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Gas-producing operation at LNG receiving terminals by using mathematical science and operations research methodologies

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ABSTRACT

Tokyo Gas receives over 300 liquefied natural gas (LNG) vessels annually from all over the world. Operators allocate the vessels to three LNG terminals and manage the inventory of approximately 50 LNG tanks for stable city gas production under many constraints, such as calorific value adjustment, pipeline capacity, and vaporizer capacity. In particular, calorific value adjustment causes operational difficulties; Japanese city gas must be adjusted to a constant calorific value (in the case of Tokyo Gas, 45 MJ/m3N) determined by contracts with customers, which is a situation peculiar to Japan. Hence, operators must mix LNG of various calorie levels in tanks and add high-calorie LPG to fulfill the calorific constraints during the city gas production process. Minimizing LPG usage is also a key issue since LPG is more expensive than LNG in general. Therefore, the inventory must be managed in view of the need for cost reduction as well as stable gas production.

To solve these operational difficulties regarding LNG and LPG inventory management, we developed a new optimization model using mathematical science and operations research methodologies. The technical ingenuity of this study is as follows: The calorific value of city gas is a nonlinear function of its volume, and such a large-scale nonlinear optimization problem is quite difficult to solve. Therefore, we applied some heuristic rules to the model so that it could be approximated by linear programming. This enabled the problem to be solved within a realistic period.

The new model can help in devising an annual operational plan that satisfies the need for cost minimization and operational stability. The necessary planning time is also dramatically reduced to 10-15 minutes from 2-3 days. Tokyo Gas now utilizes this new model for decision making about facility investments in addition to its 2014 annual operational plan.

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1. Introduction

Tokyo Gas is Japan's largest city gas supplier, with over 10 million customers. It vaporizes liquefied natural gas (LNG) imported from other countries and supplies it as city gas and fuel gas for power generation to customers.

We receive over 300 LNG vessels annually at three terminals in Negishi, Sodegaura, and Ohgishima from all over the world, including countries and states such as Malaysia, Brunei, Australia, Alaska, Qatar, and so on. Operators allocate the vessels to the three LNG terminals and manage the inventory of LNG tanks for stable city gas production under constraints such as calorific value adjustment, pipeline capacity, and vaporizer capacity. In particular, calorific value adjustment causes operational difficulties; Japanese city gas must be adjusted to a constant calorific value (in the case of Tokyo Gas, 45 MJ/m^3N) determined by contracts with customers, which is a situation peculiar to Japan. Hence, operators must mix LNG of various calorie values in tanks and add high-calorie LPG to fulfill the calorific constraint during the process of producing city gas. Minimizing LPG usage is also a key issue since LPG is generally more expensive than LNG; therefore, the inventory must be managed in view of the need for cost reduction as well as stable gas production.

2. The unloading arrangement for LNG vessels and tank inventory management

In this section, we give an overview of the unloading arrangement for LNG vessels and tank inventory management. The imported LNG is received in berths at each terminal. Berths are the facilities at which LNG and LPG carriers dock, and they are equipped with unloading arms for transferring the LNG from the carriers to the terminal. There are the compatibility constraints between ships and the berths; therefore, whether LNG vessels can be received or not depends on the ship type and berth vacancy. Also, there are other compatibility constraints between the LNG tanks and the LNG projects because of their calories and composition. Hence, in which tank out of the Tokyo Gas's approximately 50 LNG tanks the unloaded imported LNG to be stored is determined in advance of its unloading. In the vaporizers, LNG flows at a temperature of -160 degrees through aluminum pipes that are warmed from the outside with seawater to return the LNG to a gaseous state. The calorific value of LNG varies according to the source and, for use as city gas, the calorific value adjustment mixers maintain the calorific value at a fixed level (in the case of Tokyo Gas, 45 MJ/m3N) based on the addition of high-calorie LPG, which is a situation peculiar to Japan. For its use as fuel for power generation, this calorific value adjustment process is not required. Thus, using the inventory of high-calorie LNG for city gas, as much as possible, leads cost reduction since LPG is generally more expensive than LNG.

