Multi-Site Utility Integration – An Industrial Case Study

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Abstract

Mitsubishi Kasei and Mitsubishi Petrochemical merged to become Mitsubishi Chemical in 1994 making it the largest chemical company in Japan. This allows two original companies' production sites, especially for those are physically built next to each other, to improve themselves by multi-site integration. Mitsubishi Yokkaichi production plant site is one of the typical examples, which consists of three individual plant sites in the old company structure. Each plant site contains a utility plant to generate steam and electricity for chemical production. After the company merge, connecting steam and electricity among plant sites have been carried out for better flexibility, efficiency as well as capability of the utility systems. Besides these, there are still many other improvement alternatives. A Site-Model, which includes all three utility plants and production units, was then developed to explore further opportunities. In this paper, applications at Mitsubishi Yokkaichi production site are presented to illustrate the features of the site-model.

Keywords: Site-Model, Multi-Site Optimization, Site-Wide Optimization

1. Introduction

A petrochemical production plant site consists of two types of plants; production and utility plants. Production plants convert raw materials into products by consuming utilities, mainly steam and electricity. A utility plant on the other hand consumes fuel to generate utilities for the production. Utility balance between the production plants and the utility plants should be maintained at all the time to guarantee smooth operation. Whenever a change occurs in the production plant site, such as adding a new production plant, the utility plant might need to make suitable modifications to sustain the balance. To obtain the best option for the balance keeping, plant engineers currently rely mainly on their own experiences and / or apply some simple material and energy balance calculating routines. Due to the complexity inside a production site, this approach is time-consuming and easily to miss out good opportunities. To overcome this, a mathematical programming model that contained detail energy and mass balances of the utility plant was proposed for finding the best operating conditions and / or configuration of the utility plant (Iyer and Grossmann, 1997 and 1998). Industrial applications of this technique were also reported by Hui and Natori (1996).

Mitsubishi Yokkaichi plant site is one of the largest chemical production plant sites of Mitsubishi Chemical Corporation in Japan. It includes three production areas. Each area is equipped with its own utility plant. Steam and electricity can be exchanged among themselves when it is desirable. Due to this special and complex configuration in Yokkaichi plant site, optimization of the utility system becomes a very complicated task.

To deal with this, a site-model for the Yokkaichi plant site was built. The site-model is formulated as a multi-period and / or multi-scenario model, so that production planning and

scenario analysis can be studied using the same model. The model simultaneously takes into account operation conditions, product and utility demands, material prices of all planning periods, etc., in the optimization process. The model is currently used for budget planning, investment decision-making, electricity contract optimization and shutdown maintenance scheduling. These applications will be discussed later in this paper.

2. Site-Model Definitions and its Modeling Environment

A site-model is a mathematical model that contains the major material and energy balances of both production and utility systems of a chemical production plant site. Some site-wide constraints, such as seasonal production and utility demands, fuel and electricity supply contracts, can also be considered. As the site-model is targeted for production planning, it is formulated in a multi-period framework, such as days, months or separate scenarios. Production planning can withstand larger tolerance on accuracy. This then provides a chance for the site-model to adopt linear model for solving large industrial scale problems efficiently and sufficiently. Those problems are usually required huge computational efforts with nonlinear models. Furthermore, nonlinear models are easily stuck in local optimum or even unable to provide solution. Such unfavorable conditions however can be eliminated by applying linear models. This is practically important for industrial engineers to investigate their problems. For some particular problems (e.g. shutdown maintenance scheduling), integer variables can also be employed in the site-model for determining equipment on/off, and/or selections.

