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Innovative Applications of O.R.

Adding flexibility in a natural gas transportation network using interruptible transportation services

Marte Fodstad [a,b,*], Kjetil T. Midthun [a], Asgeir Tomasgard [a,b]

[a] SINTEF Technology and Society, Applied Economics, Postboks 4760 Sluppen, 7465 Trondheim, Norway
[b] Norwegian University of Science and Technology, Dept. of Industrial Economics and Technology Management, Sentralbygg I, Alfred Getz veg 3, 7491 Trondheim, Norway

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ABSTRACT

We present a modeling framework for analyzing if the use of interruptible transportation services can improve capacity utilization in a natural gas transportation network. The network consists of two decision makers: the transmission system operator (TSO) and a shipper of natural gas. The TSO is responsible for the routing of gas in the network and allocates capacity to the shipper to ensure that the security of supply in the network is within given bounds. The TSO can offer two different types of transportation services: firm and interruptible. Only firm services have a security of supply measure, while the interruptible services can freely be interrupted whenever the available capacity in the transportation network is not sufficiently large. We apply our modeling framework on a case study with realistic data from the Norwegian Continental Shelf. The results indicate substantial increased throughput and profits with the introduction of interruptible services.

1. Introduction

In this paper we discuss whether the introduction of interruptible transportation services in a natural gas network can increase throughput without deteriorating the security of supply. In our modeling framework we include both firm and interruptible transportation services, where firm services are characterized by a guaranteed level of security of supply while interruptible services are delivered provided there is available capacity on the given day. We present a general model framework and a case study based on realistic data from the Norwegian natural gas transportation system that covers nearly 20 percent of European gas consumption (Norwegian Petroleum Directorate, 2012).

Interruptible transportation services are well known within the natural gas supply chain, as they are available in the US and in several European systems (including the Norwegian). These services allow the TSO to oversell the capacity by reselling capacity that is booked firm but not nominated without relieving the obligation to the original buyer, as described in Doane, McAfee, Nayyar, and Williams (2008). It is usually required that all firm capacity, defined by a predefined static limit, is sold before any capacity can be resold as interruptible. The intention of the interruptible services is to improve the short term redistribution of transportation capacity to support an efficient use of the network (Ruff, 2012). Our motivation for introducing interruptible transportation services is different. We focus on increasing the capacity initially made available by the TSO rather than redistribution of allocated capacity between the producers. The latter will increase the utilization of the offered capacity in the network, while the former will increase the capacity offered. This implies a slightly different definition since we discuss interruptible contracts in a primary market without any assumption on resale. We are not aware of any natural gas network or examples in the literature where interruptible services are used for this purpose.

A high level of security of supply is important on the market side, for the shippers to be able to deliver in long-term contracts. It is also important on the production side, to ensure that the oil production on the fields with associated gas will not be decreased. In order to maintain a high level of security of supply on firm services, it is necessary for the system operator to withhold some capacity in the system at the time of booking to have flexibility to handle uncertainties in the final operation. This withheld flexibility can decrease the capacity utilization in the network. Security of supply can be expressed through different measures. Within the power sector the N-1 method, requiring feasible operation even if one element in the network goes down, is a traditional way of providing robustness in case of contingencies (see for instance Vournas, 2001). Bopp, Kannan, Palocsay, and Stevens (1996) use a set of business rules to achieve satisfactory

* Corresponding author. Tel.: +47 92616498.
E-mail addresses: Marte.Fodstad@sintef.no (M. Fodstad), Kjetil.Midthun@sintef.no (K. T. Midthun), Asgeir.Tomasgard@iot.ntnu.no (A. Tomasgard).

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security of supply when optimizing the planning problem of a local natural gas distribution company. Guldmann and Wang (1999) include a curtailment cost on not satisfied demand for a similar problem. In the stochastic programming literature a variety of risk measures are presented (see for example Rockafellar, 2007), but so far these are rarely applied in natural gas applications. We define the security of supply level as the expected throughput in the whole system relative to the total firm booking:

$$\text{Security of supply} = \sum_{s \in \text{Scenarios}} \text{Probability}_s \frac{\sum_{i \in \text{Nodes}} \text{Flow}_{is}}{\sum_{i\text{Nodes}} \text{Booking}_{is}} \quad (1)$$

This is the same definition as used by Hellemo, Midthun, Tomasgard, and Werner (2013), but in contrast to them we also report numerical analysis.

Unplanned events, such as outages and technical failure, cause uncertainty in the available capacity in the transportation network. Furthermore, the system operator must take into account system effects that make it impossible to a priori determine fixed capacities (see Midthun, Bjørndal, & Tomasgard, 2009). This corresponds to the arguments by Vazquez, Hallack, and Glachant (2012) who point out that the shipper's simplified view on the transportation network, only acting in accordance with entry and exit booking points, requires the TSO to withhold some capacity to match the booking obligations with the physical network capabilities.

