Economic Evaluation of Propulsion Systems
for LNG Carriers:
A Comparative Life Cycle Cost Approach

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Daejun Chang, Taejin Rhee, Kiil Nam, Sejoong Lee
Byungjin Kwak, Jongpil Ha

Hyundai Heavy Industries
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Propulsion System for LNG Carriers

- LNG carriers are getting bigger with their route longer.
- Several new propulsion systems were introduced.
  - Two of them have started their service.
  - The others are waiting for commercialization.
- More design freedom for choice of propulsion systems
- Guidelines for system selection:
  - Safety
  - Economics
  - Operational convenience
  - etc.
Economic Analysis

- Principles to improve economics of propulsion systems;
  - The propulsion system should be reliable.
  - BOG should be used or recovered as much as possible.

- Little attention to rigorous economic analysis and life-cycle optimization;
  - How reliable the propulsion system should be?
  - How much the BOG should be used or recovered?
  - The system is overdesigned or underdesigned?
  - Which option is the best for a fixed condition?
OBJECTIVES OF STUDY

- To suggest an unbiased economic evaluation method

- To relate the quality of the system (reliability and efficiency) to the economic value of the system

- To prove the validity of the methodology by presenting case studies
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Options for LNGC Propulsion

- Categorization
  - Fuel Flexibility: Duel Fuel (DF) or Single Fuel (SF)
  - Prime Mover: Steam Turbine, Diesel Engine, Gas Turbine
  - Nature of Drive: Electrical or Mechanical Driven
  - BOG Recovery: Recovered or Consumed as Fuel

- Comparison Set

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Name</th>
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<tbody>
<tr>
<td>DFSMR</td>
<td><strong>Dual-Fuel</strong> Steam turbine <strong>Mechanical</strong> propulsion, Reheating</td>
</tr>
<tr>
<td>DFDE</td>
<td><strong>Dual-Fuel</strong> Diesel Electric (medium speed)</td>
</tr>
<tr>
<td>DFDM</td>
<td><strong>Dual-Fuel</strong> Diesel Mechanical (low-speed)</td>
</tr>
<tr>
<td>SFDM+R</td>
<td><strong>Single-Fuel</strong> Diesel Mechanical with Reliquefaction (low speed)</td>
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System Boundary Definition

- Apple-to-Apple comparison does not hold because of the severe interaction between the three systems: main engines, electric generation, and BOG treatment.

- Unclear system boundary leads to biased comparison or wrong conclusions.

- For impartial comparison, the scope of the propulsion system should consist of:
  - Main engines
  - Electric generators
  - BOG treatment system
Measure of Economic Performance

- Measure for key cost parameters
  - Fuel cost
    - Engine efficiency
  - Delayed delivery due to propulsion failure
    - Availability for propulsion function, \( A_p \)
  - BOG burning due to BOG treatment failure
    - Availability for BOG treatment function, \( A_{BOG} \)

- Other costs
  - Electric consumption other than propulsion
  - Delayed penalty
  - Maintenance cost (corrective and preventive)
  - etc.
Comparative Life Cycle Cost

Life Cycle Cost (LCC)
- Sum of all the costs over ship’s life cycle
- Two components;
  - CAPEX: CAPital EXpenditure (capital cost)
  - OPEX: OPerating EXpenditure (operating cost)
- Enormous efforts required to estimate the LCC

Comparative LCC
- To neglect the common parts and focus on the different parts.
- To concentrate on cost rather than profit since profit is fixed for fixed performance.
- To consider the loss of profit due to poor performance.
Components of Comparative LCC

Income over life cycle

Profit

LCC

LCC^C

LCC^P (Propulsion)

CAPEX^P

OPEX^P

- Equipment failure
- BOG evaporation
- Delayed delivery penalty
- Fuel consumption
- Maintenance
- ......
Components of Annual OPEX\textsuperscript{p}

\begin{itemize}
\item \( C_1 \) Delivery loss cost due to propulsion failure, $/yr
\item \( C_2 \) Natural BOG loss cost due to BOG evaporation, $/yr
\item \( C_3 \) BOG loss cost due to BOG treatment failure, $/yr
\item \( C_4 \) Penalty cost due to delayed delivery, $/yr
\item \( C_5 \) Fuel consumption cost for propulsion, $/yr
\item \( C_6 \) Fuel consumption cost for BOG treatment, $/yr
\item \( C_7 \) Fuel consumption cost for GCU operation, $/yr
\item \( C_8 \) Lubricant consumption cost, $/yr
\item \( C_9 \) Preventive maintenance cost for propulsion system, $/yr
\item \( C_{10} \) Corrective maintenance cost for propulsion system, $/yr
\end{itemize}
How to estimate the component cost: Example

\[ C_1 : \text{Delivery loss cost due to propulsion failure, \$/yr} \]

\[ C_1 = N_{\text{Voyage}} \cdot (M_{\text{Offload}} \cdot C_{\text{CIF}} - M_{\text{Load}} \cdot C_{\text{FOB}}) \cdot UAP \]

- **No of annual voyage**
- **Propulsion unavailability**
- **Value of offloaded LNG**
- **Value of loaded LNG**

**Benefit/voyage**

**Loss of benefit due to propulsion failure per voyage**
Procedure of Comparative LCC

Step 1: Define the system configurations and functions.
   - System configuration
   - Design specification

Step 2: Assess the system performance.
   - Electric load analysis
   - Fuel (BOG and liquid oil) consumptions

