Automatic Scheduling System of LNG Storage Operations Using Mathematical Programming

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1. Background

The Osaka Gas Senboku LNG Terminal began handing LNG imports from 1972. The suppliers were diversified as the quantity of LNG purchases increased. The terminal presently receives a total of about 5 millions of LNG per year from projects in seven countries.

Senboku LNG Terminal II comprises 18 LNG tanks, 2 berth for receiving LNG, and pipelines (specifically, the receiving pipeline system that connects LNG tankers to storage tanks, the distribution pipeline system that runs from the tanks through the gasification line to send out natural gas to end users, and pipelines for the transfer of LNG among the storage tanks). Figure 1 presents the outline of Senboku LNG Terminal II. This terminal receives LNG tankers in accordance with LNG receiving schedules that are arranged in advance, and sends out natural gas to end users in line with demand forecasts. As for natural gas sent from this terminal, the heating value in each moment has to be higher than 44 MJ/Nm^3 and the average heating value per month has to be nearly equal to 45 MJ/Nm^3. To achieve these goals, operators choose the tanks for receiving or sending LNG, and control the volume of LNG by the transfer of LNG among the storage tanks. This series of works is collectively referred to as “LNG storage operations.” LNG storage operations are exceedingly difficult works because the LNG tank consumption volumes vary by season, the LNG heating values differ by production location, and the LNG terminal pipeline networks are extremely complex. Furthermore, physical phenomena, like “LNG roll-over” which is occurred when different LNGs are mixed, must be considered.

To date, daily schedules for LNG storage operations have been made manually. Because the diversity of the heating values of received LNG has increased with the diversity of LNG projects, however, the making of daily schedules for LNG tank operations has become far more difficult. On the other hand, demand uncertainties caused by global economic instability and structural changes in the LNG market make it necessary to simulate future LNG storage operations before deciding the design or investment of future LNG facilities.

To address these issues, we developed a system using mathematical programming which automatically derives daily schedules for LNG storage operations.

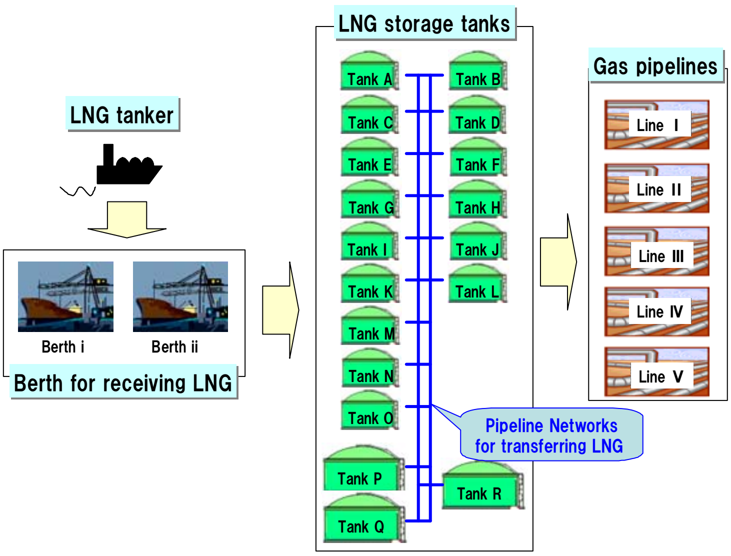


Figure 1. Outline of Senboku LNG Terminal II

2. Purpose

In the past, operators have made daily schedules for LNG storage operations using the following type of sequential simulation.

1. Make the Day N schedules for LNG storage operations based on the inventory conditions (liquid level and heating value) in each tank at the end of the Day N-1.
2. Calculate the inventory conditions in each LNG tank at the end of the Day N based on the inventory conditions in each tank at the end of the Day N-1 and the Day N schedules for LNG storage operations.
3. Repeat steps 1 and 2 until the end of the scheduling period.

The works burden of making daily schedules for LNG storage operations is heavy because these schedules have to be revised every time changes are made to LNG receiving schedules or to gas demand forecasts. Also, it is almost impossible to make a 365-day simulation for future scheduling which is necessary for arranging the facilities of an LNG terminal. The purpose of this research is to develop a system that can automatically derive daily schedules for LNG storage operations for different conditions in a short period of time, in order to solve these problems.

3. Methodology

The LNG storage operations are modeled using mathematical programming.

First the equilibrium conditions of the LNG inventory volume and heating value are formulated. Because a linear approximation can be made between the heating value and the density, the heating value is converted to density for the formulation. Specifically, as shown in Figure 2, the principles of volume preservation and conservation of mass are formulated considering 1) receiving from LNG tankers, 2) transferring LNG from other tanks, 3) transferring LNG to other tanks, 4) sending natural gas to end users, 5) the generation of BOG (boil off gas) in the tanks, and 6) LNG circulation for pipeline cooling.

