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Optimization of gas loss and CO2 emission during disruption on a natural gas network

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Abstract**—**It was predicted in 2012 that the global demand for energy over a period of 28years (2012-2040) will increase by 48%. This will raise the total global energy consumption from 549 quadrillion British thermal units (Btu) in 2012 to 815 quadrillion Btu by 2040. As a strategic player in the energy mix, a reduction in the emission of CO_2 to the environment from the natural gas network will result in environmental and cost savings. Although several researchers have alluded various opportunities associated with renewable energy feedstocks and have examined various strategies for optimized energy supply, the possible structural adjustments to gas infrastructure to align with future policies on climate will bring about a sustainable strategy for future economic growth. The motive of work is to investigate the problem associated with exogenous interruptions to a gas network resulting in loss of gas to the environment. The research also proposed a mitigation strategy for gas loss and emission reduction. To achieve this, a mixed integer linear programming (MILP) optimization model is developed that establishes a strategy for loss reduction in gas supply chain. Data from real case study have been accessed which enhances the applicability of the proposed model which was run on the GAMS 26.14 software using the CPLEX solver 12 in an intel ® core ™ i7 and a zero-optimality gap within reasonable solution time. The result obtained revealed a reduction from 555.1million kg of CO_2 to 8.06 million kg of CO_2 after optimization while still delivering on projected throughput. The proposed methodology can help natural gas operators to optimize performance considering disruption time estimation.

Keywords— (Natural gas supply chain, Emission, Mitigation, Relief pipeline, Optimization, Mixed integer linear programming, Loss reduction)

I. INTRODUCTION

Natural gas has been identified as a strategic player in the energy mix and the bridging gap between conventional and renewable energy sources in this era of alternative sources of energy. Like other intricate and long supply chains, the natural gas supply chain is vulnerable to both internal and external disruptions which result in loss through emissions, prolonged shutdowns, and supply shortages. Two major identifiable causes of shutdowns on the network nodes include planned and unplanned disruptions caused by both endogenous and exogenous factors.

Disruptions to supply chain are usually low in occurrence, yet, the economic and social impacts are significant [1–3] as much as the environmental impact. This means that if any form of disruption occurs, an associated cost is incurred. For instance, a shrinkage cost can be calculated from the difference between inflow and outflow of product from the supplier to the consumer nodes. Preventing or reducing the disruption period and impact will help reduce the cost burden. In some countries with huge gas deposits, there is the concern of minimal infrastructure and yet social unrest have constantly caused prolonged shutdowns resulting in huge emissions and therefore, environmental cost. Due to its high-cost impact, there are three identified reasons to promote a robust supply chain for natural gas. First is the recent studies by researchers to repurpose the natural gas supply chain for hydrogen which is a likely additional pathway from fossil to renewables [4]. The possible structural changes of gas infrastructure to align with future policies on climate is the second reason. The third reason is the recent increase in the use of carbon capture and storage (CCS) technologies. A competitive gas supply chain should be robust not only for flow flexibility and reduction in gas shortage supply but also for loss reduction.

II. LITERATURE REVIEW

Natural gas supply chain is a composition of complex infrastructures interconnected by both transmission and distribution pipelines. For the transportation of natural gas from the supply to the demand nodes, the pipeline and compressor station are very relevant components. Therefore, several studies have been carried out on the optimization of natural gas transportation mainly on the gas pipeline [5–7] and other physical entities like the compressor [8,9]. For instance, [7] presented a review of natural gas transportation optimization problems using a stochastic approach where a steady-state model based on time were analyzed. The idea was to fill the gap associated with seasonal demand. The researchers tried to solve the problem from an operational perspective using non-linear programming transient models. In [8], a numerical model for natural gas transportation was developed to study the pipeline in an unsteady-state to capture the boundary conditions resulting from demand variation and rupture of the pipeline. However, [10] synchronized the different levels of the supply chain as a portfolio of activities by providing insights to the complexities associated with planning for natural transportation optimization.

On the other hand, [11] used a deterministic model in a strategic decision level where the natural gas network design is considered an investment problem. Existing infrastructure were considered for potential expansion from a system perspective. By formulating a deterministic mixed-integer linear program, existing natural gas infrastructure model was extended by adding pressure flow relationships. To address the possible demand and price variation, various operational time periods were introduced to assess operational profitability.

