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Capacity Performance Modelling And Optimization Of Natural Gas Transmission Pipeline Networks

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Natural gas plays a pivotal role in the global energy landscape, accounting for over 20% of the world's primary energy demand (Jiang, Cai, Zhang, Xie and Liu, 2023) and it is estimated to reach 25% by the year 2030 (Su et al., 2022).

However, the gas pipeline network disruptions pose significant risks to the natural gas supply resilience (Marino and Zio, 2021). Various studies have focused on modelling and optimization of natural gas pipeline network performance (NGPNs) by developing reliability, vulnerability and recovery related indicators or by conducting gas pipeline process analysis. Reliability-related evaluation indices focus on stochastic transitions of network states according to components' transition rates (e.g., failure and repair rates) (Zio, 2016). Other studies resort to complex network analysis methods where network flow algorithms such as maximum flow and shortest path algorithms are adapted for pipeline network analysis (Jiang et al., 2023; Marino and Zio, 2021; Su et al., 2022; Yang et al., 2023). For instance, Marino and Zio (2021) introduced a resilience analysis framework for NGPNs, integrating the physical pipeline system with the SCADA system to access network robustness and recovery from cyber and physical failures, including a case study showing the vulnerabilities to disruptions, highlighting the importance of systemic resilience management. Su et al. (2022) presents a dynamic state-space model for natural gas pipeline networks, incorporating key components (e.g., pipelines, LNG terminals) using graph theory and gas dynamics for assessing the supply security through simulations. Jiang et al. (2023) introduced a novel methodology combining Monte Carlo simulation and hydraulic analysis evaluating the resilience of NGPNs under random leakage, incorporating resilience metric and accounting for system uncertainties.

One of the fundamental elements in such studies is the network capacity performance model that can be used to estimate the network flow while its topological and operational characteristics change with time given the inherent vulnerability of NGPNs to various forms of disruptions, most notably, compressor failures and pipe deteriorations due to corrosion, etc. Such a model can be further used for optimal operation and maintenance (O&M) management of NGPNs to improve the operational capacity of pipeline infrastructures, and also for enhancing the network and gas supply resilience to ensure the business continuity, and ultimately benefit the Society.

This study presents a network capacity performance model, where it combines the reliability related evaluation indices with complex network theory to optimize the gas supply at network demand nodes and thus the gas supply resilience of pipeline network given operational and topological constraints of the network.

Monte Carlo Simulation techniques (Zio, 2013) are used to simulate the stochastic transitioning of the state of the network components, and thus the network topology. The proposed model considers virtual demand edges that help optimize the amount of gas supplied at individual demand nodes while introducing a penalty cost for the amount of demand that is not delivered. In addition, whereas in previous studies, the compressor stations have often been excluded from the network analysis, the current study considers compressor stations as key network components that compensate for the pressure drop in transmission pipelines, and whose failure leads to shortage of supply. Methodologically, each compressor station is substituted with a virtual edge, whose dynamic capacity is determined according to its stochastic failure and repair processes of the corresponding compressor stations. By resorting to graph theory and steady state gas flow, network flow optimization techniques are then employed to maximize the network flow while minimizing the total operating and penalty costs.

To demonstrate the practical application of this framework, the simplified NGPN of the Norwegian Continental Shelf (Figure 1), which supplies gas to Germany, France, Belgium, and the United Kingdom, is considered as a case study. While minimizing the total network operating and penalty costs, the network flow capacity is optimized, by incorporating the stochastic transitioning of the network components.

A tiered cash-out mechanism for calculating the penalty costs for each demand node, using the gas index price as a baseline with the natural gas price being the 5-year average reported by Norskpetroleum, around 4.5 MNOK per mmcm. Component failure rates, and repair rates for both pipes and compressors were based on data from the OREDA handbook (OREDA, 2015). The simulation has been performed for 1000 days with 5000 simulations.

The simulation outcomes indicate that by approximately 250 days, all measurements stabilize, signifying the network's equilibrium based on the provided inputs. Figure 2A outlines the average demand at each node: Dornum reaches 83% of its maximum demand, Emden hits 84%, Dunkerque and Zeebrugge both achieve 78%, and Easington tops at 87% of the maximum demand. The sum of all the supplied gas in the demand nodes highlight that the network's average demand delivery stands at about 290 mmcm per day, compared to the required demand delivery of the system that is 349 mmcm per day at the equilibrium state the network is supplying 83% of the required demand. Figure 2B outlines the average total cost over time for the network, this total cost is the sum of penalty costs for all the demand nodes and the operational cost for the network. The total cost that the operators of the system need to pay at this equilibrium state is around 4800 MNOK.

Further research may focus on incorporating the proposed capacity performance model in O&M and resilience modelling and optimization of NGPNs.

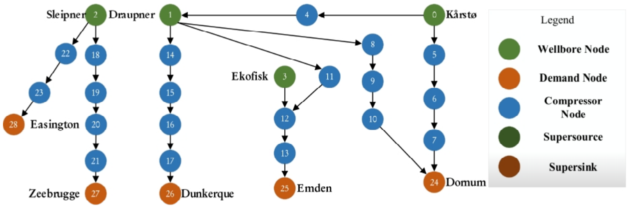

Fig. 1. Simplified network

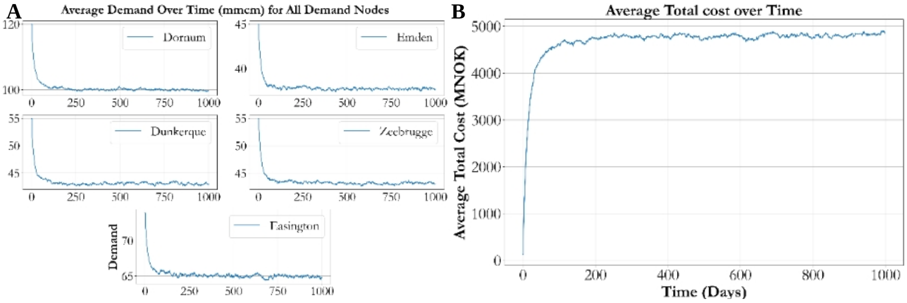

Fig. 2. Average demand for all demand nodes(A), Average total cost (B)

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