The site-model mainly handles large-scale industrial problems; an effective model management is therefore necessary for applying the technique. A site-modeling environment

was then developed by HKUST⁺, which was tailored for multi-period and multi-scenario problems. The environment integrates a graphical user interface (GUI), relational database (Access^{*}), spreadsheets (Excel^{*}) and mathematical programming solver (GAMS, Brooke et al., 1992) providing a flexible and powerful environment for managing large-scale problems. The GUI employs a layer-by-layer and object oriented structure that allows users to define their site model in different details. Figure 1 shows the top and the second layers of the Yokkaichi model. In the top level, three main plant sites of Yokkaichi and their power stations are defined. In the second layer, details of the power plant equipment are input. Each object contains its own variables and equations, which are used in the site-model. Every variable is defined by three indices, a plant name (e.g. ETY – ethylene plant), a material name (e.g. MP – medium pressure steam) and an alternative (e.g. GEN – generation), so that, the variable names are much more meaningful. With this three indices system, the GUI can tabulate other model information, such as equations, variable bounds and cost data easily. These data tables are then linked from the GUI to a relational database (Access). The site-model environment users therefore can utilize the effective data handling ability of the relational database without dealing with difficult database structure, but just playing with the tailor made GUI. Special constraints, which cannot be tabulated, and the objective function are input in a standard optimization model (GAMS) file. The standard model syntax can be modified and amended according to requirements of different applications. Once there is sufficient information, the GUI can execute a solver to optimize the problem and capture the optimized results afterwards. If users need more flexibility on their model input and output formats (e.g. tables and charts), spreadsheets (Excel) are available for customization. A summary of the site-modeling environment is shown in Figure 2.

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^{*} Access and Excel are products of Microsoft Corporate, <http://www.microsoft.com>

3. Technique of Parameter Preparation: Universal Plant Modeling (UPM)

Model parameters have to be prepared before a model can be constructed successfully. A site-model contains all production and utility plants, so an effective parameter preparation is very important. Plant model parameters are normally regressed directly from historical plant data that provide the relationships between production rates, utility consumption, etc. at different operating conditions. In order to eliminate disadvantages from nonlinearity (e.g. huge computational involvement, stuck in local optimal), linear regression is more suitable in the site-model. However, the model accuracy should be reasonable though linear constraints are used. A linear regression model, Universal Plant Model (UPM) proposed by Cheung *et al.* (2002a), is therefore adopted in the site-model to fulfill above criteria.

Normally, plant model regression only considers the relation between the production rate and the utility consumption as equation (A-1).

$$Y = aX + b \quad (\text{A-1})$$

where Y = Utility consumption,

X = Production rate,

a, b are corresponding regressed parameters.

With known pair X and Y , a and b can be estimated by regression. Since the productions vs. utility consumption relations in plants are usually not linear, equation (A-1) often obtains unsatisfactory results. In fact, the plant performance is also affected by external conditions like the ambient temperature (the seasonal effect). Probably, the seasonal effect can be handled by several regressed equations for different seasons or periods to obtain higher

accuracy. The idea of this method is simple, but it will induce disjunctive equations in the model and is not preferable. Instead of disaggregating the equations, UPM includes the temperature as one of the independent variables like equation (A-2). The temperature varies throughout different seasons. Its data variation will participate in the parameter estimation, so the seasonal effect can be taken into account automatically.

$$Y = aX + b + cT \quad (\text{A-2})$$

where Y = Utility consumption,

X = Production rate,

T = Ambient temperature,

a , b and c are corresponding regressed parameters.

The model will also encounter similar discrete situations when dealing with plant shutdown maintenance. During the maintenance, plant material and utility balances are interrupted. If disjunctive equations are employed, there are at least four equations to represent only a single relation.

$$[Y_1 = a_1X_1 + b_1] \vee [Y_2 = a_2X_2 + b_2] \vee [Y_3 = a_3X_3 + b_3] \vee [Y_4 = a_4X_4 + b_4] \quad (\text{A-3})$$

where Y = Utility consumption,

X = Production rate,

a and b are corresponding regressed parameters,

$\vee$ is an exclusive “OR” operator,

1, 2, 3 and 4 are subscripts to represent shutdown, overhaul, startup and normal operations respectively.

Applying the method of UPM however can compress the number of equations to one as the plant operations are indicated by binary variables.

$$Y = aX + b + cZ_1 + dZ_2 + eZ_3 \quad (\text{A-4})$$

where Y = Utility consumption,

X = Production rate,

$Z_1, Z_2,$ and Z_3 = Binary variables to indicate the status of shutdown, overhaul, startup and normal operations respectively,

a, b, c, d and e are corresponding regressed parameters.