Mixed-integer nonlinear programming for the gas pipeline extension was presented in [12] for multiple demand scenarios while [13] suggested two convex and non-convex formulations to minimize the energy consumption along the transmission in an existing pipeline due to pressure drop. A model for controlling the flow of gas in an existing pipeline network was proposed in [14] where the problem of selecting appropriate compressors, valves and pipes was discussed. For [15], the optimization for the transmission network was to achieve expansion for medium to long term operational and strategic decision planning.

Furthermore, [16] developed a simulation model where critical performance parameters of the compressors such as speed, flow rate, suction pressure, discharge pressures and suction temperature are incorporated in the equation. The focus of the work was to increase capacity flow in the transmission network and reduce power consumption, which has a direct impact on the performance of the system. Their work was extended in [17] where the optimal solution of steady-state transportation optimization problems was addressed on two levels: an optimization of compressor station which is the local level, and optimization of pipeline network as a whole which is the global level. The solution was based on simulation and evolution strategy algorithm bringing about an integration of deterministic and stochastic elements to form the modified algorithm of evolution strategies by assigning value of fitness function and verifying feasibility.

Sukharev and Kosova [18] considered the problem associated with technical parameters identification in an unsteady-state using the nonlinear model. The objective was to improve qualitatively the operative control for gas transmission systems using a specialized software suite. An earlier work by [19] puts it that the industry acceptance of modeling software have encouraged the optimization application to both existing and new pipelines. This brings about robust configurations of pipeline for optimal operating strategies.

III. PROBLEM DEFINITION

This work addresses the strategic and tactical planning problem of a natural gas network using a proposed mitigation strategy to reduce loss during the shutdown of a plant node. In this supply chain, the main valves from the pipeline to the compressor(s) is closed when there is a shutdown in the compressor station. During the shutdown of the compressor, the remnant of high-pressured gas within the compressor and the isolation valves is emitted into the environment. The loss and downtime affect supply to consumers that result in demand and supply disequilibrium.

On the other hand, natural gas predominantly methane (CH4) after processing. To get the correlation between the natural gas and the amount of CO_2 emanating from the gas, Kurz et al.[20] presented that, methane is usually measured about 20 times potent greenhouse gas as CO_2. Hence, 1Kg of methane correspond to 20kg of CO_2.

Therefore, a gas infrastructure transportation solution is proposed in the event of emergency shutdown resulting in emission where the receiving facilities are also shutdown especially in the absence of dedicated storage. The optimization for resilience establishes the subject of this study. Particularly, the loss from shutdown of a gas network is addressed. The supply chain problem is formulated as a MILP problem and a mitigation strategy for disruption effect on the supply chain. Additional considerations for the problem under study follow. Firstly, the peculiarity of the problem is that the case study under review do not have dedicated storage. Secondly, the case study involves multiple sources, single processing plants, four compressor stations, two main pipelines, one relief pipeline, and single consumer. It is assumed that the flow is originally in a steady-state and an isothermal flow where temperature remains same along the nodes such that there is no significant variation in temperature and pressure**.**

IV. MODEL FORMULATION

The model is formulated to result in capacity expansion and optimum flow of gas making it a combination of a planning and operation problem during the period under review. All necessary parameters for the case study are provided in table 1. The optimization framework is divided into constraints and objective function expressed as:

TABLE I. MAIN PARAMETERS

Symbol	Description	Unit
t	Duration of each time period	months
T	Total number of time period (horizon)	months
d_a(mt)	Demand of gas for consumer m	mmscfd
emission(k)	Loss through emission during shutdown	mmscfd
δP(t)	Minimum number of shutdowns	days
θPmax (p)	Maximum proportional capacity expansion rate	rate
θPmin (p)	Minimum proportional capacity expansion rate	rate
Inc(p)	capacity of plant p before expansion	mmscfd
δ (k)	Minimum offline time	days
o(k)	Maximum offline time	days
Ψ(k)	Minimum online time	days
s_max/s_min	Max/Min mass flow rates	mmscfd

