Strategic Engineering of Large Infrastructure Systems: 
Real Options, Staged Development, and the Role of Flexibility

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Outline

- Background about offshore oil/gas field development project
- Motivation and research questions
- Integrated Matlab model of offshore oil/gas project
- Applications of the integrated model
  - Design optimization
  - Reservoir and market uncertainty modeling and simulation
  - Flexibility in oil/gas field development
  - Simulation case study of flexible staged development
- Conclusion and Future work
Background

- Generic stages for oil/gas exploration and production project

- Exploration
- Appraisal
- Development
- Production
- Abandonment

Geographical location
Reservoir identification (seismic)
Local environment policy, economic conditions, etc...

Drill appraisal wells to learn more about reservoir and reduce uncertainty (reservoir volume, fluid properties, etc.)

Based on reservoir properties, selects reservoir type, facility concept designs
Reservoir and Facility Models capture link between physical dynamics and facility configuration
Estimate the production profile, field development cost
Select -> Define -> Execute

Actively monitor and manage reservoir production
Determines Abandonment Conditions
- Technical condition
- Economical condition

Abandon Reservoir?
Sell the field to low cost operating company?

Potential further field development

- Exploration
- Acceptable Uncertainty
- Update estimation
- More Exploration

An illustration of offshore oil/gas field in deep water

Some other types of facility:

Surface well head on Tension Leg Platform
Production Facility
Pipeline
Temporary crude storage facility
Subsea wells
Mobile drilling unit

Background - cont.

- An illustration of offshore oil/gas field in deep water

- Mobile drilling unit
- Production Facility
- Pipeline
- Temporary crude storage facility
- Subsea wells

- Surface well head on Tension Leg Platform
- Mobile drilling unit
- Production Facility
- Pipeline
- Temporary crude storage facility
- Subsea wells

Some other types of facility:
Motivation

- Large-scale engineering systems, such as offshore oil gas platforms, are very complex in nature due to the interactions among multiple disciplines, such as reservoir engineering, facility designs, project economics, etc.

- Existing tools are very domain specific and a lot of integration effort is required from decision makers in the early field development stages.

- Furthermore, multi-billion dollars investment decisions on offshore infrastructure have to be made under a wide range of uncertainties such as reservoir, market conditions, and political environment uncertainties. Traditional practice of designing the “optimal” facility to the specifications potentially leads to undesired outcomes (e.g., opportunity loss, high risk).

- Therefore, there is a need for major oil companies to think more strategically in their offshore oil and gas development.

Research Questions

- The key research questions are:
  - **Modeling**: How to model the essential interactions among multiple disciplines for strategic decision making in offshore field development?
  - **Flexibility**: How can flexibility in design and operation improve projects expected value under uncertainties?
  - **Strategic Engineering Framework**: In the context of offshore oil and gas projects, how to develop a strategic engineering framework for field development which is robust and adaptive to future environment?
Overview of Model Structure

- Conceptual structure
  - Integrated Modeling and Simulation
    - Reservoir dynamics model
    - Facilities model
    - Economics model
  - Standardization
    - Commonality
    - Learning effect
    - Bulk effect
  - Flexibility
    - Configuration flexibility
    - Operation flexibility
    - Flexibility valuation

- Implementation structure
  - GUI
  - Five reservoir operation modes
  - parafile.mat
  - reservoir.m
  - q_rates
  - q_capacities
  - facilities.m
  - OPEX
  - CAPEX
  - finance.m
  - NPV.m

Model Capabilities

- The integrated model intends to consider following the scenarios (with focus on B and D)
  - Staged Development
    - Standardization
    - Flexibility
  - Tie-back options
    - Flexibility
  - Staged development of a large reservoir
  - Tie-back a small reservoir
  - To facility 5 as capacity becomes available
  - number of facility
  - number of reservoir
  - # of Facilities
  - # of Reservoirs
  - Staged Development of a large reservoir
  - Tie-back a small reservoir
  - To facility 5 as capacity becomes available
Multi-reservoir Multi-facility Integrated Model

Different Simulation Options

(1) Reservoir Dynamics Module
(2) Facility Module
Feedback (economic recovery rate)
(3) Project Economics Model
(4) Simulation Control

Reservoir dynamic model

- A simplified reservoir with water / gas / aquifer drive
- Five reservoir operation modes
  1. Primary depletion
  2. Water drive
  3. Aquifer drive
  4. Gas cap drive with gas injection
  5. Combination drive
Parametric facility cost model

