Spatial aspects in decision making applied to Oil & Gas production systems

Flow Assurance problem

in the context of the exploitation of deepwater and ultra-deepwaters fields

French project

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For the benefit of business and people
1. Introduction

2. Usual offshore decision problems

3. Utility theory applied to the Flow Assurance problem (new technologies)

4. Use of risk or decision methods

5. Conclusion
The final development stage of the Marlim field will include seven floating production platforms and one floating storage unit.
1 Introduction

Offshore field: general configuration
Usual offshore decision problems

Precision of the estimation (% of the total cost of the project)

Studies

-30%

0

+30%

Preliminary studies
Conceptual studies
Pre-project
Basic engineering
Detailed engineering

Definition of the final concept

Choosing a production system

"Prospect" studies

Potential cost reduction according to the various steps
Usual offshore decision problems

Prospect studies

VAN: Net Actual Value

Reservoir size: 250 Mb? With VAN=320 M$

- No prospect
  - 250 Mb: VAN=320
  - > 250 Mb: VAN=400
  - <250 Mb: VAN=200
  - nothing

Prospect Cost $C_p$

Prospect Cost $C_p$

Diagram showing decision tree for reservoir size and associated VAN values.
Deepwater production system for a development offshore West Africa.

**Choices:**
1) **act early and buy a production system** that could be adapted in case the reservoir turned out to be larger than expected
2) **wait for more information and optimize the size of the system.**

**Early decision**
- quicker production of first oil
- flexibility to allow for future additions of fluidprocessing modules or wells
- based on minimal information.

**Drill more wells**
- acquire more information
- buy a production system optimized for the reservoir size
- additional expense, production delay

Four development concepts under consideration.

*Two concepts were adaptive structures*
- the Aker adaptive spar
- DPS-2000.

*The other two were designs that could be optimized to suit the reservoir size:*
- a Floating Production, Storage and Offloading (FPSO) system
- optimized spar.

All four concepts allowed oil storage.

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*Schedule of Decision Tree events. The adaptive concepts start first and produce first, while production from the optimized projects lags by about 18 months.*
Flow Assurance

Basic Offshore Production system

Two types of failures:
- Failure of equipments
- Failure of flow

Characteristics of deepwater & ultradeepwater fields:
- Severe environmental conditions
- Unaccessibility of equipments

FPSO (Surface unit)
Subsea production system
- Flowlines-risers
- Manifold
- Well heads
- Well jumpers

MeOH injection system and Pump

Command system
- Subsea distribution systems
- Umbilicals

Maintenance system (ROV – subsea)
Decision steps

1) The problem
2) The technologies
3) Performances Criteria
4) Utility functions
Minimisation of unavailability due to curative maintenance operations
Flow Assurance

Physical Chemistry phenomena

- Hydrate risk:
  - Prevention solution: insulation of the flowline for keeping high temperature (>30°)
Fluid flow

Various types of flows in vertical and horizontal pipes

Successive inflows of waves of gas and waves of liquids in separators leading to stops of production
Thermal management

Two types of regime:

**Permanent regime**
- Key point: wax formation
- Key parameter: U-value

**Transient regime**
- Key point: hydrates formation
- Key parameter: CDT-value

U-value: Equivalent heat exchange coefficient

CDT: Cool Down Time
Time, in case of interruption (ordinary shutdown), for reaching the critical temperature for hydrates formation
Flow assurance

Contractor

Operator

Technologies

Operating strategy

Safety policy as a tool in new technologies offering

Thermal stakes

Design flow lines:
- With high insulation
- Able to maintain the flow at high temperature during flowline interruption
Two kinds of technologies:

**Passive systems** fulfil their thermal functions without energy from the surface

**Active systems** fulfil their thermal functions using energy from the surface

In that case, surface installations are more important because they have to include power generators.
Passive systems:

Pipe in Pipe (usual technology)

2 Coaxial Pipes
External pipe insure pressure protection
**Insulation sealed by polyurethane foam**

CDT: low or middle
U-value: low (an U-value low corresponds to a good insulation)

Bundle gel (new technology)