TABLE II. SETS AND INDICESD

Set	
i	Set of all suppliers, $i \in I$, $\{I = 1,2,3 \dots I\}$
j	processing plant, $j \in J$, $\{J = 1,2,3 \dots J\}$
k	compressor plant, $k \in K$, $\{K = 1,2,3 \dots K\}$
m	power plant consumer, $m \in M$, $\{M = 1,2,3 \dots M\}$
t	periods in time, $t \in T$, $\{T = 1,2,3 \dots T\}$
p	pipelines, $p \in P$, $\{P = 1,2,3 \dots P\}$
z	relief pipeline, $z \in Z$, $\{Z = 1,2,3 \dots Z\}$
w	gas storage $w \in W$, $\{W = 1,2,3 \dots W\}$
	Binary Variables
	$X_{(k,t)}$ =1, if the compressor is in operation; else 0
	$Y_{(k,t)}$ =1, if the compressor starts operating; else 0
	$R_{(k,t)}$ =1, if the compressor stops operating; else 0
	$H_{(z,t)}$ =1, if relief pipe operates when compressor is shutdown; else 0
	$PI_{(j,k)}$ =1, if flow from node j to node k; else 0
	$PI\_{(k,z)}$ =1, if flow from node k to node z; else 0
	ALIAS (t,tprime)

A. Constraints

Constraint (1) shows that if the node k starts operating in the time period where $Y(k,t)$ =1, then a startup takes place but shutdown $R(k,t)$ = 0. If node k is operating prior to startup then $X(k,t) = 1$.

$$Y_{kt} - R_{kt} = X_{kt} - X_{k,t-1} \quad \forall_{k \in K,\ t \in T\ :\ t = -1} \tag{1}$$

$$\begin{aligned} Y_{kt} + R_{kt} &\le 1 && \forall_{k \in K,\ t \in T} \\ 1 - R_{kt} &\ge Y_{kt} && \forall_{k \in K,\ t \in T} \end{aligned} \tag{2}$$

For constraints (3) and (4) the minimum online time for the plant node k after its startup is modeled. Here, it is expected that the plant will operate for a given time period after its startup. Here the total period that plant node k has been operating continuously since its last startup is greater than the minimum online time.

$$X_{kt} \ge \sum_{t'=t}^{t+\Psi_k-1} Y_{kt} \quad \forall_{k \in K,\ t \in T\ :\Psi_k > 1} \tag{3}$$

$$X_{kt} = 1 \quad \forall_{k \in K,\ t \in T\ :\Psi P_k - \psi_k :\ \psi_k < \Psi P_k} \tag{4}$$

Similarly, the minimum shutdown time of plant node k since after its shutdown is modeled in constraint (5) and (6).

In constraints (7) and (8) the maximum idle time is the maximum time duration that plant k is continuously switched off after its last shutdown which is expected to be higher than when plant shutdown $R(k,t)$ = 1.

$$1 - X_{kt} \ge \sum_{t'=t}^{t+\Delta_k-1} R_{kt} \quad \forall_{k \in K,\ t \in T\ :\Delta_k > 1} \tag{5}$$

$$X_{kt} = 0 \quad \forall_{k \in K,\ t \in T\ :\Delta_k - \delta z_k : \delta z_k < \Delta_k} \tag{6}$$

$$\sum_{t'=t}^{t-o_k} R_{kt} \le o_k \quad \forall_{k \in K,\ t \in T} \tag{7}$$

$$\sum_{t'=t}^{t-(o_k-\delta Z_k)} R_{kt} \le o_k - \delta Z_k \quad \forall_{k \in K,\ t \in T} \tag{8}$$

Constraints (9) and (10) ensures that the supply from the gas field is less than or equal to the supply capacity and the supply delivered to the production plant is less than or equal to the production plant capacity.

$$\sum_{j \in J} ZA_{ijt} \le sc_{it}, \quad \forall_{i \in I, t \in T} \tag{9}$$

$$\sum_{i \in I} ZA_{ijt} \le jc_{jt}, \quad \forall_{j \in J, t \in T} \tag{10}$$

Constraints (11) ensures that the supply from the processing plant to the compressor do not exceed the compressor capacity. To account for the loss during plant disruption, the shutdown of the plant is taken into consideration when there is a flow from plant j to compressor k.

$$\sum_{j \in J} XP_{jkt} - ZE_t + \sum_{w \in W} YM^{+}_{kwt} - YM^{-}_{wkt} \le cp^{max}_{kt}, \quad \forall_{k,t} \tag{11}$$