According to the experience of Cheung *et al.* (2002a), the accuracy of UPM is much higher than normal linear regression. It can also overperform the nonlinear one. Besides the high accuracy, the UPM eliminates the need for disjunctive equations making it easier to solve. This is especially crucial for large scale models such as the site-model.

4. Site-Model Formulations

In order to adapt the data format of the GUI and utilize the ability of UPM, the site-model formulations are carefully arranged. This however does not affect its simplicity and flexibility.

Indices:

p Plant or unit.

m Material (includes utilities and manpower).

a	Alternative (property of variable).
t	Time period / Scenario.
s	Shift in a time period, t .
r	Material or utility balance equation index.

Sets:

P	Set of plants and units.
M	Set of materials (includes utilities and manpower).
A	Set of alternatives.
T	Set of time periods or scenarios.
S	Set of time shifts.
R	Set of material and utility balance equation indices.

Parameters:

$E_{r,p,m,a,t,s}$	Coefficient of variable at plant p with material m and alternative a in period t , shift s for material balance equation r .
$L_{p,m,a,t,s}$	Lower bound for variable at plant p with material m and alternative a in period t , shift s .
$U_{p,m,a,t,s}$	Upper bound for variable at plant p with material m and alternative a in period t , shift s .
$SL_{t,s}$	Time length of shift s in period t .
$C_{p,m,a,t,s}$	Cost/price of material m with alternative a at plant p in period t , shift s .

Positive continuous variables:

$F_{p,m,a,t,s}$ Variable of material m with alternative a at plant p in period t , shift s .

Continuous variables:

$Cost_{t,s}$ Operating cost in period t , shift s .

Material and energy balance equations:

For the material and energy balances, a specific set of (p, m, a) is assigned for each index r .

A general balance equation is then defined as:

$$\sum_{r \in (p,m,a),t,s} (F_{p,m,a,t,s} \times E_{r,p,m,a,t,s}) = 0, \quad r \in R, t \in T, s \in S. \quad (B-1)$$

Bounds of variables:

Site-model variables are constrained by certain maximum and minimum, for examples, boiler capacity and minimum electricity intake.

$$F_{p,m,a,t,s} \leq U_{p,m,a,t,s}, \quad p \in P, m \in M, a \in A, t \in T, s \in S. \quad (B-2)$$

$$F_{p,m,a,t,s} \geq L_{p,m,a,t,s}, \quad p \in P, m \in M, a \in A, t \in T, s \in S. \quad (B-3)$$

Cost calculation:

Following equation is applied to obtain the production site operating cost in period t , shift s .

$$Cost_{t,s} = \sum_{p,m,a} (F_{p,m,a,t,s} \times C_{p,m,a,t,s} \times SL_{t,s}), \quad p \in P, m \in M, a \in A, t \in T, s \in S. \quad (B-4)$$

Objective function:

The site-model objective is to minimize the total cost (or maximize the total profit) of the production site for all planning periods t by varying the utility system's operation. At the

same time, the site-model keeps the material and energy balances inside the production site.

$$\min \sum_{t,s} Cost_{t,s}, \quad t \in T, s \in S. \quad (B-5)$$

Equations (B-1) to (B-5) compose a basic site-model and are implemented to the site-modeling environment. The model is developed in GAMS and solved by the solver OSL (IBM, 1991)

In summary, the site-modeling environment has achieved to put a very powerful numerical tool on hands of plant engineers who are not well trained in the numerical arena to analyze such highly complicated and interacted production plant sites. With this tool, engineers can focus their efforts on evaluating the model results physically and determining their appropriate reactions on the changes in the overall system. Moreover, this convenient GUI is essential as the plant site infrastructure is constantly changing.

