A System Dynamics approach for managing the LNG procurement for an Offshore platform feeding a power plant

ENRICO BRIANO
CLAUDIA CABALLINI
DAVIDE MODULA
ROBERTO REVETRIA
ALESSANDRO TESTA

DIPTEM – Department of Industrial Production, Technology, Engineering and Modelling
Via Opera Pia 15, 16145, Genoa, ITALY
enrico.briano@dipconsortium.org; claudia.caballini@unige.it; davide.modula@dipconsortium.org;
roberto.revetria@unige.it; alessandro.testa@unige.it

Abstract - The purpose of this study was the development of a simulation model to verify the logistic feasibility of the construction of a new regazification offshore terminal feeding a power plant located in Africa, subjected to a possible future doubling. In particular the model was used to test the proper supply of LNG (Liquefied Natural Gas) in the power plant real operating conditions and with particular reference to certain sizing configurations of vessels involved (dimensional range for tank buffer, shuttle ship size range). The model, taking into account sea conditions data available on site, extensively characterized during the oceanographic studies made, and with reference to defense works type realization and preliminary sizing (and specifically the breakwater dam and the its effect on the perturbation conditions in the proximity of the ship's mooring points) has assessed the risk of the power plant supply failure and the consequent lack of production (Unavailability of LNG or shut down). Moreover, the model estimated, for the scenarios simulated, the residence berthing times, the maximum frequency of unloading and the mooring / unmooring frequency reachable.

Key Words – Simulation, What if analysis, Logistics, System Dynamics

1. The Model Specification

By a caisson breakwater dam is moored a buffer-tank vessel capable of storing LNG. The ship is connected to a gas plant installed on a fixed platform, which feeds a landside power plant ground with combined-cycle gas turbine. The scenario provides a system of shuttle vessels capable of supplying the LNG necessary to the unit permanently moored in order to provide the power plant functioning. Naval shuttle units, starting from the liquefaction terminals (Guinea and / or Qatar), will reach ship-tank and proceed to the unloading of LNG that will be stored on board and re-gasified according to the operative conditions of the power plant. The gasifier will transform the LNG in gasified NG and send it to gas turbine plant.

A rendered representation of the offshore platform is provided in Figure 1.
Here below are the detailed logical and functional characteristics of the model developed in reference to the following operations:

1. LNG supply.
2. Loading profile of the plant and discharge rate of shuttle ships.
3. Calculation of demurrage time and costs
4. Safety stock level.

The contract for the LNG supply will most likely not directly stipulated by the power plants with gas supplier countries, but will be delivered by a consortium of investors, in order to acquire, as well as greater bargaining power, even greater operational flexibility. It was thought in this regard, the establishment of a pool with other regasification plants in Spain and this was expected that, if the vessel arrives later failing the lead time deadline of dedicated shuttle ships, to divert to Africa one of the ships directed daily to Spanish terminals, in order to perform a partial discharge at the plant: this ship was named, for simplicity, spot ship. The next shuttle ship will refund the gas discharged from the spot ship (in other words, if shuttles have a capacity of 140,000 cubic meters and the spot ship has discharged 35,000 cubic meters of LNG, during the next trip the shuttle can be discharge into the platform only 105,000 cubic meters of LNG.). The model can simulate three different alternatives:

- a dedicated shuttle ship;
- two dedicated shuttle ships;
- emergency spot ship where the cycle times of dedicated ships are unable to comply with the proper feeding of the plant.

For what concern the LNG origin, two geographical areas have been identified (but the model is able to set other), whose characteristics are reported in Table 1. On the contrary, spot ships shall be considered always available when required.

Table 1: Traveling and loading times for shuttle ships

<table>
<thead>
<tr>
<th>LNG Origin</th>
<th>Ongoing Travel Time</th>
<th>Coming Back Travel Time</th>
<th>Loading Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guinea</td>
<td>130 hours</td>
<td>130 hours</td>
<td>29 hours</td>
</tr>
<tr>
<td>Qatar</td>
<td>333 hours</td>
<td>333 hours</td>
<td>29 hours</td>
</tr>
</tbody>
</table>

For what concern the approaching maneuvers to the dam, the shuttle ship, once arrived at the harbor gate, makes two preliminary checks:

1. **Light conditions.** The ship can carry out the entering maneuver only in daylight, considering the time of the year.