It is expected that all gas flow from compressor station in the transmission pipeline do not exceed the power plant capacity in constraint (12).

$$\sum_{k \in K} YW_{kmt} \le rc^{max}_{mt}, \quad \forall_{m,t} \tag{12}$$

In constraint 13, based on the contractual agreement, at every time period, demand from consumers should be satisfied.

$$\sum_{k \in K} \sum_{t \in T} YW_{kmt} = \bar{da}_{mt}, \quad \forall_{m \in M, t \in T} \tag{13}$$

The material input-output balance is modeled in constraints (14). The consideration here is that there is no mass build-up in any node of the system. For every of the method studied, each node of the network will be constrained to the mass balance law.

$$\sum_{i \in I} \sum_{j \in J} ZA_{ijt} = \sum_{j \in J} \sum_{k \in K} XP_{jkt} \quad \forall_{t \in T} \tag{14}$$

Constraint (15) is introduced when the relief pipe is fully in operation and the loss has been rechannelled.

$$\sum_{jk} XP_{jkt} - ZE_t = \sum_{km} YW_{kmt} + \sum_{kg} YF_{kgt}, \quad \forall_{t \in T} \tag{15}$$

Constraint (16) represents a steady state where inlet pressure equals outlet pressure.

$$P_p^{in} = P_p^{out}, \quad \forall_{p \in P} \tag{16}$$

In constraint (17), for each node in the gas network, the relief pipeline operates within the maximum and minimum pressure bounds at each time period. Constraint (18) shows when there is a flow from j to k and from k to z during shutdown such that a 0 flow from either node at a time do not affect the pressure balance.

$$Zh_z^{min} \geq P_z^{Bar} \leq Zh_z^{max}, \quad \forall_{z \in Z} \tag{17}$$

$$P_{jkt}^{in} - P_{kzt}^{out} + bigM_{zt}(PI_{kz}^{-} - PI_{jk} - 1) \leq bigM_{zt}, \quad \forall_{j,k,z,t} \tag{18}$$

In constraint (19), to model the cumulated capacity for expansion, a lower and upper bound is introduced on the flow into the relief pipeline. This relief pipeline capacity is modified in constraint (20) by introducing the compression factor. In constraint (21), the proportional capacity for expansion is modeled. The relief pipeline is o

$$\sum_{p \in P} Inc_p \theta P_{\min_p} \geq \sum_{k \in K} RF_{kzt} \leq Inc_p \theta P_{\max_p} - Inc_p, \forall_{z,t} \tag{19}$$

$$\sum_{k \in K} RF_{kzt} \varepsilon_k \leq rp_{zt}^{\max}, \quad \forall_{z \in Z, t \in T} \tag{20}$$

$$Inc_p \theta P_{\min_p} \geq \delta Inc_z \leq Inc_p \theta P_{\max_p}, \quad \forall_{p \in P, z \in Z} \tag{21}$$

Constraint (22) ensures the loss through emission during shutdown of the compressor plant do not exceed the capacity of the relief pipeline and this constraint should be ignored if flow to relief pipeline should only occur when the binary for the relief pipeline is 1. A corresponding upper and lower bound for flow before and during the shutdown is introduced in constraints (23 and 24).

$$ZE_t \leq RF_{kzt}, \quad \forall_{t \in T} \tag{22}$$

$$s_k^{\min} X_{kt} \leq XP_{jkt} \leq s_k^{\max} X_{kt}, \quad \forall_{j \in J, k \in K, t \in T} \tag{23}$$

$$v_z^{\min} R_{kt} \leq RF_{kzt} \leq v_z^{\max} R_{kt}, \quad \forall_{k \in K, z \in Z, t \in T} \tag{24}$$

The overall optimization goal is to optimise for resilience at the transmission node and flow volume flexibility from nodes k to node z. The optimization increases flow to consumers to meet demand and loss reduction during plant shutdown. For simplification, the multi-objective has been compressed as a single objective function. The objective function represented as Z1 is shown below:

$$\sum_{ijt} g_i^{\max} ZA_{ijt} + \sum_{jkt} h_j^{\max} XP_{jkt} - \sum_{kt} o_k ZE_t + \sum_{kwt} s_k^{\max} YM_{kwt}^{+} - YM_{wkt}^{-} + \sum_{kmt} s_k^{\max} YW_{kmt} + \sum_{kt} \psi_k Y_{kt} + \delta_k R_{kt} + \sum_{kzt} v_z^{\max} RF_{kzt}$$

