variations of the demand and new sources in the network. The model covers the nonlinearities related to the pressure drop in the pipe and compression temperature. The results of the case study show that under certain fuel price settings it is beneficial to extend the network to LNG terminals and to inject regasified LNG into it: Terminals in Turku and Inkoo may supply natural gas to the network if the demand and the price of alternatives fuels are high. For such cases, the flow in parts of the network may be reversed. This situation could also arise if these are restrictions in the natural gas supply from the existing main pipeline. It is possible to extend the network model to studying problems of larger size and to more thoroughly analyse the sensitivity of the distribution to changes in the future price and availability of natural gas.

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