2. **Marine weather conditions.** In terms of certain marine parameters (wavelength, wind direction, etc...) the vessel may be unable to carry out the maneuvers of entry. The weather and sea conditions affect, once entered inside the dam perimeter, also the LNG pumping capability. By worsening of weather conditions is necessary to quickly unmoor the ship. Regarding the emergency unmooring procedure, while the ship arrives in harbor, the weather is monitored for the next 18 hours. If an emergency unmooring is needed, the vessel will not enter in 80 cases out of 100. This is
to simulate the mechanism of marine weather forecast that can be used to decide to postpone a berth in order to avoid the risks and costs of an unmooring and a new mooring procedure. The percentage of 80% was included to allow the possibility that the forecast is incorrect.

Once verified the possibility of entering, the vessel carries out the coupling to the jetty and proceed with the operation of coupling pipes, cooling pipes, pumping until the shuttle ship is empty, drainage pipes and release. During these operations are continuously performed checks on weather: if they are no longer satisfying, the vessel interrupts the current operation, and carries out the maneuver whether an emergency unmooring is required. In case of unmooring, the ship disengages from the platform going to the harbor gate and then repeats all the operations carried out previously once appropriate weather conditions are restored.

In the case everything will be successful, once dropped the arms, the ship disengages from the platform to return to the port of origin, waiting for the next scheduled mission.

The Flow Chart in Figure 2 shows the logic at the basis of the model that has been implemented:

![Flow Chart](image)

**Figure 2: Offshore Platform Flow Chart**

The cycle of the shuttle ship provides the sequence of logic states at which transactions are executed: these states have previously been shown in the Figure 2 flow chart. The table in Appendix 1 shows the time distribution according to a triangular one, in which the maximum, the minimum and more likely times are reported.

For what concern the power plant workload three different scenarios have been implemented, considering three different maximum gasifying capacities for the power plant., whose values are presented in Table 2:

**Table 2: Gasifying Capacity for the three scenarios**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1E+09</td>
<td>365</td>
<td>98%</td>
<td>24</td>
<td>1.28E+05</td>
<td>213.56</td>
</tr>
<tr>
<td>2.2E+09</td>
<td>365</td>
<td>98%</td>
<td>24</td>
<td>2.56E+05</td>
<td>427.11</td>
</tr>
</tbody>
</table>
At present only the second scenario, because more compelling has been simulated due to limited implementation time. The plant workload profile is variable daily with also a 30% decrease respect to the peak workload registered. It has been clarified with the plant owners that there are no significant variations during the year (it means no seasonality). The demand reductions are often concentrated in the night hours, but there is no linking to this trend and a typical daily or weekly variability profile.

During the simulation two workload hypothesis have been considered:

- A constant consumption corresponding to the 100% of the plant nominal power (427,11 m³/h)
- A constant consumption corresponding to the 92% of the plant nominal power (393 m³/h)

The pumping rates (from the shuttle ship to the buffer tank) varying according to the scenario considered; in other words, according to the plant workload profile, the shuttle ship will transfer the LNG quicker to the buffer tank. The transfer rate will vary according to a triangular distribution as following in table 3:

Table 3: Transfer rate for the shuttle ships

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Optimistic</th>
<th>Most Likely</th>
<th>Pessimistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7777.78 m³/h</td>
<td>6086.96 m³/h</td>
<td>5000 m³/h</td>
</tr>
<tr>
<td>2;3</td>
<td>10000 m³/h</td>
<td>10000 m³/h</td>
<td>7368.42 m³/h</td>
</tr>
</tbody>
</table>

Another operation taken into account is the calculation of the demurrage times and costs: for the former it is intended the time interval from the ship arrival to the harbor gate until the end of the unmooring operation, while the latter is a function of two parameters: the demurrage time and the ship type. The calculation of the annual demurrage costs was made with the only purpose of providing an indication of the ability of terminal to properly ship it direct.

Regarding the safety stock analysis, a model on the sea conditions in the dam and their translation into the docking and pumping possibility has been developed. These reviews have revealed the boundary conditions in terms of waves, wind and current, to:

- perform mooring / unmooring maneuvers;
- make unloading;
- remain moored to the terminal.

Based on these results, three Boolean variables have been associated with any condition of the historical data series, indicating the positive or negative status associated with the three options above.

Analyzing the duration of periods when sea conditions remain above the berth threshold of operation two scenarios for the safety stock level have been identified. Such scenarios should ensure both the planning of any spot ship and the correct advance with which vessels should occur when the storage becomes empty in relation to seasonal sea conditions.