3. Problems and objective

The inventory must be managed in view of the need for cost reduction as well as stable gas production under many constraints related to stock, calorific values, and so on. Operators have been allocating LNG vessels to the terminals and managing the inventory of LNG tanks by considering these constraints. Further, they must rearrange the plans whenever there are changes in shipping schedules or fluctuations in the demand for city gas. Such operational constraints and changes make the vessel allocation planning complicated and cumbersome. Therefore, to solve these operational difficulties regarding LNG inventory management, we developed a new method to formulate plans quickly and reduce the required amount of labor.

4. Development of a new method

4.1. Overview

We developed a new optimization model for LNG inventory management using mathematical programming. This is a mathematical method that searches choices to achieve the best outcome (such as maximum profit or lowest cost) while fulfilling the constraint conditions. Formulating all the conditions, such as the objective, constraints, and variables enables us to calculate the optimum result by using the solver for the optimization model. An overview of this model is shown in Table 1.

Table 1. Overview of the developed model

Input data	1) Amount of LNG transferred from ships to tank through berth
	2) Daily demand for city gas and generation
	3) Initial tank condition (amount of LNG in each tank and calorific value)
	4) Shipping LNG volume (domestic trucks and vessels)
Constraints	5) Berth and tank constraints
	6) Transfer and withdrawal constraints of pipelines
Output data	7) Daily ship schedule
	8) Inventory and calorific value of tank
	9) Amount of LPG consumption

4.2. Technical problems for modeling

In this study, there are two major technical problems in developing the optimization model for LNG and LPG inventory management. The first element is the complexity of the mathematically formulated problems. In mathematical programming, it is generally difficult to solve a large-scale optimization problem with numerous variables. Therefore, it is necessary to divide the model into two models. In addition, though it is ideal to set LPG consumption as the objective function for the minimization of production costs, the calculation of the calorific value of LNG is nonlinear, and this model is too large to solve as a nonlinear problem. Thus, we have developed some heuristic rules to solve the model as a linear problem. This enabled us to calculate a solution within a realistic time. The second issue is the need to obtain an operation plan that is suitable for practical use. Since there are various important points both for reducing material costs and for stable operation, we introduce the concept to the objective function of an optimization model.

4.2.1. Large-scale optimization problem

If we describe the ship arrangement and tank inventory management of each tank as one model, it is difficult to solve because of its size. Therefore, we divided the model into two models. The first-step model involves deciding which terminal will receive ships with lesser constraints (ex.: reducing the number of tanks). The second-step model involves developing the tank inventory management plan under the premise that ships considered in the first-step model have been allocated.

In the first-step model, by solving inventory management for the seven groups of tanks (Fig. 1), the ship arrangement for the first two months is decided. In the next two months, the ship arrangement and tank inventory are calculated by locking the results of the ship arrangement until the last month (the tank inventory is calculated again since the joint term every two months is not discontinuous.) This step executes all terms continuously. In the second-step model, the tank inventory in each terminal is calculated based on the ship arrangement results from the first-step model (Fig. 2).