2 parallel lines **insulated by gel**

CDT: high
U-value: low

Criteria of comparison:

- **Cost**
- **System availability (functioning time)**
- **Maturity**

Usual Design philosophy:
Justify an U-value equal to 1 W/m²K
### Design exemple : FPSO Girassol

<table>
<thead>
<tr>
<th></th>
<th>U value</th>
<th>Insul Thk</th>
<th>OD bundle</th>
<th>OD ILS</th>
<th>CDT (45-20)</th>
<th>Design criteria</th>
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<td></td>
<td></td>
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<tr>
<td>Gel Bundle</td>
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<td></td>
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<td></td>
<td>18.6</td>
<td>U value</td>
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<tr>
<td>Gel + ILS bundle</td>
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<td></td>
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<td>559</td>
<td>27.9</td>
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(PUF – Mousse de polyuréthane)

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<tr>
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<tr>
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<th>Design criteria</th>
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<td>596</td>
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<td>CDT</td>
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<tr>
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<td></td>
<td>1000</td>
<td>700</td>
<td>170.5</td>
<td>CDT</td>
</tr>
</tbody>
</table>

**Ordinary Section (0.9)**

**Parts of the flowline with connections: insulation less effective (U>1)**
Main stake:

To master flow assurance along distances more and more important where:

- *Risks are « more and more » important*

- *Environmental conditions are « more and more » severe*

For defining new technologies, contractors have to know attitude of operators against risk.
The critical time for hydrate formation is a function of 5 driving parameters:

- **P1**: manifold pressure (Pa)
- **T1**: manifold temperature (K)
- **GOR**: overall fluid gas oil ratio (Sm3/m3)
- **WC**: water cut production relative to the nominal oil production as it affects significantly the pressure profile in the system (-)
- **QBBBL**: total liquid production (bbl/d)

**Also an important parameter is the U-value**: Equivalent heat exchange coefficient relative to inner diameter (W/m²/K)
3 Flow Assurance

Under the following assumptions:
- Initial pressure and temperature conditions in the line are provided by TACITE steady state calculations.
- The local fluid composition is only gas (pure methane), since it is the worst case for cool-down estimation and hydrate stability curves.
- The local cool-down process is supposed to happen at constant pressure.
- The cool-down process takes into account wall thermal inertia,

\[
P_2 = f_{P_2}(GOR, WC, QBBL, P_1, T_1, U\text{value})
\]

\[
T_2 = f_{T_2}(GOR, WC, QBBL, P_1, T_1, U\text{value})
\]

The critical time for hydrate formation is evaluated as a function of \(P_2\) and \(T_2\) and so as a function of the 5 driving parameters and the U-value:

\[
t_{cr2} = f_{T_{cr2}}(GOR, WC, QBBL, P_1, T_1, U\text{value})
\]
Unique Response Surface of the critical time for hydrate formation as a function of the five driving parameters and the U-value (Pipe-in-Pipe technology)

$$t_{cr2} = 30.609 + 0.044*GOR - 1.702*P1 + 1.945*QBBL + 2.265*T1 - 4.683*UValue + 0.45*WC - 0.015*GOR*WC - 0.071*P1*QBBL + 0.24*P1*UValue - 0.037*QBBL*UValue - 0.252*QBBL*WC - 0.318*T1*UValue + 0.131*P1^2 - 1.001*QBBL^2 - 0.121*T1^2 + 0.65*UValue^2$$

Critical time density estimate assuming $U=1.5 \text{ W/m}^2/\text{K}$

Cumulative distribution of the critical time under various assumptions on the U-value
3 Flow Assurance

Extrapolation to Availability (1)

Model is integrated with fluids characteristics
availability of the system

Shutdown & hydrates critical time distributions

Probability of hydrate formation
given an operational shut down
- Maintenance strategy including ordinary shutdowns
- Shutdown time distribution
- Identification of the most critical locations for hydrate formation
- Critical time for hydrate formation
- Time of repair in case of hydrate formation

Probability distribution function of availability

<table>
<thead>
<tr>
<th>PiP availability (end life)</th>
<th>93.8% (337.7 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bundle gel availability</td>
<td>96.5% (347.4 days)</td>
</tr>
</tbody>
</table>
The problem is to choose between several flow assurance technologies (Pipe-in-Pipe and Bundle Gel). In particular the goal of the study was to compare insulation systems for different types of flowlines as a means to deal with flow assurance issues.