2. The proposed Approach

The logistics of the LNG supply was modeled through the use of detailed models developed by DIP Consortium, in cooperation with the University of Genoa Department of Engineering (DIPTEM), who are able to provide a true representation of the processes involved. In particular, model development was focused on the logistic aspects, leaving the "productive" process (everything downstream the Buffer Tank) as a possible next step. The battery limits
of the model are upstream, such as the calls for shuttle vessels devoted to feed the LNG of the plant, and downstream, depending on the load profile of the power consumption of LNG. The simulator allows the simulation of different plant conditions:
- Changes to the inputs of the system (power absorbed by the plant).
- Changes to the parameters of a single block / process (running time and macro-process)

The primary use of the model was the performance of "what if" analyses for assessing the logistic solution with lower cost and LNG unavailability. The model has been set, both for the methodology and the characteristics of the package chosen, in order to be extended, if necessary, to all the logistic management operations, making the model a true and open application structured able to grow with the needs of the owner.

The model has been developed using the System Dynamics methodology, particularly suitable for complex systems in which external conditions, such as weather, play a great role. The System Dynamics is an approach devoted to understand the behavior of complex systems over time, considering internal feedback and delays logical steps that affect the behavior of the whole system. These elements help describe how even seemingly simple systems are subject to a disconcerting non-linearity. System Dynamics is a methodology developed at the Massachusetts Institute of Technology (MIT) in 1950 as a tool for managers to analyze complex problems. Its main audience is still composed by managers, even if it has spread widely in academia.

For the simulation model will be used the simulation platform Powersim Studio 8 ™ Expert. The Powersim simulations are based on System Dynamics. The dynamic simulation with Powersim Studio 8 ™ Expert allows businesses to create and analyze future scenarios in a controlled, user-friendly scenario. The simulation model management is achieved through specially dashboards by which users can act on decisional levers having an immediate output in graphical form, easily exportable to the most common tools of Office Automation like MS-Excel, MS-Access, etc… In addition, data can be readily acquired through ODBC connection, from any relational database. The result is an incredible benefit for companies performing decision-making, operational, tactical or strategic activities. The platform Powersim Studio 8 ™ Expert has a sophisticated Risk Evaluation engine that includes in any model all the sensitivity assessment features and bandwidth of confidence results.

3. The Validation Phase

In order to verify the consistency of the model with the real system the walk-through methodology was adopted. This method describes the inspection process of algorithms and source code. The purpose of this procedure is to provide a warranty of fitness for purpose of the algorithm or code, and to assess the completeness of the model implemented.

In order to make a proper validation of the model without any code errors masked by the behavior of the stochastic model, validation was performed in a deterministic system. This simplification will be overtaken once validated the model and the integration of the stochastic system will be carried out.

The validation procedures are concerned:
1. The interaction of the weather conditions during the shuttle ship cycle and the loading of the Buffer Tank.

2. The calculation of demurrage costs in relation to the "loading time".

Regarding the first point, depending on weather and sea conditions of the breakwater dam surroundings, it is possible to have the following critical conditions:

1. **Entrance into the dam.** If this condition is not satisfied, the vessel cannot perform the maneuvers of entry and it must remain at anchor until the weather conditions stabilize.

2. **Arms coupling and pumping phase.** If this condition is not satisfied, the vessel may stay moored inside the dam but it cannot pump the LNG to the Buffer Tank since it cannot be maintained the adduction LNG link between this and the shuttle.

3. **Emergency Unmooring.** In case that this condition has occurred, the ship must stop all ongoing operations and exit from the dam. The ship will remain at anchor until the weather conditions stabilize. Once inserted again within the dam, the ship will end pumping the LNG remained in the hold.

It is worth highlighting that every shuttle vessel in the model leaves the origin port full and returns empty, downloading all the LNG content, regardless of time needed for that cycle.

Figures from 3 to 10 show the behavior of the model in relation to the vessel unloading, the duration of the adverse weather conditions and depending on the type of the simulated weather and sea conditions.
Figure 6: Validation of the model in the pipe-coupling phase: adverse weather conditions for 12 hours.

Figure 7: Validation of the model in the LNG pumping phase: favorable weather conditions.

Figure 8: Validation of the model in the LNG pumping phase: adverse weather conditions for 6 hours.

Figure 9: Validation of the model case of emergency unmooring during the pipe-cooling phase: adverse weather conditions for 6 hours.

Figure 10: Validation of the model case of emergency unmooring during the pumping phase: adverse weather conditions for 6 hours.