V. RESULT AND DISCUSSION

The proposed model was run on the GAMS 26.14 software using the CPLEX solver 12 in an intel ® core ™ i7 and a zero-optimality gap. The shutdown and the subsequent introduction of the relief pipeline is observed in a steady-state. The interactions between the nodes in the supply chain is then adjusted to mitigate potential risks and increase efficiency. Firstly, the performance level of the compressor when in operation with respect to corresponding minimum mass flow rate is displayed in fig. 1. This is calculated as a flow constraint to compressors k1 to k4 by multiplying the minimum mass flow rate by the operating time of the compressors. A better performance of the compressors is seen towards the end of the planning horizon with k3 outperforming other compressors even though none of the compressors reached its maximum capacity load.

Each node in the network is within the lower and upper bound limits of the pressure as obtained. The material input and output balance are introduced for all parameters less loss through emissions during the compressor shutdown. The normalized flow is obtained by relaxing the disruption period such that the shutdown time is defined.

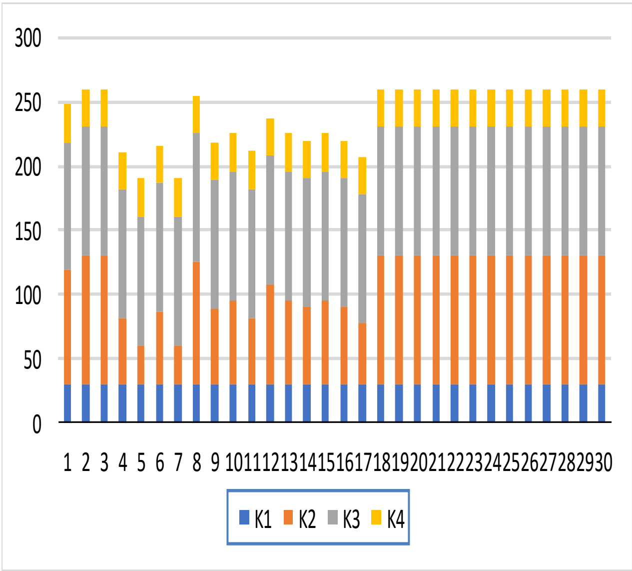

Fig. 1. Peroramnce level of compressor with respect to mass flow rate

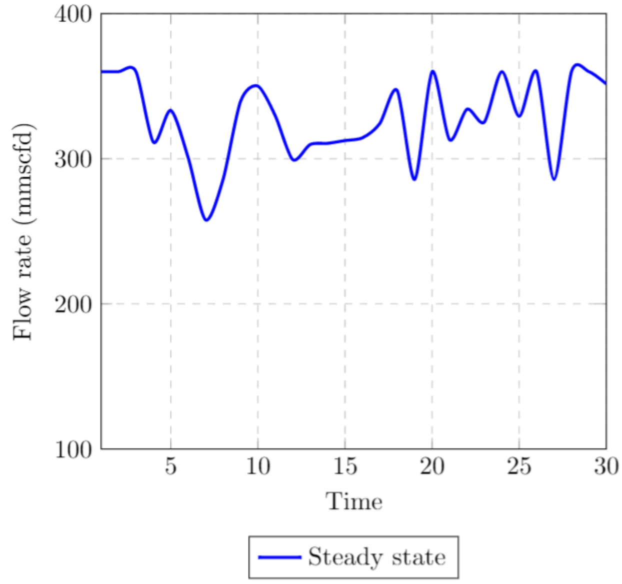

Fig. 2. Normalized flow without pressure drop

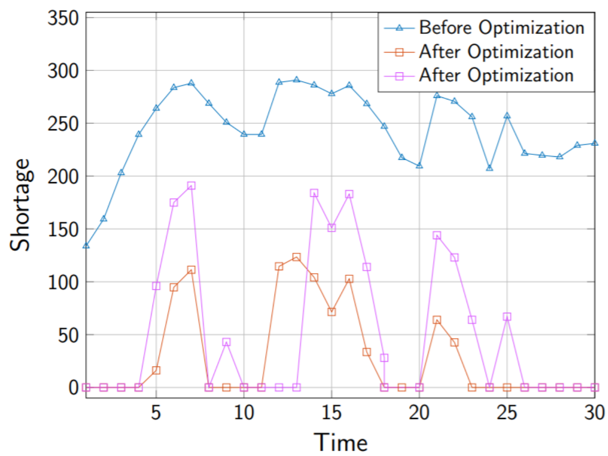

Fig. 3. Shortage recorded at different flow rates

TABLE III. VARIATION IN OUTPUT PERFORMANCE

Scenario	Offline	Flow rate	Final solve
X_P=1040	No. of offline increased from 3 to 4	300/200	6.852488e+7
X_P=1040	No. of offline increased from 3 to 6	320/200	6.702802e+7
X_P=1040	No. of offline increased from 3 to 5	340/200	6.630019e+7
X_P=1040	No. of offline increased from 3 to 6	380/200	6.495804e+7
X_P=1040	No. of offline increased from 3 to 8	380/200	5.390145e+7
X_P =630	No. of offline increased from 3 to 10	300/200	5.390145e+7

In fig. 2 the disruption where R(k,t) equals 1 is introduced. A normalized flow is obtained from the result of the computation. Assuming the number of plant nodes is same for all operating time period, then mean flow is increased from 200.38 to 327.67 mmscfd. The comparison at baseline and after optimization for shortages is obtained in fig. 3. The result in table (III) displays different outputs analyzed based on flow rates and performance of the initial node(s) in a steady-state. When the flow constraint is introduced at different flow rates then the offline time changes but only increases. Specifically, the table is summarized as follows: (1) For all possible scenarios, no mass build-up in any node of the network, (2) Each node is constrained to the mass balance law, (3) Best possible scenario with the least offline period is when mass flow rate is 300/200 psia, (4) the capacity of the initial nodes determines the performance of subsequent nodes. In table (IV) the shrinkage savings on emission in loss volume is shown as well as the cost savings. Here, 98.57 % of trapped gas obtained was lost through emission before optimization reduced to 1.43% after optimization with respecte to time.