The preferences of two groups of operators have been elicited thanks to two contractors who had an extensive experience of dealing with these groups of operators respectively. That’s means the preferences of operators are assessed through an intermediary person.

Three attributes (i.e. partial choice criteria, that can help discriminate between various design options) have also been identified:

- **Maturity**
- **Availability**
- **Competitiveness**

Each technology $k$ is characterised by some level of each selected quality or attribute

$$V_k = (\tilde{x}_1^k, \tilde{x}_2^k, \ldots, \tilde{x}_n^k)$$

$\tilde{x}_i^k, i=1,n :$ probability distribution function of quality $i$ for the technology $k$
The objective is to identify how potential buyers of technologies value the different qualities when they decide to buy. Objective is fulfilled by building a scoring function $S_c(k)$ which synthesizes the attitude of operator $c$ regarding the technology $k$.

$$S_c(\bullet) = S_c(\tilde{x}_1, \tilde{x}_2, \ldots, \tilde{x}_n)$$

Optimizations consist for each contractor to present each client $c$ the technology $V_{k^*}$ such that:

$$k^* = \arg \max S_c(k)$$

Steps of the decision procedure according to the usual Multi-attribute Theory (Keeney and Raiffa, 1976)

- For each attribute, definition of an index according to a scale of some undefined mathematical nature
- "Preferences elicitation" and determination of "partial utility functions"
- Determination of the functional form of the multi-attribute function (MAUF)
- Determination of the scale coefficients of the MAUF
« Maturity »: this attribute corresponds to a combination of factors that characterizes a technology (e.g. whether it has been field proven or not). The underlying scale for this attribute ranges from 1 (lowest maturity) to 10 (highest maturity).

« Availability »: this attribute corresponds to a yearly rate of availability for the flowline, that depends among other factors from the cooldown time that resulted from the insulation (in case of an interruption in production) and from its proneness to failure (e.g. the fact that it may not prevent the adverse phenomena that we mentioned in the introduction). The underlying scale for this attribute was measured in days per year, from 330 to 359 days. This range corresponds to the range that has been probabilistically predicted for the technologies that were to be compared ultimately.

« Competitiveness »: this attribute takes into account the CAPEX of a technological solution, its installation costs and its OPEX. The competitiveness has been assessed on a relative scale, that is by comparison with other solutions available on the market: a score of 0.7 represented an additional cost of the technology in the amount of 30%, a score of 1.3 represented an advantage in terms of costs of 30% by comparison with the average price for a substitute (that did not necessarily however have the same features in terms of maturity and availability).
Utility functions: Determination of the partial utility functions - principle

Each consequence $x_i$ is replaced by the following lottery:

$$
\begin{array}{c}
\pi_i & x^* \\
1-\pi_i & x_i \\
\end{array}
$$

avec $x^* = \text{Max}\{x_i\}$ et $x^* = \text{Min}\{x_i\}$

With $\pi_i = U(x_i)$, the generic lottery will be evaluated by:

$$
\sum_i p_i \pi_i = \sum_i p_i U(x_i)
$$

Generic lottery

Expected value?

Utility functions: Determination of the partial utility functions - principle
Utility functions : Determination of the partial utility functions - principle

flow Assurance

« Equivalent certain » method

\[ U(x') = 0.5u(x^*) + 0.5u(x) = 0.5 \]
\[ U(x') = 0.5 \]

\[ U(x'') = 0.5u(x^*) + 0.5u(x') = 0.75 \]
\[ U(x'') = 0.75 \]

Equivalent probability method

\[ U(x) = pU(x^*) + (1-p)U(x^*) \]
so:
\[ U(x) = p \]
Interview of 2 engineers about operators preferences for availability of the system, the cost and the maturity.