5. Industrial Case Studies

To cope with the rapid emerging global economy, chemical companies have to improve their own technologies as well as their ability in managing their production plants. Mitsubishi Yokkaichi Plant Site is a very good example, which consists of three production sites, Shiohama North, Shiohama South and Kawajiri. All three production plant sites have their own utility plants to supply steam and electricity for the productions. Shiohama North and Shiohama South sites are located physically beside each other. Inter-site steam and electricity networks have been established between them, so utility supply can be backup by each other. As Kawajiri site is relatively far away from Shiohama sites, there is no steam interconnection among it and the other two sites. Nevertheless, they can still exchange

electricity through the public electricity company network (Figure 3). With above interconnections, the three production and utility systems become very complicated and difficult to manage. A Dynamic Matrix Control (DMC⁺) system has been implemented recently for improving the controllability of the utility system, however, potential for improvement still remains and is very difficult to be identified. Site-model was therefore adopted to perform the studies and helped engineers to investigate potential opportunities.

The three production plant sites were then modeled using the site-modeling environment. Since the aim of the following studies is to examine the impact of various plant modifications to the overall utility infrastructure, the model involves detail of all three utility systems.

5.1 Budget Planning

Budget planning has to be performed annually to estimate annual operating cost of the whole production site and to guarantee feasibility of all operations during the fiscal year. Although budget planning has to be done every year, it is still a very complicated and time-consuming task to be performed manually in particular when other issues such as shutdown maintenance, material purchasing contracts are considered simultaneously. So far, no commercial software is available for performing this task. With a site-model, engineers can now update the model parameters (costs/prices, production and utility demands) to perform case studies rapidly and effectively.

Operating cost includes raw material, fuel, water, electricity and labor cost, which may vary seasonally or even between day and night. To make an annual budget plan, data of product

⁺ DMC is AspenTech's product

demands, material prices, etc. hence should be predetermined. Such data are stored in a process database. As the site-modeling environment has its own database, data extraction from the previous database is necessary. Users can examine and modify the process data through the environment-attached Excel spreadsheets before they are used in the site-model. After the site-model calculation, the planning results are stored in the site-model database. If necessary, users can also customize the result output formats by Excel spreadsheets. Finally, the results are transferred from the site-model to a specific budget planning database for further management processing. Figure 4 illustrates how the site-modeling environment is applied in the budget planning.

The site-model optimizes the total operating cost and the use of utilities by better balancing the supply and demand between the utility and production plants. Although the budget planning can be done by traditional method, the engineers need to repeat the calculation in each scenario (month) for only one year's budget. The site-model indeed calculates all scenarios simultaneously as it is formulated as multi-period. This speeds up the budget planning process a lot, and the engineers can so spend the saved time on further improvement studies. For instance, the importation of electricity can be optimized at different seasons and time periods since electricity prices are fluctuated at different time periods and consumption levels. Selection of different fuel types in different seasons or time in order to meet the emission limits restricted by the government is also possible. The site-model can certainly be applied on all the cases. By knowing all the information ahead in time allows the engineers to negotiate better fuel and/or electricity supply contracts also.

5.2 Investment Decision Making

Purchasing new equipment or plants are often required for improving the infrastructure of a production plant site. The site-model can be used to investigate whether the investment is feasible and economical. If many options are available, the site-model can also be used to select the best option. In Yokkaichi plant, modifications on the Shiohama South production site decreased the demand of steam usage hence reduces the ability for cogeneration. A new steam turbine is proposed for Shiohama South utility plant for taking the advantage to the surplus steam. The utility plant currently contains two boilers, two back-pressured turbines and a condensing turbine, Figure 5. New turbines that take and draw steam at different levels (shaded units in Figure 5) are added into the site-model allowing it to identify the best design option with considerations on seasonal utility demands, prices and new electricity contract.

In this study, the first consideration was to add a medium pressure – condensate (MP-CT) turbine. The maximum capacity of the MP-CT turbine is set at 15MW due to the investment limit. After the site-model calculation, the electricity generation rate of the MP-CT turbine hits the maximum in some scenarios. The total cost decreases about 3.8% with respect to the original configurations, mainly from reducing the electricity purchasing cost. Although 3.8% seems to be not so much, it is already a good reference point for other alternatives.