For what concerning the demurrage costs, they depend on the discharge time, in particular of hours exceeding 48 hours of discharge. In other words, for all operating times below this value (48 hours) the cost is zero, for higher values it must be paid in proportion to the number of excess hours.
4. The simulated scenarios

The authors have implemented in the model three different scenarios:

1. dedicated Ships from Guinea with the possibility of a spot ship restoring
2. dedicated Ships from Qatar with the possibility of a spot ship restoring
3. dedicated Ships from Qatar and Guinea (1 x) with the possibility of a spot ship restoring

In scenarios it is configured the amount that the spot ship must unload in the buffer: 1, 2, 3 or 4 holds (typically 35,000 cubic meters of LNG each).

In order to understand the significance and the importance of the factors involved (size of the shuttle ships, safety stock level, etc...) on the target functions (LNG unavailability and the logistic configuration costs), the simulator has been used to conduct a correct experimental campaign. The response surface was detected using the DOE (Design Of Experiment) methodology using a $2^4$ factorial design, in which the factors analyzed are:

1. Shuttle Ship 1 size
2. Shuttle Ship 2 size
3. Safety Stock configuration
4. Possibility to enter in the harbor during the night hours

As previously stated, the first scenario foresees the LNG procurement from shuttle ships arriving only from Guinea and, in this case, the Response Surface Methodology (RSM) has underlined the following results for what concern the logistic configuration costs:

![Figure 11: Response Surface of the logistic costs in function of the ship sizes](image)

Figure 11 shows that the logistic configuration cost depends only on the size of the two shuttle ships, and that it is scarcely influenced by the spot ship presence because of its very low frequency (0-1 ships every 10 years)

For what concern the LNG unavailability the results are provided in Figure 12:

![Figure 12: Response Surface of the LNG unavailability depending on the safety stock and the possibility to enter the harbor in the night](image)

Figure 12 shows that the unavailability is below 1% only when the safety stock level is high and there is the possibility to enter in the harbor in the night, while the shuttle ship capacity is not a significant factor for the regression analysis.

Analyzing the results of the second scenario it is possible to state that this solution is not feasible because of the longer distance (from Qatar instead of Guinea), so no regression analysis on this scenario has been performed.

The last simulated scenario foresees the procurement with a shuttle ship arriving form Guinea and one from Qatar. The cost of the configuration was mainly
influenced by the size of the shuttle ships but also on the level of stocks: in particular, the larger is the ship shuttle 2 (Qatar) and the greater is the cost.

For what concern the LNG unavailability, the most significant factors are the same of the first scenario, but in a less marked way, as shown in figure 13.
Figure 13: Response Surface of the LNG unavailability for the third scenario

5. Conclusion

In order to identify the best logistic solution for the LNG procurement for a gas turbine plant, a simulation model has been implemented using the System Dynamics methodology, particularly suitable for this kind of system because of its complexity. Once determined the model specification, a validation campaign has been performed, with a particular focus on the sea and weather conditions and their impact on the procurement operation. After the validation phase the model has been run in three different scenarios, with the shuttle ships coming from Guinea (Scenario 1), Qatar (Scenario 2) and both (Scenario 3). Analyzing the results with the Design of Experiment (DOE) and the Response Surface Methodology (RSM), the best solution to adopt is to procure LNG from Guinea, because of lower lead times and, consequently, lower costs and unavailability, especially in case of shuttle ships with bigger capacity.

The simulation model, thanks to its decisional cockpit, allows formulating “What if” analysis, varying ships, plants and buffer capacity, generating dozen of different scenarios that can be analyzed in the future as further developments.

References

### Appendix 1 – The Triangular Time Distribution

<table>
<thead>
<tr>
<th>Dam Entering Times</th>
<th>Mooring Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most Likely</td>
<td>Optimistic</td>
</tr>
<tr>
<td>Depends on distance, no longer than 20/24 min.</td>
<td>108 min.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pipe Coupling</th>
<th>Pipe Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most Likely</td>
<td>Optimistic</td>
</tr>
<tr>
<td>54 min.</td>
<td>36 min.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pipe Drainage</th>
<th>Pipe Unlinking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most Likely</td>
<td>Optimistic</td>
</tr>
<tr>
<td>72 min</td>
<td>144 min.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unmooring</th>
<th>Dam Quitting Times</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most Likely</td>
<td>Optimistic</td>
</tr>
<tr>
<td>72 min</td>
<td>72 min</td>
</tr>
</tbody>
</table>