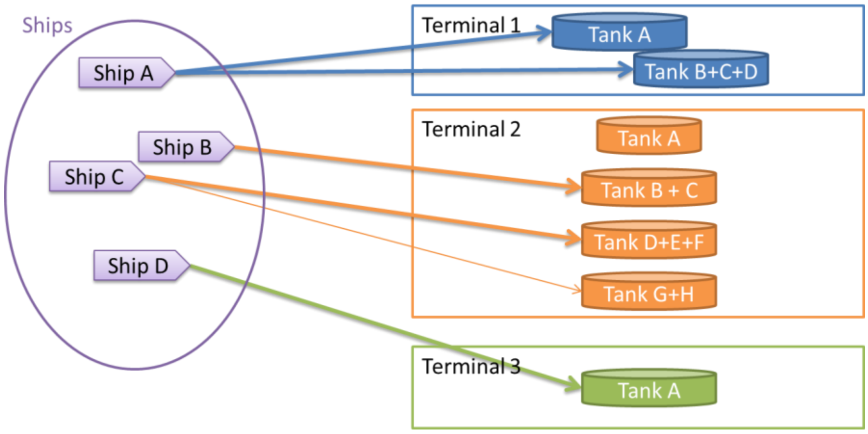

Fig. 1. Outline for the first-step model

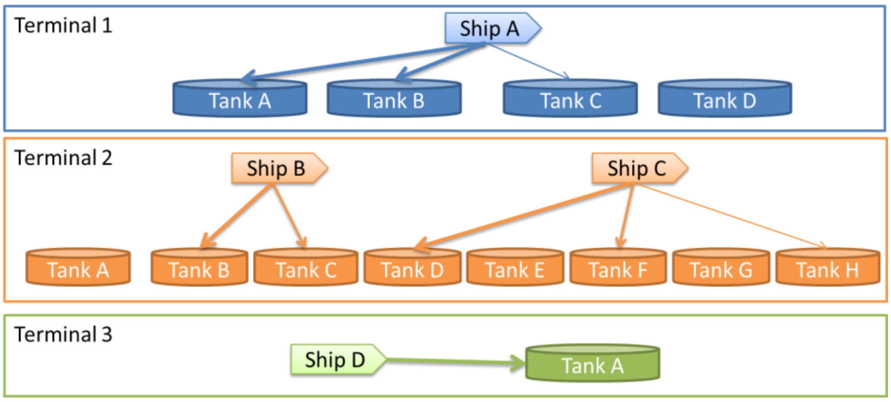

Fig. 2. Outline for the second-step model

4.2.2. Nonlinear problem

Calorific value in a LNG tank moves up/down as time passes because low-calorific value components of LNG are vaporized and various calorific LNG from ships are mixed. That is why we must control the calorific value in LNG tanks not to exceed 45 MJ/m^3N for use as city gas.

The modeling of this LNG calorific value variation is nonlinear, and the model is too large to solve as a nonlinear problem. Therefore, we have developed some heuristic rules to solve the model as a linear problem. We performed modeling as shown in Fig. 3 by using virtual tank calorie points to control the calorific value in each tank.

1. Give the ships the points "SCP_s(*ship calorie point*)" according to the calorific value and by considering the effect of vaporization.
2. Calculate the average retaining time "ART_t" for each tank.
3. Set "$TCP_{t,d}$ (*tank calorie point*)" for each tank. Add "SCP_s" when the tank receives LNG from the ship.

$$TCP_{t,d} = \sum_{d'=d-ART_t}^{d} \sum_{b} \sum_{s} SCP_s * V\_ShipTank_{s,b,t,d'}$$

$$\forall t \epsilon Tank, \forall b \epsilon Berth, \forall s \epsilon Ship,\ \forall d, d' \epsilon Day$$

$$s.t \quad TCP_{t,d}^{min} - P_{t,d}^{cl} \leq TCP_{t,d} \leq TCP_{t,d}^{max} + P_{t,d}^{cu}$$

where

$TCP_{t,d}$: Proxy variable denoting the calorific value of tank *t* on day *d*

SCP_s: Proxy variable denoting the calorific value of ship *s*

$V\_ShipTank_{s,b,t,d}$: Amount of LNG transferred from ship *s* to tank *t* through berth *b* on day *d*

ART_t: Average retention time of LNG in tank *t*

$TCP_{t,d}^{min}$, $TCP_{t,d}^{max}$: Upper and lower limits of $TCP_{t,d}$ in tank *t*

$P_{t,d}^{cl} \geq 0$: Penalty amount for falling below $TCP_{t,d}^{min}$ (lower limit of tank calorie points in tank *t*)

$P_{t,d}^{cu} \geq 0$: Penalty amount for exceeding $TCP_{t,d}^{max}$ (upper limit of tank calorie points in tank *t*)

Fig. 3. Linear formulation for controlling calorific values

Fig. 4 shows examples of unloading arrangements using the $TCP_{t,d}$ (tank calorie points). The left-side section is a good example of controlling the calorific value, which is effectively controlled by storing low-calorie LNG after high-calorie LNG.