Utility functions: determination of the partial utility functions - interview to encode
These curves show that operator T is more averse to non qualified technology.

**U₁ (maturity) for operator T**

![Graph showing U₁ for operator T with Bundle and PiP labels.]

**U₁ (maturity) for operator E**

![Graph showing U₁ for operator E with Bundle and PiP labels.]

Utility functions: determination of the partial utility functions - interview to encode.
These curves show that operator E is less influenced by the cost difference criteria than operator T.

U₃ (competitiveness) for operator T

U₃ (competitiveness) for operator E
First of all, each partial utility function for company E is a concave transformation of that of company T. E exhibits therefore a stronger risk aversion than T, regardless of the attribute. This means in practice that E would be much warier of the variability (in terms of performance and competitiveness) that is characteristic of a novel technology features than company T. However, the difference seems to be less drastic for the « availability » criterion. This is consistent with what has been observed elsewhere, in that availability is a direct approximation of the operating cost.
Flow Assurance

\[ V_k = (\tilde{x}_1^k, \tilde{x}_2^k, \ldots, \tilde{x}_n^k) \]

\[ S_c(\bullet) = S_c(\tilde{x}_1^*, \tilde{x}_2^*, \ldots, \tilde{x}_n^*) \]

\[ k^* = \arg \max S_c(k) \]

\[ E[S_{ci}^k(\tilde{x}_i)] \]

**Expected Utility Rule**
(from Neumann & Morgenstein)

Under different assumptions, we have three usual forms:

**Additive form**
\[ E[S_c(\tilde{x}_1, \tilde{x}_2, \tilde{x}_3)] = c_1 E[s_{c1}(\tilde{x}_1)] + c_2 E[s_{c2}(\tilde{x}_2)] + c_3 E[s_{c3}(\tilde{x}_3)] \]

**Multiplicative form**
\[ E[S_c(\tilde{x}_1, \tilde{x}_2, \tilde{x}_3)] = \prod_{i=1}^{\max} \left\{ k c_i E[s_{ci}(\tilde{x}_i)] + 1 \right\} \left( \frac{1}{k} - \frac{1}{k} \right) \]

**Multilinear form**
\[ E[S_c(\tilde{x}_1, \tilde{x}_2, \tilde{x}_3)] = c_1 E[s_{c1}(\tilde{x}_1)] + c_2 E[s_{c2}(\tilde{x}_2)] + c_3 E[s_{c3}(\tilde{x}_3)] + c_{12} E[s_{c1}(\tilde{x}_1)] E[s_{c2}(\tilde{x}_2)] + c_{13} E[s_{c1}(\tilde{x}_1)] E[s_{c3}(\tilde{x}_3)] + c_{23} E[s_{c2}(\tilde{x}_2)] E[s_{c3}(\tilde{x}_3)] + c_{123} E[s_{c1}(\tilde{x}_1)] E[s_{c2}(\tilde{x}_2)] E[s_{c3}(\tilde{x}_3)] \]
The determination of scale coefficients is achieved using choices between hypothetic alternatives:

\[ p \Rightarrow (X_1^*, X_2^*, \ldots, X_n^*), \quad (X_1^0, X_2^0, \ldots, X_i^*, X_{i+1}^0, \ldots, X_n^0) \]

\[ 1-p \Rightarrow (X_1^0, X_2^0, \ldots, X_n^0) \]
3 Flow Assurance

Utility theory: Comparison of technologies

<table>
<thead>
<tr>
<th>Operator T</th>
<th>Operator E</th>
</tr>
</thead>
<tbody>
<tr>
<td>PiP</td>
<td>bundle</td>
</tr>
<tr>
<td>U₁ (maturity)</td>
<td>1</td>
</tr>
<tr>
<td>U₂ (Availability)</td>
<td>0.3</td>
</tr>
<tr>
<td>U₃ (cost)</td>
<td>0.55</td>
</tr>
<tr>
<td>k₁</td>
<td>0.368</td>
</tr>
<tr>
<td>k₂</td>
<td>0.369</td>
</tr>
<tr>
<td>k₃</td>
<td>0.114</td>
</tr>
<tr>
<td>k</td>
<td>0.647</td>
</tr>
</tbody>
</table>