Low pressure – condensate (LP-CT) turbine with 15MW maximum capacity is another alternative. The resulted capacity of the LP-CT turbine is 10MW. Overall saving however increases to about 4.5%. This is because the LP-CT turbine can fully utilize the existing turbines. In order to feed LP steam into LP-CT turbine, SP steam passes through the back-pressured turbine to LP level therefore produces more electricity than just letting-down

from SP to MP in the case of MP-CT turbine.

While examining the LP-CT turbine study carefully, it discovers that there is a purge at HP steam level in some operating periods. To prevent wasting the valuable HP steam, a HP-LP turbine is recommended together with the LP-CT. This combination eliminates the steam purge and introduces the excess steam through the HP-LP turbine to LP level for the LP-CT turbine usage. The total electricity generation is then increased by the increment in the LP-CT (increase to 13MW) and the additional amount from the HP-LP turbine (about 1MW). Finally, the total cost is saved by 6.7%, 1.5 times more than the MP-CT case.

5.3 Electricity Contract Optimization

Steam and electricity are the major utilities of a chemical production site produced by its utility plant. The main difference between steam and electricity is that electricity can either be produced in-house or purchased from the local electricity company but steam can only be generated locally. Instead of having a utility plant that is large enough to supply both electricity and steam for the whole production site, for reducing investment to the utility plant, a utility plant is normally designed for just guaranteeing the supply of steam. Electricity is normally backup by a local electricity company with an annually supply contract.

In an electricity contract, the cost is usually divided into two categories, variable cost and fixed cost. Different kinds of variable cost calculation method are adopted in current commercial practice, and they can be briefly classified into three types. First, the variable cost only has one fixed value. The variable cost solely depends on the purchased amount and the fixed cost parameter. Second, the electricity company will define a cost profile,

which divides the electricity purchased amount into different ranges, and each range has its own cost parameter. The variable cost will then be calculated by the purchased amount and its corresponding cost parameter. Third, the cost parameters vary according to the time shifts, such as, day, night and mid-night. The variable cost therefore depends on the total importing amount and the time period of the importation. Yokkaichi plant site now is using the third type variable cost calculation.

Besides the variable cost, fixed cost also takes a very important role in the electricity supply contract. Fixed cost is a fixed annual fee that the plant site has to pay every year, which mainly depends on the maximum importation peak on the contract period. Allowing a higher maximum import level, the production site may improve ability in production and/or maintain its productions even during utility equipment failure. On the other hand, a higher maximum importation rate increases the fixed cost. The profit gain due to higher productivity or the additional security of electricity supply may not be able to compensate the additional payment of the electricity contract. Hence, careful optimization on electricity contract is necessary. For this reason, the site-model for budget planning is modified for optimizing the electricity contract of the whole Yokkaichi plant site. Due to boilers and turbines shutdown, the electricity importation peak usually appears during the maintenance period. Prior to the availability of this total site model, the importation peak normally appears at November night shift (maintenance period) with a value of approximately 50MW. Using the site-model, an optimum solution of 27MW (Figure 6) is predicted. Because of this, the total electricity cost (variable and fixed costs) can almost decrease by half. Although fuel cost is increased due to the increase of power generation, the total operating cost is still reduced by approximately 4%.

5.4 Shutdown Maintenance Scheduling

Preventive maintenance is a very important task for every chemical production site. It has to be performed regularly for preventing equipment failure and accidents. Shutdown maintenance scheduling can be classified as long-term and short-term for determining the best combination of plant shutdown and the detail schedule of the maintenance respectively. The main objective of shutdown maintenance scheduling is to reduce the overall maintenance fee and production losses.

Every process unit requires to be maintained in every 1 to 3 years. Not all the plants have to be shutdown simultaneously at each maintaining period. A good long-term schedule is therefore to guarantee the feasibility of utility and material balance at every maintenance period. The long-term scheduling achieves above objective by determining the plant shutdown frequency and combination in each maintenance period. It can also be used to determine inventory strategies for raw and intermediate materials before and during the shutdown maintenance periods. Examples of long-term maintenance scheduling are illustrated by Cheung and Hui (2003).