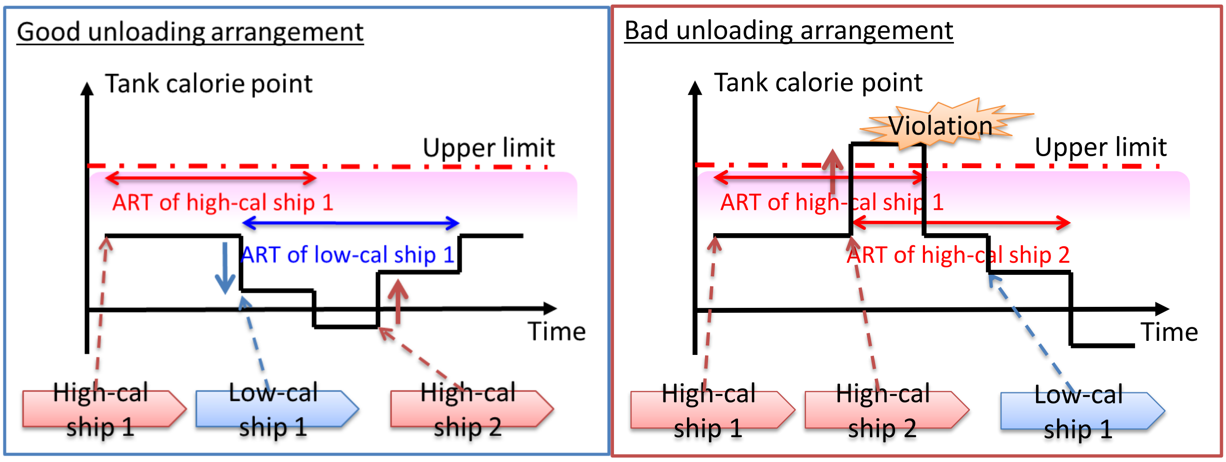

Fig. 4. Examples of linear formulation for controlling calorific values

4.2.3. Objective function suitable for practical use

When we represent an objective function of the model by considering only cost reduction, an impractical solution could be obtained, resulting in, for example, an imbalance in the stock level of LNG in each terminal. Therefore, we set the objective function by weighting the important points of inventory management in view of the need for stable gas production as well as cost reduction (Fig. 5). For instance, since reducing LPG consumption for the calorific value adjustment process leads to cost reduction, we set the weight to achieve a ship arrangement that enables, as much as possible, the use of high-calorie LNG as city gas and low-calorie LNG as fuel gas for power generation.

Minimize

(1) (2) (3) (4)

$$\mathrm{W}^{\mathrm{pb}} * \sum_{d}\sum_{tm} P^{pb}_{tm,d} + \mathrm{W}^{\mathrm{pn}} * \sum_{d}\sum_{b} P^{pn}_{b,d} + \mathrm{W}^{\mathrm{tl}} * \sum_{t}\sum_{d} P^{tl}_{t,d} + \mathrm{W}^{\mathrm{tu}} * \sum_{t}\sum_{d} P^{tu}_{t,d}$$

$$+\mathrm{W}^{\mathrm{vu}} * \sum_{v}\sum_{d} P^{vu}_{v,d} + \mathrm{W}^{\mathrm{cl}} * \sum_{t}\sum_{d} P^{cl}_{t,d} + \mathrm{W}^{\mathrm{cu}} * \sum_{t}\sum_{d} P^{cu}_{t,d} - \sum_{s}\sum_{tm}\{W^{sh}_{s,tm} * N_{s,tm}\}$$

(5) (6) (7) (8)

Purpose of each term

(1) Avoidance of receiving multiple ships at the same terminal in one day

(2) Avoidance of receiving ships for two straight days

(3) Avoidance of falling below tank lower limits

(4) Avoidance of exceeding tank upper limits

(5) Avoidance of exceeding vaporizer capacities

(6) Avoidance of lower limits of tank calorie points

(7) Avoidance of upper limits of tank calorie points

(8) A specific ship is received at a specific tank

Fig. 5. The concept of the objective function

5. Results

We have optimized the annual operation plan by using a solver engine. Table 2 shows a comparison of the human calculations and the model results for calculation time and LPG consumption. Both the time required for planning and LPG consumption amounts were reduced dramatically to 10-15 minutes from 2-3 days and by 86%, respectively. The application results for the ship schedule, calorific value, and inventory in a particular tank are derived as shown in Fig. 6 and Fig. 7. We can evaluate the operational stability using these results. In this way, the new model can enable us to develop an annual operational plan that satisfies the needs for cost minimization and operational stability.

