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A Production Allocation Framework for Natural Gas Production Systems

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Abstract

Production planning in upstream natural gas production systems is a unique challenge due to the multiproduct network, nonlinear pressure-flowrate relationships in the wells and the trunkline network, and production-sharing contracts (PSC) and operational rules. A nonconvex mixed-integer nonlinear programming (MINLP) model of the upstream production system including all the features described above is formulated and applied to a real-world case study in Malaysia. The model is solved with GAMS/BARON and a hierarchical multiobjective case study is presented.

Keywords: Natural gas supply chain, natural gas contracts, production sharing contracts, nonconvex optimization, global optimization, production planning

1. Introduction

The production planning model presented in this work is inspired by the Sarawak gas production system (SGPS). The SGPS comprises 12 offshore fields and 3 associated gas fields that supply gas to the LNG plant complex in Bintulu, Sarawak in East Malaysia. For modeling purposes, the upstream system is defined from the wells to the LNG plants (excluding the plants). The SGPS network has multiple gas qualities due to different gas compositions produced from each field and multiple mixing and splitting nodes. Therefore,

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optimal routing of gas in the network is required to meet the gas quality constraints at LNG plants. The network is controlled by regulating pressures at certain nodes and hence realistic prediction of pressures is important.

The SGPS is operated by a single operator even though several parties have ownership stakes in the fields and LNG plants. Therefore, a complex PSC framework governs operation of the system, since unlike oil production, upstream natural gas production systems generate final products that must be shared. A field cannot arbitrarily supply to any LNG plant. Instead each field is associated with a PSC. Each PSC has a mandated demand. *Inter-PSC transfers* may be required because production network and customer quality constraints may lead to a mismatch between the demand and supply resulting in a PSC being in *excess* or *deficit*. The *inter-PSC transfer rules* dictate the conditions for inter-PSC transfers. They may also define operational rules to implement such transfers on the network.

Traditionally, an iterative approach of first optimizing the production system with a continuous local optimizer, investigating if the customer requirements, PSC and operational rules are satisfied and running another scenario if the rules are violated, has been employed for production planning. This approach is unsatisfactory for several reasons. The production network model is nonconvex and a local optimization method may provide a suboptimal solution or no feasible solution at all. Moreover, there is no guarantee about the optimality of the solution in the second step or even if a solution feasible with respect to PSC rules etc., will be found at all.

2. Model Overview

The model is supposed to serve as a decision support tool for the system operators who plan optimal steady-state operations over a short term (2-12 weeks). A single planning period is considered since the model is intended to support decision making between planned or unplanned events. As discussed, it is important to incorporate blending and splitting, nonlinear pressure-flowrate constraints and logical constraints resulting from PSC and operational rules. Hence, the final model is a relatively large nonconvex MINLP (several hundred continuous variables and tens of binary variables). This makes the use of global optimization approaches indispensable. Additionally, model formulation is quite important.

The upstream production planning model can be viewed as comprising the following two interacting components. *The infrastructure model* is the model of the actual production network and facilities. *The contractual rule model* includes constraints other than the actual physical constraints, i.e., the customer requirements, the PSC model and the operational rules. The presentation of the full model is out of the scope of this paper, hence only important features are summarized here.

3. Infrastructure Model

The infrastructure model consists of models of the trunkline network, wells and compression facilities. Ideal gas behavior is assumed at the standard condition used for natural gas metering. The reservoir pressure and the fluid composition from wells are assumed to be invariant, justified by the short planning period. Perfect mixing is assumed at junctions.

3.1. The Trunkline Network Model

The trunkline network is modeled as a *directed graph*. The demands (LNG plants) are modeled as sinks in this framework with a negative production rate. The arcs in this network are divided into the following four subsets for purposes of modeling flow. Most trunklines are modeled using the *Weymouth equation* [1] as the pressure-flowrate relationship which is nonconvex. Trunklines in the second subset can be opened and closed during normal operation and therefore require a binary variable and two additional continuous variables. Arcs in the third subset represent certain facilities and are modeled with a constant pressure drop as suggested by the operating data. Finally, for subsea connections between a platform (serving multiple fields) and fields, it is sufficient to force a pressure inequality between wellhead pressures and pressure at platform since the pressures are reduced by chokes.

The material balances are formulated as molar balances involving eight chemical species, CO_2, H_2S, N_2, C_1, C_2, C_3, C_4 and C_5+, to facilitate modeling of multiple qualities of gas. The relationship between standard volumetric and molar rate is formulated using the ideal gas assumption. The model of splitter and mixer nodes in the network introduces bilinearities and hence additional nonconvexity in the model.

3.2. The Well Performance Model

The well performance comprises the In-flow Performance (IFP) and Vertical-Lift Performance (VLP), both of which are nonlinear equalities and hence are nonconvex. IFP models the flow from the reservoir bulk to the bottom of the well bore while VLP models the flow in the well bore itself. Natural gas liquids (NGL) production is assumed to be proportional to the dry gas production with a constant condensate gas ratio for each well.