- Develop facility cost –capacity parametric model using OGM software and Design of Experiment (DOE) method for Steel Pile Jacket substructure

\[ \hat{y} = A\hat{x} + B \]

- A linear relationship seems to capture the facility cost - capacity model very well

- Compare predictions of facility model with OGM model outputs
- The average error for field development cost is less than 3%

Typical flow rates and cash flow profile for oil/gas project

- CAPEX: equally spread out in project development phase
- Learning effect on CAPEX reduction for stage development: define learning factor internally (e.g., 90%)
- OPEX: fixed OPEX + variable OPEX
Applications of Integrated Model

Uncertainty and flexibility in oil field project

- Multi-stage strategy to take into account uncertainties

<table>
<thead>
<tr>
<th>Deterministic inputs:</th>
<th>Baseline NPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 50% OOIP</td>
<td></td>
</tr>
<tr>
<td>• Bespoke facilities design</td>
<td></td>
</tr>
<tr>
<td>• Fixed oil/gas market price</td>
<td></td>
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</tbody>
</table>

| Reservoir: OOIP               |              |
| + Bespoke Design              |              |
| + Oil / gas price             |              |

Traditional Practice:
Single number for NPV as decision Making criteria

New Paradigm:
Value-at-Risk-Gain Curve (VARG)
- Expected NPV
- Maximal Gain
- Maximal loss
- Reduced initial CAPEX
- Value of Flexibility

| Reservoir: OOIP               |              |
| + Flexible, staged facilities + decision rules | NPV distribution + RU + MU + flexible, staged facility |
| + Oil / gas price             |              |

| Reservoir: OOIP               |              |
| + Flexible facilities + decision rules + tie-back flexibility | NPV distribution + RU + MU + flexible facility + tie-back option |
| + Oil / gas price             |              |

RU: reservoir uncertainty
MU: market uncertainty
Reservoir uncertainty

This green line represents one instantiation of estimation of mean for STOOIP over time (many possible trajectories!)

With flexibility, decision making is based on current estimation of STOOIP

"underlying" STOOIP (unknown!)

Acceptable range to start development (execution)

Number of years for field development and operation

Distribution of reservoir volume estimation

- Assume initial estimation of reservoir volume follows some distributions, e.g.,
  - Normal distribution with negative tail cutoff
  - Lognormal distribution (using in practice)

Learning processes will narrow the distribution of STOOIP over time.

The standard deviations for blue, green, and red curves are: [600 1279 3146] mmstb.
Market uncertainty

- Crude oil price constantly changes over time
- Field development strategy needs to adapt accordingly
- Some mathematical techniques are available to model price evolution (e.g., binomial tree model)

### Binomial tree model

- Initial oil price: $35
- Drift rate: $0.02$ per annum
- Volatility: $0.1$ per annum
- Drift rate + $2$% per annum
- $T_{max} = 30$ years
- $\Delta t = 3$ years

\[ u = e^{\mu \Delta t} \]
\[ d = \frac{1}{u} \]
\[ \Delta = \sigma \sqrt{\Delta t} \]
\[ p = \frac{e^{\mu \Delta t} - d}{u - d} \]

This figure shows that different STOIP estimates can lead to different optimal facility sizes.

Bespoke design

- Given P50 estimation of STOIP, design a facility to optimize project NPV
- Bespoke designs for different STOIP estimations (400, 800, 1600 mmstb)

This figure shows that different STOIP estimates can lead to different optimal facility sizes.

Single factor facility sizing: $\alpha^*$ [200 150 150 200] mbd or mmscf/d for [Total fluid rate, oil production rate, gas production rate, water production rate]
**Bespoke designs + reservoir volume uncertainty**

- Bespoke designs for three STOOIP estimates (800, 400, and 1600 mmstb)
- Monte Carlo simulation (2000 runs) for each bespoke design with OOIP uncertainty (normal distribution, mean 800, std 400, cutoff at 5)

This figure shows that different bespoke designs will behave differently under reservoir uncertainty:
- Bigger facility can take larger upside opportunity but will potentially lose big
- Smaller facility is a relative conservative strategy

**Flexibility in oil/gas field development**

- There are many possible ways to embed flexibility into oil/gas field development:
  
  **Field level**
  - Postpone, abandon field development.
  - Add new platforms, tie-back other reservoir fluids to platforms, etc.