Substituting partial Utility in global utility formula

\[ 1 + kU_t(x_1,\ldots,x_n) = \prod_{i=1}^{n} [kk_iU_i(x_i) + 1] \]

<table>
<thead>
<tr>
<th>Global Uₜ (T, PiP)</th>
<th>Global Uₜ (T, Bg)</th>
<th>Global Uₜ (E, PiP)</th>
<th>Global Uₜ (E, Bg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.069</td>
<td>0.125</td>
<td>5.734</td>
<td>6.388</td>
</tr>
</tbody>
</table>
Use of risk & decision methods

| Criteria     | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T |
| Numerical analysis |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| DCF analysis  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Holistic view |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Monte Carlo   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Risk/uncertainty |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Portfolio theory |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Options theory |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Preference/utility |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Qualitative/quantitative |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |

Ranking companies by their level of decision-making sophistication. Research done at the University of Aberdeen showed that the decision-making practices of 20 companies (labeled A to T) active in the North Sea correlate well with the success of their investment decisions. Companies scored highest (red) if they fully implemented the decision-making criteria shown in ascending order of sophistication in the left column. If the criterion was partially implemented by the company, a green square is indicated in the chart. Uncolored squares indicate that the company did not use the particular risk-assessment method.

From «taking a calculated risk», William Bailey and coll., Oilfield review, 2000
Conclusion

- Use preference of operators in the choice of the technology to be offered to operators
- Tool for stakeholders
- Help for decision making
- Tool for design of technologies
- Tool for the qualification process of technologies
- Common work in the project between companies with different cultures
### Performance criteria

**Pipe in pipe**

**CoolDownTime (hours)**

\[
CDT = \frac{m_{\text{steel}} \cdot C_{p_{\text{steel}}} + m_{\text{gas}} \cdot C_{p_{\text{gas}}} \cdot \ln\left(\frac{T_{in} - T_{ext}}{T_H - T_{ext}}\right)}{U \cdot S}
\]

**U value (W/m²K)**

\[
U = \frac{1}{\frac{1}{2\lambda_{\text{acier}}} \ln\left(\frac{OD_{\text{piped}} + 2w_{\text{piped}}}{{ID}_{\text{piped}}}\right) + \frac{1}{2\lambda_{\text{isolant}}} \ln\left(\frac{OD_{\text{pipe}} + 2w_{\text{insul}}}{ID_{\text{piped}}}\right) + \frac{1}{2\lambda_{\text{air}}} \ln\left(\frac{ID_{\text{pipeext}}}{OD_{\text{insul}}}\right) + \frac{1}{2\lambda_{\text{steel}}} \ln\left(\frac{OD_{\text{pipeext}}}{ID_{\text{pipeext}}}\right)}
\]
Flow Assurance

Input parameter distributions

Pipe in pipe

Conductivity variation follows:

thickness insulation follows:

thickness steel follows:
Flow Assurance

Global distribution of Performance

Pipe in pipe

Regression sensitivity for PiP U value

Regression sensitivity for PiP CDT

Second Conference IFED, Lake Louise, Canada, April 26-29, 2006
**Bundle Case**

- OD internal pipe 1
- OD internal pipe 2
- δ spacing
- ID Carrier
- Conductivity

**Input parameter distributions**

- Distribution for écartement [mm] / variable
- Distribution for épaisseur Pipe interne [mm] / variable
- Distribution for conductivity [W/mK] / variable
- Distribution for ID Carrier [mm] / variable

**Flow Assurance**

- OD internal pipe 1
- OD internal pipe 2
- δ spacing
- ID Carrier
- Conductivity

**Flow Assurance**

- OD internal pipe 1
- OD internal pipe 2
- δ spacing
- ID Carrier
- Conductivity
Distribution for U bundle [W/m²K] / variable/E48

Distribution for CDT bundle [heures] / variable/E49

Regression sensitivity for Bundle U value

Regression sensitivity for Bundle CDT

Global distribution of Performance

Flow Assurance