3.3. The Compression Model

The compression power is calculated assuming a polytropic process. The compression constrains the maximum production from the corresponding field since compressor power is limited by the corresponding rated power.

4. The Contractual Rule Model

The contractual rule model includes the PSC model, the operational rules and the customer specifications. The framework for incorporating operational rules is similar to the modeling of transfer activation rules (Section 4.1.2) and hence is not explicitly described.

4.1. The Production Sharing Contracts Model

There are two major issues in the PSC modeling. Firstly, the calculation of the *PSC excesses/deficits* is non-trivial since the transfer rules between different PSC interact with each other, i.e., to determine if a PSC is in excess requires not just the knowledge of the supply and demand, but also if the PSC has transferred gas to or received gas from any other PSC. A *PSC network* representation is proposed to overcome this difficulty. Secondly, modeling of *inter-PSC transfer rules* involves the mathematical representation of logical conditions. Moreover, a mathematical representation requires the inference of a rule (i.e., all possible outcomes) to be built into the model or else there is a possibility of solutions that will be deemed as violating the PSC and hence infeasible by human operators.

4.1.1. The PSC Network Representation

A PSC can be represented as a subnetwork. The supply of the PSC forms the source and the demand corresponds to a sink. The levels of excess/deficit can be represented as nodes and the flowrate in the arcs originating at these represent the excesses/deficits at corresponding levels. A positive flowrate indicate that the PSC is in excess at that level. Inter-PSC transfers are represented as arcs between different PSC subnetworks. The origin and destination nodes for a particular transfer arc are determined by its priority. The network so formed is the PSC network representation. The excess and deficit calculations are now simple volume balances on this network.

4.1.2. Transfer Activation Rules

A mathematical representation of transfer rules involves the following steps. The states of the PSC, the inter-PSC transfers, the priorities and the operational states are represented by Boolean variables. Binary variables corresponding to these are defined. Constraints are formulated to relate these binary variables to the flowrates in the PSC network. These enforce the equivalence of binary variable states and the conditions they represent. A transfer rule can be represented as a logical expression in terms of the Boolean states. This logical representation of the transfer rule can be converted automatically to binary constraints [2,3]. However, the transfer rules as stated in the PSC are not sufficient to fully define the problem and additional logical constraints must be added to represent each rule's inferences.

4.2. Customer Specifications

There are upper and lower bounds on both the demand rates and delivery pressures at LNG plants for proper operation. Furthermore, there are gas quality specifications, most important being the gross heating value of the feed gas. Also, there are composition thresholds for almost all the components.

5. Model Solution and Results

The model is a nonconvex MINLP with 827 variables including 23 binaries. There are 1094 constraints of which 702 are equalities. The model is solved using a global branch-and-cut algorithm with reduction heuristics as implemented in GAMS [4]/BARON [5,6]. The relative gap for convergence is 10%.

5.1. Hierarchical Multiobjective Case Study

Table 1: Hierarchical Multiobjective Case Study

	Dry gas production	**NGL**	**Priority**	**Solution Time**
	MMscfd	bbl	MMscfd	CPU s
Dry gas production	3,333	134,036	224	9363
NGL	3,333	137,433	224	75
Priority	3,333	137,433	224/294[+]	>705,379

This problem has multiple optimal solutions with the same optimal solution value. Moreover, it has multiple objectives with a clear priority. This can be exploited to obtain a solution that is optimal for all objectives, i.e., a win-win situation. The primary objective is to maximize dry gas production to satisfy contractual demands. The secondary objective is to maximize NGL production as this increases revenue for the upstream operator. The tertiary objective is to prioritize production from certain fields. This may be related to long-term objectives.

Hierarchical multiobjective optimization is performed by optimizing for the first objective, constraining that objective at its optimal value and then reoptimizing for second objective, and then repeating the same for other objectives. Results of a multiobjective study are presented in Table 1. Each of the three solutions in Table 1 has a different pressure-flowrate distribution in the network, driven by the particular objective, even though the objective values are close. NGL

[+] Not converged (Best possible value)

production rate can be increased by around 2.5% while maintaining the same dry gas production rate. This is equivalent to an approximate increase in annual revenue by $60-70 million for the upstream operator.

6. Conclusion

An operational planning framework that incorporates production network constraints as well as contractual rules has been developed for the first time to the best of our knowledge. Results indicate that the model can have huge economic implications by increasing the production of secondary products and ensuring optimal long-term asset management while simultaneously satisfying the short-term contractual gas supply requirements and customer specifications. A more robust solution procedure is required for solving large instances of the problem.

7. Future Work

Future work involves exploiting the problem structure for a more reliable numerical solution. The model can be extended to incorporate a simplified representation of the LNG plants to enable plants to respond to upstream events.

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