  **Platform level**
  - Capacity expansion (i.e., add extra water injection equipment)

  **Operational level**
  - Well and production management (i.e., shut down wells, increase / decrease water injection volume)
Pre-determined vs. Flexible Staged Development

Compare three field development strategies:

1) Pre-determined staged development
   - Three identical stages (33% capacity each) in year 0, 2 and 4
   - 90% learning factor on CAPEX reduction

2) Flexible staged development
   - Stage options: 33%, 50%, 100% capacity
   - 1~2 stages (33%, 100%, 100% + 50%, 100% + 100%) depending on STOOIP estimates
   - A decision rule has been coded in the program to determine when to add additional stage with how much capacity

3) One big monolithic facility development
   - Single stage in year 0 with 100% capacity

Decision rules for flexible staged development

- This is an example of the decision rule

```
S(t0) ≤ 1200 mstb
  No action

S(t0) ≥ 1200 mstb
  33% capacity
  Add 50%

S(t) ≤ 4000
  100% capacity
  Add 50%
  Add 100%

S(t) ≥ 4000
  Add 100%

S: estimation of STOOIP over time
P: oil price over time
```

*Adding stage can be made only when P(t)>$35
Pre-determined three stages development

Production and injection profiles, RF = 48.3512% (total 21 years)

Clone facilities

1st facility

2nd facility

3rd facility

Total NPV = 3.6468 Bn $ in 21 years

1 stage development (one big monolithic facility)

Production and injection profiles, RF = 48.2282% (total 21 years)

Assume 3.25 years development time

5 years for drilling ramp up 90 wells!

Total NPV = 4.3884 Bn $ in 21 years

No learning benefit
Comparison results

In this simulation case study, the flexible staged development strategy is better than the single stage big monolithic facility:

- Increases ENPV by 1.79 Bn.
- Allows to increase capacity when it is needed, as a result, it can take significant amount of upside opportunity (6.71 Bn).
- Decreases maximal downside loss by 1.34 Bn.
- Decreases minimal initial CAPEX by 1.72 Bn.

Key factors for Expected NPV

The figure on the left shows the relative importance of several factors on project ENPV. The top three factors are:

- Market Uncertainty
- Reservoir Uncertainty
- Discount rate

A design of experiment is conducted to study the relative importance of these factors contributing to ENPV.

The exact sequence or relative importance scale will depend on the various assumptions and range of levels for each factor.
Contributions and Future Work

- The main expected contributions are followings:
  - Operationalize Strategic Engineering (system design for uncertainty environment, flexibility in design) in the context of oil/gas field development project.
  - Demonstrate the integrated technical / economical modeling and simulation as an approach for Engineering Systems design.

- Future work
  - Apply the models and approaches to a real offshore oil/gas field development.
  - Propose a generic Strategic Engineering framework to be applicable to large-scale infrastructure systems.

Back up slides
How does estimation of Recovery Factor (RF) change over time?

This green line represents one instantiation of estimation of mean for RF over time (many possible trajectories!)

- RF doesn’t necessarily converge uniformly to a value!
- e.g., slight increase of RF due to active reservoir well management
- e.g., when oil price increase significantly, enhance recovery technique become economical, injection of miscible gas CO₂ to enhance oil recovery
- e.g., discover new information about reservoir: fractured reservoir

How does estimation of Recovery Factor (RF) change over time?

Start appraisal

Acceptable range to start development (execution)

Decision rules for flexible staged development

This is an example of the decision rule

- Initial stage
  - 33% capacity
  - 100% capacity

- No action
  - 33% capacity
  - 100% capacity

- Add 50%
  - 33% capacity
  - 100% capacity

- Add 100%
  - 33% capacity
  - 100% capacity

- Add 50%
  - 33% capacity
  - 100% capacity

- Add 100%
  - 33% capacity
  - 100% capacity

S: estimation of STOIQP over time
P: oil price over time

- S(t₀)

- <1200 mstb
  - 33% capacity
  - 100% capacity
  - No action
  - Add 50%
  - Add 100%
  - Add 50%
  - Add 100%

- ≥1200 mstb
  - 33% capacity
  - 100% capacity
  - No action
  - Add 50%
  - Add 100%
  - Add 50%
  - Add 100%

*Adding stage can be made only when P(t)>35