Based upon a long-term scheduling, detail timings of plant shutdown and startup are then scheduled by using a short-term scheduling model. The assigned maintenance period usually lasts for three to six weeks. Within a maintenance period, plants that require maintenance have to go through shutdown, overhaul and startup. During these stages, significant variations on utilities, materials and labor demands increase the complication for optimizing the maintenance schedule. For an example, plant startup will usually require a

lot of steam to bring the process to a normal operating condition. Steam may not be enough to support all the production plants if they all startup at the same time. To take into account all these factors, a site-model is used to optimize the short-term shutdown schedule to guarantee the feasibility of material and utility balances, and to minimize production losses, labor cost, etc. A detail discussion on the short-term maintenance scheduling is presented by Cheung *et al.* (2002b).

5.5 Fuel and Water Balances

Beside steam and electricity, fuel and water are the main elements to be considered in a budget planning model. The usages of fuel and water are optimized together with all other utilities. In fact, the usages of utilities, water, fuel, etc., affect each other and it creates rooms for manipulation. For an example, minimizing water regeneration from some processes may reduce the fuel consumption for the regeneration, but requiring more fresh water in overall. Using clean fuel in a furnace might reduce water usage for treating dirty flue gas. These are actually optimization problems. The trade-off between the utilities can be optimized to maintain the profitability of a plant site and/or meeting the tightening environment regulations. Engineers traditionally solve these problems according to their experience and with some simple heuristics. Different engineers may turn out different results. With the site-model, the problems can be solved much faster, easier and more accurate.

6. Conclusions

A general mathematical programming model, Site-Model, is developed for solving site-wide optimization problems. Yokkaichi Plant Site of Mitsubishi Chemical Corporation has

established a site-model to deal with multi-site utility problems. With a user-friendly modeling environment, plant engineers can perform their normal daily functions much faster and higher accuracy as well. The engineers can also be able to evaluate more scenarios and hence opportunities can be identified. So far, this numerical tool has been successfully applied on solving annual budget planning, investment decision-making, electricity contract optimization, shutdown maintenance scheduling and fuel/water balances problems.

7. References

Brooke, A., Kendrick, D., and Meeraus, A. (1992). *GAMS - A User's Guide (Release 2.25)*. San Francisco, CA: The Scientific Press.

Cheung K.Y., Li, W.K., Hui, C.W, Sakamoto, H., Hirata, K. and O'Young, L. (2002a). Universal Plant Model for Production Planning, *Proceedings of the 5th Conference on Process Integration, Modeling, and Optimization for Energy Saving and Pollution Reduction (PRES'02)*, Praha, Czech Republic.

Cheung, K.Y., Hui, C.W., Sakamoto, H., Hirata, K., and O'Young, Lionel. (2002b). Short-Term Site-Wide Maintenance Scheduling. *Proceedings of European Symposium on Computers Aided Process Engineering-12 (ESCAPE-12)*, The Hague, The Netherlands, 655.

Cheung, K.Y. and Hui, C.W. (2003). Total-Site Scheduling for Better Energy Utilization. *Journal of Cleaner Production*, In press.

Hui, C.W. and Natori, Y. (1996). An Industrial Application Using Mixed-Integer Programming Technique: A Multi-Period Utility System Model. *Computers and Chemical Engineering*, 20 (Suppl.), S1577-S1582.

IBM. (1991) *OSL (Optimization Subroutine Library) Guide and Reference (Release 2)*. NY, Kingston.

Iyer, R.R. and Grossmann, I.E. (1997). Optimal Multiperiod Operational Planning for Utility

Systems. *Computers and Chemical Engineering*, 21 (8), 787-800.

Iyer, R.R. and Grossmann, I.E. (1998). Synthesis and Operational Planning of Utility Systems for Multiperiod Operation. *Computers and Chemical Engineering*, 22 (7), 979-993

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List of Figures:

Figure 1: Site-Modeling Environment.

Figure 2: Site-Modeling Environment Data Flow Diagram.

Figure 3: Simplified Yokkaichi Map.

Figure 4: Data Flow Diagram for Budget Planning.

Figure 5: Simplified Shiohama South Utility Plant Configuration.

Figure 6: Electricity Importation Profiles.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6