Journal of Petroleum Science and Engineering 124 (2014) 180–197

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Multistage stochastic programming approach for offshore oilfield infrastructure planning under production sharing agreements and endogenous uncertainties

Vijay Gupta, Ignacio E. Grossmann *

Department of Chemical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA

ARTICLE INFO

Article history:
Received 20 December 2013
Accepted 1 October 2014
Available online 23 October 2014

Keywords:
multistage stochastic programming
endogenous uncertainties
non-anticipativity constraints
Lagrangean decomposition
oil & gas exploration
production sharing agreements

ABSTRACT

The paper presents a new optimization model and solution approach for the investment and operations planning of offshore oil and gas field infrastructure. As compared to the conventional models where either fiscal rules or uncertainty in the field parameters is considered, the proposed model is the first one in the literature that includes both of these complexities in an efficient manner. In particular, a tighter formulation for the production sharing agreements based on our recent work, and a perfect positive or negative correlation among the endogenous uncertain parameters (field size, oil deliverability, water–oil ratio and gas–oil ratio) is considered to reduce the total number of scenarios in the resulting multistage stochastic formulation. To solve the large instances of the problem, a Lagrangean decomposition approach allowing parallel solution of the scenario subproblems is implemented in the GAMS grid computing environment. Computational results on a variety of oilfield development planning examples are presented to illustrate the efficiency of the model and the proposed solution approach.

1. Introduction

The life cycle of a typical offshore oilfield project consists of the following five steps: (1) Exploration: This activity involves geological and seismic surveys followed by exploration wells to determine the presence of oil or gas; (2) Appraisal: It involves drilling of delineation wells to establish the size and quality of the potential field. Preliminary development planning and feasibility studies are also performed; (3) Development: Following a positive appraisal phase, this phase aims at selecting the most appropriate development plan among many alternatives. This step involves capital-intensive investment and operating decisions that include facility installations, drilling, sub-sea structures, etc.; (4) Production: After the facilities are built and wells are drilled, production starts where gas or water is usually injected in the field at a later time to enhance productivity; (5) Abandonment: This is the last phase of an oilfield development project and involves the decommissioning of facility installations and subsea structures associated with the field.

Given that most of the critical investments are usually associated with the development planning phase of the project, this paper focuses on the key strategic/tactical decisions during this phase of the project. The major decisions involved in the oilfield development planning phase are the following: (1) selecting platforms to install and their sizes; (2) deciding which fields to develop and what should be the order to develop them; (3) deciding which wells and how many are to be drilled in the fields and in what sequence; (4) deciding which fields are to be connected to which facility; (5) determining how much oil and gas to produce from each field.

Therefore, there are a very large number of alternatives that are available to develop a particular field or group of fields. However, these decisions should account for the physical and practical considerations, such as the following: a field can only be developed if a corresponding facility is present; nonlinear profiles of the reservoir that are obtained from reservoir simulators (e.g. Schlumberger, 2008) to predict the actual flowrates of oil, water and gas from each field; limitation on the number of wells that can be drilled each year due to availability of the drilling rigs; and long-term planning horizon that is the characteristic of these projects. Therefore, optimal investment and operating decisions are essential for this problem to ensure the highest return on the investments over the time horizon considered. By including all the considerations described here in an optimization model, this leads to a large-scale multiperiod mixed-integer nonlinear programming (MINLP) problem that is difficult to solve to global optimality. The extension of this model to the cases where we explicitly

* Corresponding author.
E-mail addresses: v.gupta.cmu@gmail.com (V. Gupta), grossmann@cmu.edu (I.E. Grossmann).

http://dx.doi.org/10.1016/j.petrol.2014.10.006
0920-4105/

consider the fiscal rules with the host government and the uncertainties can further lead to a very complex problem to model and solve.

In terms of the deterministic approaches, the oilfield development planning has been modeled as LP (Lee and Aronofsky, 1958; Aronofsky and Williams, 1962) or MILP (Frair, 1973) models under certain assumptions to make them computationally tractable. Simultaneous optimization of the investment and operating decisions has been addressed in Bohannon (1970), Sullivan (1982) and Haugland et al. (1988) using MILP formulations with different levels of details. Behrenbruch (1993) emphasized the need to consider a correct geological model and to incorporate flexibility into the decision process for an oilfield development project. Iyer et al. (1998) proposed a multiperiod MILP model for optimal planning and scheduling of offshore oilfield infrastructure investment and operations. The model considers the facility allocation, production planning, and scheduling within a single model and incorporates the reservoir performance, surface pressure constraints, and oil rig resource constraints. Van den Heever and Grossmann (2000a) extended the work of Iyer et al. (1998) and proposed a multiperiod generalized disjunctive programming model for oil field infrastructure planning for which they developed a bilevel decomposition method. As opposed to Iyer et al. (1998), they explicitly incorporated a nonlinear reservoir model into the formulation but did not consider the drill-rig limitations. Barnes et al. (2002) optimized the production capacity of a platform and the drilling decisions for wells associated with this platform. The authors addressed the problem by solving a sequence of MILPs. Ortiz-Gomez et al. (2002) presented three mixed-integer multiperiod optimization models of varying complexity for the oil production planning. Carvalho and Pinto (2006a) considered an MILP formulation for oilfield planning based on the model developed by Tsarbopoulou (2000), and proposed a bilevel decomposition algorithm for solving large-scale problems where the master problem determines the assignment of platforms to wells and a planning subproblem calculates the timing for the fixed assignments. The work was further extended by Carvalho and Pinto (2006b) to consider multiple reservoirs within the model. Recently, Gupta and Grossmann (2012a) proposed a general multiperiod MINLP formulation for offshore oilfield development planning that simultaneously optimizes facility installation, well drilling, and production decisions considering oil, water and gas flows profiles. To solve the resulting non-convex MINLP problem, they reformulated it as an MILP using two theoretical properties and piecewise-linear approximations.