TABLE IV. SHRINKAGE COST

Shrinkage cost for losses	Volume of loss (mmscfd)	$3 per MMBtu (converted to mmscfd)
Before optimization/expansion	11782.15	36,760,308.00
After optimization/expansion	171.09	533,800.80

To determine the emission resulting from the gas loss from the pipeline, 1 mmscfd of gas at 15^0C is equals 847210.92kg/hr. However, the present study operates at an isothermal condition of 60^0C while the inlet and outlet pressure were 700psi and 1000psi, respectively. Based on this operating condition, 1 mmscfd of gas is equals 47113.96kg/hr [21]. Considering the above explanation and with reference to Table IV, the amount of CO_2 emanating from the gas loss before the optimization was 555.1 million kg, while the CO_2 after the optimization was 8.06 million kg. The result showed a significant reduction in CO_2 after optimisation.

VI. CONCLUSION

In this work, we have shown better performance in emission reduction from a natural gas supply chain by enhancing resilience during unplanned shutdown of a gas network. A multi-period, single product, transmission model is used for the optimization to satisfy loss reduction within a given time period. During the shutdown, the capacity of the plant node is increased proportionately to accommodate the stranded gas between the closed valve and the compressor station. Therefore, the capacity for expansion has been introduced in this paper. The computation is made in a deterministic environment and a steady-state performance of the network is observed.

The output obtained after running the simulation shows an increase in the flow rate and a reduction of emission loss bringing about cost and environmental savings while still delivering on projected throughput. For future study, it will be relevant to observe the tradeoff between the cost of introducing the additional pathway and resilience. Furthermore, for better comparison and decision making, the work should be extended to a dynamic state where the impact of pressure variation during the shutdown period can be observed. Moreover, different scenarios can be simulated and tested systematically to further buttress the validity of the mitigation measure proposed.

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REFERENCES

[1] Goh M, Lim JYS, Meng F. A stochastic model for risk management in global supply chain networks. Eur J Oper Res 2007;182:164–73. doi:10.1016/J.EJOR.2006.08.028.