Table 2. Results for calculation time and LPG consumption

	Human calculation	Model result
Calculation time	2–3 days	10–15 minutes
LPG consumption (when the human calculation result equals 1)	1	0.86

<table>
<tr><th></th><th>Terminal 1</th><th colspan="3">Terminal 2</th><th>Terminal 3</th></tr>
<tr><th></th><th>Berth 1</th><th>Berth 1</th><th>Berth 2</th><th>Berth 3</th><th>Berth 1</th></tr>
<tr><td>12/1</td><td></td><td></td><td>Ship Type C</td><td>Ship Type D</td><td></td></tr>
<tr><td>12/2</td><td></td><td>Ship Type B</td><td></td><td></td><td></td></tr>
<tr><td>12/3</td><td>Ship Type A</td><td></td><td></td><td></td><td></td></tr>
<tr><td>12/4</td><td></td><td></td><td></td><td></td><td>Ship Type H</td></tr>
<tr><td>12/5</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>12/6</td><td>Ship Type A</td><td>Ship Type B</td><td></td><td>Ship Type G</td><td rowspan="10">Not Available</td></tr>
<tr><td>12/7</td><td></td><td></td><td></td><td></td></tr>
<tr><td>12/8</td><td></td><td>Ship Type B</td><td></td><td></td></tr>
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<tr><td>12/15</td><td>Ship Type B</td><td></td><td>Ship Type F</td><td></td></tr>
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Fig. 6. Output image of ship schedule

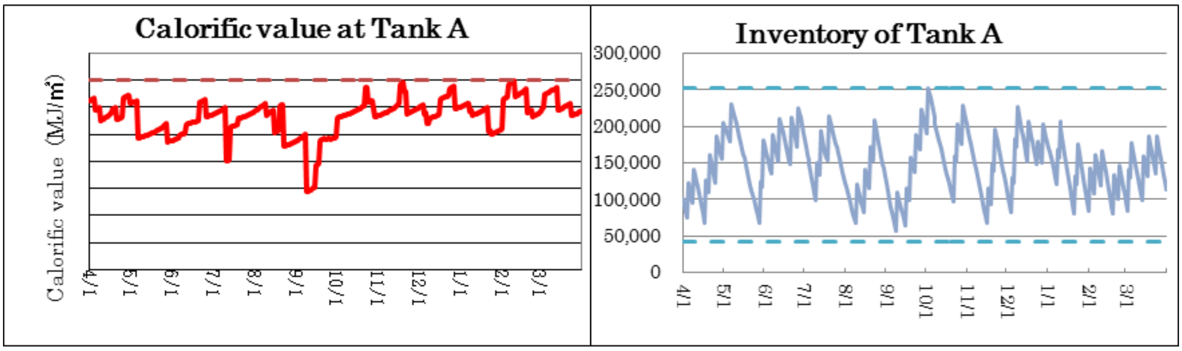

Fig. 7. Output image of the calorific value and inventory of a tank

6. Conclusion

This study describes the development of a new optimization model for LNG inventory management in light of operational difficulties such as facility constraints and the need to adjust the calorific value of city gas by using mathematical science and operations research methodologies. Tokyo Gas now utilizes this model for decision making about facility investments in addition to developing its 2014 annual operational plan. In the near future, we will upgrade this model to enable us to control the calorific value directly and to calculate the LNG and LPG ship arrangements at the same time, in anticipation of an increased variety of calorific values for LNG projects attributable to the introduction of shale gas.

7. List of tables

8. List of figures