The short-term system flexibility comes from the possibility to increase production levels in some fields, to reroute the gas, and from the storage capabilities in the pipelines (linepack). Midthun, Nowak, and Tomasgard (2007) and Keyaerts, Hallack, Glachant, and D'haeseleer (2011) show that linepack also has a commercial value that introduces a trade-off in relation to security of supply. We have not included linepack and this trade-off in our analysis to limit the model complexity and to focus the analysis on effects of interruptible contracts. In our single-period model the availability of linepack would have increased the network capacity that could reduce the value of introducing interruptible services, while in a realistic dynamic setting this effect would highly depend on the time structure of network events and the trade-off between commercial use and security of supply considerations.

Modeling the physics of gas transportation in pipeline networks is challenging, mainly due to nonlinear properties in pressure dynamics in pipelines, compressor efficiency and gas quality management. Martin, Möller, and Moritz (2006) and Tomasgard, Rømo, Fodstad, and Midthun (2007) optimizes a steady-state representation of gas network pressures and flows. Moritz (2007) models transient flows, while Ulstein, Nygreen, and Sagli (2007), Selot, Kuok, Robinson, Mason, and Barton (2008) and Li, Armagan, Tomasgard, and Barton (2011) model gas quality issues. We use a linear steady-state approximation of the pressure dynamics in pipelines. We assume a homogeneous gas quality, and thereby avoid the nonlinearities from gas quality management. This assumption is a reasonable approximation in networks with small quality variations, for instance downstream of processing, but it is otherwise a simplification.

Our contribution is both a modeling framework that allows for detailed analysis of interruptible services to address uncertainty in network capacity availability in the natural gas transportation network, as well as a case study based on realistic data and topology from the Norwegian Continental Shelf (NCS). In addition, we introduce a new production cost function for natural gas fields that takes into account associated oil production. Our models are based on stochastic programming and do not include strategic behavior of the participants. The validity of this will be discussed in further detail when we introduce our models.

In Section 2 we describe in more detail the decision sequence as well as some of our assumptions. We then present the modeling framework in Section 3, before we move on to the case study in Section 4. Finally, we conclude in Section 5.

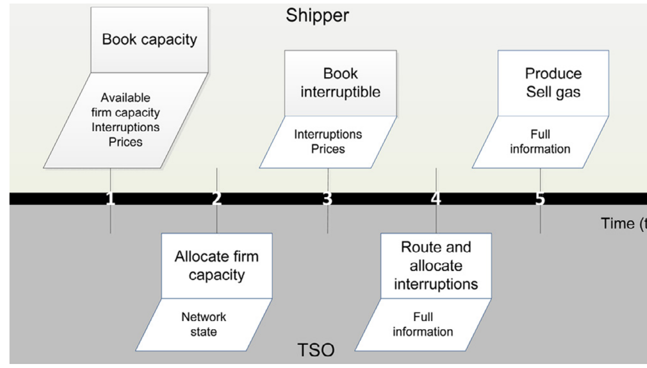

Fig. 1. Illustration of the decision sequence for a shipper and the TSO. The squares show the decisions that are made at each point, while the trapezoids show the uncertain parameters at that stage.

2. Problem statement

In this section we present the model structure and discuss the underlying assumptions. In our model framework, we establish a decision sequence involving the agents in the supply chain (see Fig. 1). At $t = 1$ the shippers submit their booking requests under the uncertainty of available firm capacity and at $t = 2$ the TSO allocates the capacity between the shippers. The TSO tries to minimize the deviation between requested booking and allocated capacity while meeting the security of supply requirements (see Eq. (1)). At $t = 3$, when the allocated firm booking is known by the shippers, they book interruptible capacity. The interruptible capacity is unlimited, but the shippers will include the probability of interruptions when making booking decisions. At $t = 4$ uncertainty regarding network events and market prices are resolved. The TSO then allocates interruptions based on a feasible routing pattern. Finally, at $t = 5$ the shippers produce and do short term trades. The decision sequence we have described is similar to the one used in the current system on the NCS, apart from the difference in use of interruptible services.

The objective of this work is to evaluate the potential from introducing interruptible transportation services for the network as a whole, while recognizing that different agents in the system have different incentives. The modeling has been guided by the Norwegian system. We have made some important modeling choices to make the model framework tractable and focus on the effects we intend to analyze:

(1) We analyze the perfect competition situation which means we can model all shippers as a single agent. It implies that any strategic behavior that could improve a single shipper's performance, but reduce the overall supply chain performance, is not captured. It is not clear if such gaming is present in the transportation market on the NCS, thus we have decided to not model gaming for our initial study. The aggregation of all shippers into a single agent reduces the uncertainty seen by the shippers, since the modeled shipper knows the total booking in the system. This also means that we find a benchmark solution for the shipper's profits in the network when interruptible services are introduced. This corresponds to maximizing the total supply chain profits in our model. With more than one shipper competing for the booking capacity, the shippers' profits in the network will be reduced (or at best stay the same) compared to the situation when all shippers are unified to one decision unit. The difference will depend on the rules for capacity allocation between the different shippers, and is not the focus of this paper.