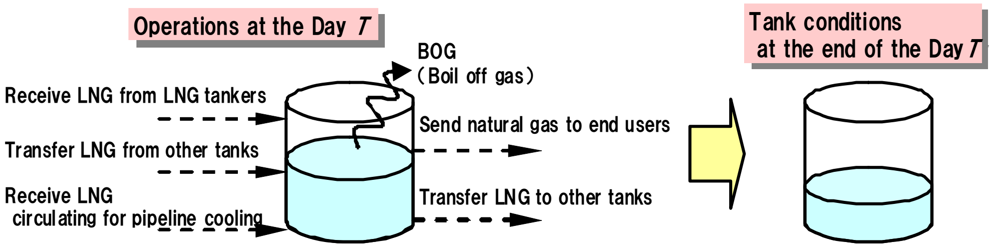


Figure 2. Inventory Volume Change Factors in LNG Storage Operations

Next, the LNG storage operations are categorized into three operations—that is, receiving operations, transferring operations and sending operations—and the constraints for each of these operations (Figure 3) are all formulated.

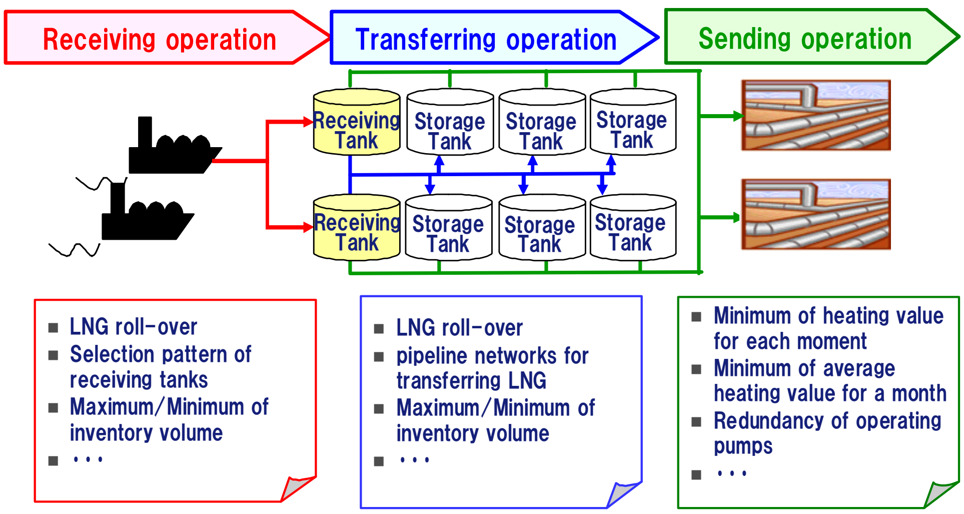


Figure 3. Constraints in LNG Storage Operations

Because the heating value (≈ density) constraints are nonlinear constraints and the pipeline networks constraints are discrete constraints, the overall problem becomes a large-scale nonlinear mixed integer programming problem. As a result, it was not possible to solve within a practical calculation period. We successfully developed a solver that can conduct the calculations in a short period of time through dividing the problem into a nonlinear programming problem and a mixed integer programming problem and also using the high-speed, nonlinear solver developed by Mathematical Systems Inc.

4. Results

To verify the effectiveness of this system, we derived an LNG storage operations plan by inputting the LNG receiving schedule for Senboku LNG Terminal II shown in Figure 4 and the demand forecasts presented in Figure 5.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	○		○			○	○					○			

17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
○			○					○				○		○

Figure 4. Daily LNG Receiving Schedule

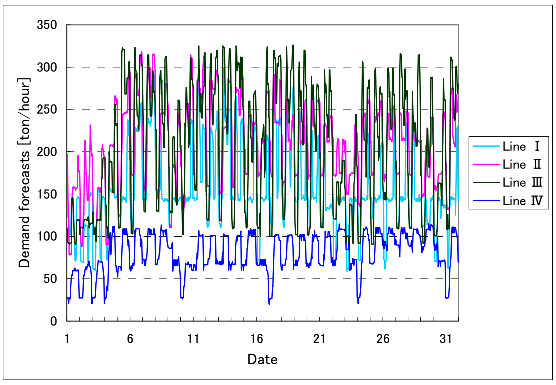
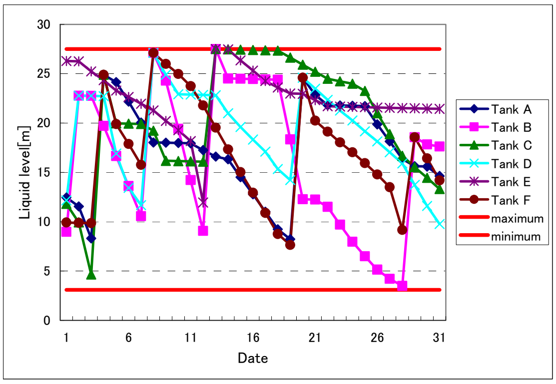