The major limitation with the above approaches is that they do not consider the fiscal rules explicitly in the optimization model that are associated to these fields, and mostly rely on the simple net present value (NPV) as an objective function. Therefore, the models with these objectives may yield the solutions that are very optimistic, which can in fact be suboptimal after considering the impact of fiscal terms. Van den Heever et al. (2000b) and Van den Heever and Grossmann (2001) considered optimizing the complex economic objectives including royalties, tariffs, and taxes for the multiple gas field site where the schedule for the drilling of wells was predetermined as a function of the timing of the installation of the well platform. Based on a continuous time formulation for gas field development with complex economics of similar nature as Van den Heever and Grossmann (2001), Lin and Floudas (2003) proposed an MINLP model and solved it with a two-stage algorithm. Approaches based on simulation (Blake and Roberts, 2006) and meta-modeling (Kaiser and Pulsipher, 2004) have also been considered for the analysis of the different fiscal terms. Gupta and Grossmann (2012b) presented a generalized mathematical framework and tighter formulations to incorporate a variety of fiscal contracts efficiently in the development planning.

In the literature work described so far, one of the major assumptions is that there is no uncertainty in the model parameters, which in practice is generally not true. Although limited, there has been some work that accounts for uncertainty in the problem of optimal development of oil and/or gas fields. Haugen (1996) proposed a single parameter representation for uncertainty in the size of reserves and incorporates it into a stochastic dynamic programming model for scheduling of oil fields. However, only decisions related to the scheduling of fields were considered. Meister et al. (1996) presented a model to derive exploration and production strategies for one field under uncertainty in reserves and future oil prices. The model was analyzed using stochastic control techniques. Jonsbraten (1998a) addressed the oilfield development planning problem under oil price uncertainty using an MILP formulation that was solved with a progressive hedging algorithm. Aseeri et al. (2004) introduced uncertainty in the oil prices and well productivity indexes, financial risk management, and budgeting constraints into the model proposed by Iyer et al. (1998), and solved the resulting stochastic model using a sample average approximation algorithm. Jonsbraten (1998b) presented an implicit enumeration algorithm for the sequencing of oil wells under uncertainty in the size and quality of oil reserves. The paper considers investment and operation decisions only for one field. Lund (2000) addressed a stochastic dynamic programming model for evaluating the value of flexibility in offshore development projects under uncertainty in future oil prices and in the reserves of one field using simplified descriptions of the main variables. Cullick et al. (2003) proposed a model based on the integration of a global optimization search algorithm, a finite-difference reservoir simulation, and economics. They presented examples having multiple oil fields with uncertainties in the reservoir volume, fluid quality, deliverability, and costs. Few other papers (Begg et al., 2001; Zabalza-Mezghani et al., 2004; Bailey et al., 2005; Cullick et al., 2007) have also used a combination of reservoir modeling, economics and decision making under uncertainty through simulation-optimization frameworks.

However, most of these works either consider the very limited flexibility in the investment and operating decisions, or handle the uncertainty without considering any correcting actions into the future. Stochastic programming provides a systematic framework to model problems that require decision-making in the presence of uncertainty by taking uncertainty into account of one or more parameters in terms of probability distribution functions, (Birge and Louveaux, 1997). The concept of recourse action in the future, and availability of probability distributions in the context of oilfield development planning problems, makes it one of the most suitable candidates to address uncertainty. Moreover, extremely conservative decisions are usually ignored in the solution utilizing the probability information given the potential of high expected profits in the case of favorable outcomes. In the context of stochastic programming, Goel and Grossmann (2004) considered a gas field development problem under uncertainty in the size and quality of reserves where decisions on the timing of field drilling were assumed to yield an immediate resolution of the uncertainty, i.e. the problem involves decision-dependent uncertainty as discussed in Jonsbraten et al. (1998), Goel and Grossmann (2006) and Gupta and Grossmann (2011). Linear reservoir models, which can provide a reasonable approximation for gas fields, were used. In their solution strategy, the authors used a relaxation problem to predict upper bounds, and solved multistage stochastic programs for a fixed scenario tree for finding lower bounds. Goel et al. (2006) later developed a branch and bound algorithm for solving the corresponding disjunctive/mixed-integer programming model where lower bounds were generated by Lagrangean duality. Ettehad et al. (2011) presented a case study for the development planning of an offshore gas field under uncertainty optimizing