Step 3: Estimate the availability.
   - Reliability block diagram
   - Availability for propulsion and BOG treatment functions

Step 4: Assess the comparative life cycle cost.
   - CAPEXP and OPEXP
   - LCCP
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### Case Study I: Conditions and Assumptions

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<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Port-Port</strong></td>
<td>Ras Laffan, Qatar - Corpus Christi, USA</td>
<td></td>
</tr>
<tr>
<td><strong>Cargo capacity</strong></td>
<td>210,000</td>
<td>m³</td>
</tr>
<tr>
<td><strong>Boil-off rate</strong></td>
<td>0.14</td>
<td>%/day</td>
</tr>
<tr>
<td><strong>BOG rate</strong></td>
<td>5.7 (laden)</td>
<td>ton/hr</td>
</tr>
<tr>
<td></td>
<td>2.6 (ballast)</td>
<td></td>
</tr>
<tr>
<td><strong>Voyage duration</strong></td>
<td>1,088</td>
<td>hr (one-way)</td>
</tr>
<tr>
<td><strong>Main engine operation</strong></td>
<td>998</td>
<td>hr (one-way)</td>
</tr>
<tr>
<td><strong>BOG generation</strong></td>
<td>1,028</td>
<td>hr (one-way)</td>
</tr>
<tr>
<td><strong>No. of voyage</strong></td>
<td>8.1</td>
<td>/yr</td>
</tr>
</tbody>
</table>
Additional Information Required

- Capital cost
- Fuel (LNG, HFO, MDO) cost
- Failure rate and repair time
- Man hour rate
- Inflation rate
- . . .

The results of the LCC analysis are case-specific.
Propulsion Options Compared

DFDE I with four engines without any redundant engine (4 x 25 %)

DFDE II with four engines with one redundant engine (4 x 33 %)

DFDM with two engines without any redundant engine (2 x 50 %)

SFDM+R with two engines without any redundant engine (2 x 50 %)

DFSMR with three turbines in series (1 x 100 %)
Cost Structure: CAPEX^P/LCC^P

- CAPEX^P is less than 8% for all options.
- OPEX^P governs LCC^P.
Cost Structure: Component Cost of OPEX

- The sum of the BOG loss and fuel cost \((C_2 + C_5)\) is dominant.
- The delivery loss due to propulsion failure is significant for DFDE I.
LCC^p for Propulsion Options

- DFDE I has the largest for high failure rate or low propulsion availability.
- Is SFDM+R inferior to the others?
Acceptance Criteria

- The less its LCC\(^p\) is, the better the option is.
- The uncertainty in cost parameters should be considered.
- For an option to be accepted, its LCC should be less than that of the others in spite of the uncertainty.

\[
LCC^p_A + \sigma_A < LCC^p_i - \sigma_i \quad \text{for all } i \neq A
\]

\[
\sigma^2_A = \sum \sigma^2_{A,j} \quad \text{for all component } j
\]

» Sensitivity analysis
Sensitivity Analysis for Fuel Price

- HFO Price
  - Option 1
  - Option 2
  - Option 3
  - SFDM+R
  - Option 4

- LNG Price
  - Option 1
  - Option 2
  - Option 3
  - SFDM+R
  - Option 4
Case Study II: Redundancy Issue

- Reliable components do not necessarily mean a reliable system.
- Process configuration with redundancy may improve the process availability.
- Increased redundancy
  - Increased Profit
  - Increased CAPEX
  - Increased OPEX due to maintenance

- Guideline for redundancy design
  - Profit should be ‘much’ greater than the cost since profit is usually less than expected and cost is more than expected.

\[
\text{Profit} > \text{DF} \cdot (\text{CAPEX} + \text{OPEX})
\]

\text{disproportionate factor}
Redundant Engine: DFDE I and II

- One redundant engine increases the propulsion availability ($A_p$) or the deliverability.

- *Is the redundant engine worth installing?*

- Cost and benefit of systems without and with the redundant engine.
  - Increase in availability = 0.092
    - Increase in benefit = 470,000 US$/yr or c.a. 9,300,000 $/20 yr
  - LCC = capital cost + maintenance cost

- DFDE II is acceptable if the LCC for one additional engine is much less than 9 million dollars. ➔ Positive
Redundant Compander for BOG Reliquefaction

- One redundant compander set increases the BOG recovery availability ($A_{BOG}$).

- *Is the redundant compander worth installing?*

- Cost and benefit of systems without and with the redundant compander.
  - Increase in availability = 0.007
    - Increase in benefit = 71,000 US$/yr or c.a. 1,500,000 $/20 yr
  - LCC = capital cost + maintenance cost

- The additional compander is acceptable if its LCC is much less than 1.5 million dollars. ➔ *Negative*
CONCLUSIONS

1. A comparative LCC approach was suggested to include the performance of the main engines, BOG treatment, and electric generation with common parts neglected.

2. The CAPEX was less than 8% of the comparative LCC, implying that optimization efforts should focus on minimization of the OPEX.

3. Of the OPEX, the fuel cost including the BOG took the major share while both the GCU operation cost and the lubricant cost were negligible.

4. When the fuel cost was changed, the option SFDM+R remained relatively invariant. This observation was attributed to the segregation of the propulsion and BOG treatment functions with the BOG recovered.
5. Improvement in the propulsion availability seemed plausible for DFDE types

6. Installing an additional compander for SFDM+R was considered unattractive.

7. In terms of LCC, the optimal option is case-specific, not universal, and the final selection should be made with uncertainty of the key parameters analyzed.