Figure 5. Hourly Demand Forecasts

The results concerning LNG Tanks A-J are presented in Figures 6-9. Figure 6 presents the changes in the liquid level in each tank for the coming 31 days. Figure 7 shows the amounts and breakdowns of LNG that can be distributed from each LNG Tank A-J to Line I at each point in time. These results demonstrate that the system can derive daily schedules for LNG storage operations that observe the minimum and maximum liquid level requirements in each tank while still meeting demand.



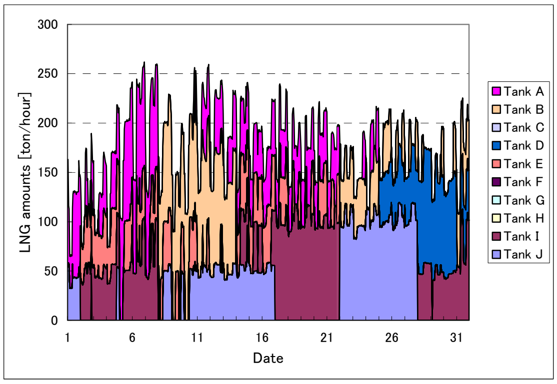
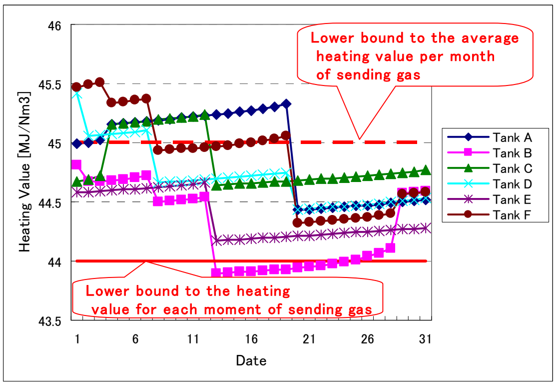


Figure 6. Liquid Level in Tanks A-F

Figure 7. LNG Amounts Sent to Line I

Next, Figure 8 presents the heating value in each LNG tank, and Figure 9 shows the heating value sent through Line I. The upper and lower lines on each graph represent the maximum and minimum limits of heating value for natural gas distributed to end users. These findings show that even when the inventory heating value in each tank greatly varies, the heating value distributed to end users can still meet the maximum and minimum control limits.



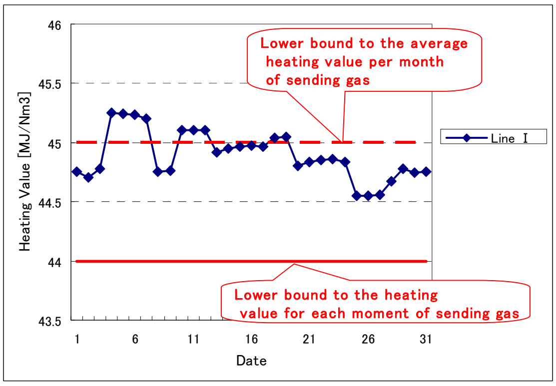


Figure 8. Heating Values in Tanks A-F

Figure 9. Heating Values Sent through Line I

5. Conclusion

We developed a system using mathematical programming which automatically derives daily schedules for LNG storage operations, for the stable conduct of LNG tank operations. This system can be used to derive daily schedules for LNG storage operations for the subsequent month in about 15 minutes. The system can also be used to make daily schedules for LNG storage operations for an entire year. Moreover, the system can derive more accurate schedules for LNG storage operations through restrictions about physical phenomena, such as LNG roll-over.

This automated system can be used to support the following three types of decisions.

1. Swift decisions on the ability to receive LNG tankers when changes are made to LNG receiving schedules (e.g., receiving of LNG spot tankers);
2. Capital investment decisions using the results of LNG storage operations simulations for preparing facilities plans; and
3. Decisions on participation and purchasing in new LNG projects using the results of LNG storage operations simulations.

Osaka Gas will continue working for stable and efficient LNG storage operations utilizing this system together with our accumulated LNG storage operations know-how.