[2] Kleindorfer, P. R. , and Saad GH. Managing Disruption Risks in Supply Chains. Prod Oper Manag 2005;14:53–68.

[3] Sawik T. Selection of resilient supply portfolio under disruption risks. Omega 2013;41:259–69. doi:10.1016/J.OMEGA.2012.05.003.

[4] Almansoori A, Shah N. Design and Operation of a Future Hydrogen Supply Chain: Snapshot Model. Chem Eng Res Des 2006;84:423–38. doi:10.1205/CHERD.05193.

[5] Abahussain MM, Christie RD. Optimal scheduling of a natural gas processing facility with Price-based Demand Response. IEEE Power Energy Soc. Gen. Meet., 2013. doi:10.1109/PESMG.2013.6672280.

[6] Bopp AE, Kannan VR, Palocsay SW, Stevens SP. An optimization model for planning natural gas purchases, transportation, storage and deliverability. Omega 1996;24:511–22. doi:10.1016/0305-0483(96)00025-4.

[7] Ríos-Mercado RZ, Borraz-Sánchez C. Optimization problems in natural gas transportation systems: A state-of-the-art review. Appl Energy 2015;147:536–55. doi:10.1016/J.APENERGY.2015.03.017.

[8] Farzaneh-Gord M, Rahbari HR. Unsteady natural gas flow within pipeline network, an analytical approach. J Nat Gas Sci Eng 2016;28:397–409. doi:10.1016/j.jngse.2015.12.017.

[9] Vasconcelos CD, Lourenço SR, Gracias AC, Cassiano DA. Network flows modeling applied to the natural gas pipeline in Brazil. J Nat Gas Sci Eng 2013;14:211–24. doi:10.1016/J.JNGSE.2013.07.001.

[10] Tomasgard A., Rømo F., Fodstad M. MK. Optimization Models for the Natural Gas Value Chain. In: Hasle G., Lie KA. QE (eds), editor. Geom. Model. Numer. Simulation, Optim., Springer, Berlin, Heidelberg; 2007. doi:https://doi.org/10.1007/978-3-540-68783-2_16.

[11] Hellemo L, Midthun K, Tomasgard A, Werner A. Natural Gas Infrastructure Design with an Operational Perspective. Energy Procedia 2012;26:67–73. doi:10.1016/J.EGYPRO.2012.06.011.

[12] Schweiger J, Liers F. A decomposition approach for optimal gas network extension with a finite set of demand scenarios. Optim Eng 2018:297–326. doi:https://doi.org/10.1007/s11081-017-9371-4.

[13] Liang Y, Hui CW. Convexification for natural gas transmission networks optimization. Energy 2018;158:1001–16. doi:10.1016/J.ENERGY.2018.06.107.

[14] Hante FM, Leugering G, Martin A, Schewe L. SM. Challenges in Optimal Control Problems for Gas and Fluid Flow in Networks of Pipes and Canals: From Modeling to Industrial Applications. In: Manchanda P., Lozi R. SA, editor. Ind. Math. Complex Syst., Springer, Singapore; 2017, p. 77–122.

[15] Üster H, Dilaveroğlu Ş. Optimization for design and operation of natural gas transmission networks. Appl Energy 2014;133:56–69. doi:10.1016/J.APENERGY.2014.06.042.

[16] Woldeyohannes AD, Majid MAA. Simulation model for natural gas transmission pipeline network system. Simul Model Pract Theory 2011;19:196–212. doi:10.1016/J.SIMPAT.2010.06.006.

[17] Sedliak A. ZT. OPTIMIZATION OF THE GAS TRANSPORT. Math Publ 2016:103–20.

[18] Sukharev MG, Kosova KO. A parameter identification method for natural gas supply systems under unsteady gas flow. Autom Remote Control 2017;78:882–90. doi:10.1134/S0005117917050101.

[19] Percell, P. B., & Ryan MJ. Steady State Optimization of Gas Pipeline Network Operation. Oklahoma: 1987.

[20] Kurz R, Lubomirsky M BK. Gas compressor station economic optimization. Int J Rotating Mach 2012.

[21] Online Calculation for Fluid flow n.d. https://www.onlineflow.de/en/calc/index.php (accessed February 9, 2020).