SITE-MODELING AND ITS APPLICATIONS

Kwok-Yuen Cheung[1], Chi-Wai Hui[1, *], Haruo Sakamoto[2] and Kentaro Hirata[2]
[1] Chemical Engineering Department, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong.
[2] Safety Engineering and Environmental Integrity Lab., Process Systems Engineering and Production Technologies Field, MCC-Group Science & Technology Research Center, Mitsubishi Chemical Corporation, 1, Toho-cho, Yokkaichi Mie 510-8530, Japan.

Abstract

A large-scale chemical production site consists of multiple production and utility plants that are interconnected with utility and material-flow networks. The idea of having an integrated mathematical model (site-model) to assist in site-wide operations and development is gradually being accepted by the industry. This paper presents some experiences in constructing a site-model based upon simple linear plant models that can be generated directly from historical plant data. To handle discrete conditions such as equipment selection, a site-model is normally built as a mixed integer linear programming (MILP) model that consists of the main energy and material balances of each plant unit and their interconnections. With discrete variables, the model is able to handle problems with multiple time periods and/or scenarios, making it suitable for various types of applications. A modeling environment has been tailored for site modeling that integrates a graphical user interface for model generation, the Access database for model management, and an Excel spreadsheet for customizing data input/output. This paper will present a few industrial applications of applying the site-model for production planning, assisting in investment decisions, maintenance planning and scheduling, and optimizing long-term material and utility supply contracts. Modeling, solution techniques and analytical methods regarding these applications will also be presented in this paper.

Keywords

Site-Modeling, Site-wide optimization, Multi-site optimization.

Introduction

Facing an emerging global economy, engineers in the chemical industry are working hard to improve the competitiveness of their production plants. Major improvements in individual production plants have been identified with the latest advanced control, simulation and optimization technologies. However, greater potential for improvement may still exist when a production complex (site) is considered as a whole. A hot topic now being discussed in the industry is the integration of control and management.

So far, engineers evaluate site-wide problems based upon their own experience and simple material and energy balance calculations. Due to the complexity inside a production site, this traditional approach is time-consuming and opportunities for saving are easily missed. Utilization of mathematical models for solving site-wide optimization problems seems to be unavoidable. Although quite a few discussions have been appeared in the literature (Hui and Natori, 1996 and Hirata et al., 2002), so far, no

---

[*] To whom all correspondence should be addressed

commercial software is tailored to site-wide design and optimization.

This paper will present some experiences of using a mathematical model, a site-model, for projects implemented in Mitsubishi Chemical's Yokkaichi plant site. The Mitsubishi Yokkaichi plant site is one of the largest chemical production sites owned by Mitsubishi Chemical Corporation in Japan. It consists of three main production areas. Each production area is equipped with its own utility plant, providing steam and electricity for its own production. Steam and electricity can be exchanged among the production areas. The complex structure of the plant site makes it difficult to be managed using conventional approaches. For this reason, a site-model for the Yokkaichi plant was built.

Together with the site-model, a technique called Marginal Value Analysis (MVA) is used for determining site-wide bottlenecks and pricing intermediate material and utility. These techniques were successfully applied to annual budget planning, investment decision-making, utility contract optimization, maintenance scheduling, and water-fuel balance. The applications will be discussed separately in this paper.

Site-Model Definitions

A site-model is a general mathematical programming model. Since the model is mainly used for production planning and scenario analysis, it does not require very high accuracy. Instead, the reliability and manageability of the model are the main concerns. For this reason, the model is built as a linear model (LP). When discrete decisions have to be determined by the model, binary variables can also be added, making it a mixed integer linear model (MIP). A site-model includes all main material and energy balances of all production and utility plants at a production site. It also contains site-wide constraints such as production targets, plant capacities and utility demands, fuel and electricity supply contracts and even government regulations.

Site-wide constraints usually vary with time. A site-model is therefore normally formulated as a multi-period model for a defined time horizon. The length of the time horizon depends on the applications, which vary from a few days to years. The size of a site-model, in terms of the number of equations and variables, is normally large since it includes a large number of plant units and sometimes many time periods. To make the model easier to manage, the contents of the model, such as equations and parameters, are tabulated so that the model can be easily managed using a relational database.

Site-Model Marginal Value Analysis (MVA)

To understand the model result thoroughly, an effective analytical technique should be adopted together with the site-model. Different meanings of marginal value were defined by Hui (2000), which has been successfully implemented into a few industrial applications. Marginal value can be classified roughly into two categories, marginal profit (MP) and marginal cost (MC). The MP of a stream (e.g. material, utility, etc.) is the additional profit by increasing a unit of a stream flow. MP can be calculated directly by most commercial LP solvers. When the optimum value of a stream flow is not restricted by its lower and upper bounds, the MP of this stream flow will equal zero, meaning that there is no additional profit from increasing or decreasing this stream flow. When the optimum value of a stream flow is on its bound, a value (normally positive) indicates the additional profit from extending the flow one unit outside its bound.

The MC of a stream flow is defined as the addition profit of adding (MC_F) or removing (MC_P) a unit of a stream from, respectively, an external source or a destination. Different from MP, MC normally has a value no matter if the stream flow is at its bounds or not. In most cases, MC_F and MC_P represent the market value and the production cost of a stream, respectively.

Based on these marginal values, users can determine the accurate cost value of materials inside the site. By examining the marginal values of different site conditions, users can locate site bottlenecks and evaluate business decisions easily and accurately. The interpretation of the marginal values is summarized in the following table:

Table 1. Interpretation of marginal values

Marginal Values	Possible Meaning
MP = 0	No cost benefit by increasing or decreasing the stream flow.
MP > 0	The bottleneck is in the stream. Additional profit can be obtained by increasing the stream flow.
MP < 0	The bottleneck is in the stream. Additional profit can be obtained by decreasing the stream flow.
$MC_P=MC_F$, $MC_F>0$ and with a value much lower than the final product(s)	Indicates the stream's production cost. The bottleneck is in the downstream process.
$MC_P=MC_F$, $MC_F>0$ and with a value close to its final product(s)	Indicates the stream's product value. The bottleneck is in the upstream process.
$MC_P=MC_F$ and $MC_F<0$	Normally comes from a byproduct or waste stream. Additional profit can be obtained by finding new user(s) or even purging of the steam.
$MC_P \neq MC_F$	The bottleneck on the stream. $MP = MC_P-MC_F$.

In the followings are some industrial applications in the Yokkaichi plant site that have successfully adopted the techniques of the site-model together with marginal value analysis.

Budget Planning

Budget planning has to be done once a year to calculate the annual operating costs of a whole production site. The budget is normally estimated based upon data from a given production plan that were generated from historical data and market forecasting. The importance of annual budget planning is not only to amass sufficient budget for production but also predict the feasibility of satisfying production targets with effective usage of resources (equipment, by-products and utilities) inside the production site. It is also important for determining long-term materials and utilities supplies by taking into account plant maintenance, inventories and site-wide development.

A site-model was therefore established for the Yokkaichi plant site. It utilizes planning data including plant capacities, utility demands, cost parameters, etc. With all these factors, the site-model can optimize the overall operating cost for the whole production site. Besides overall annual operation profits, the model can also provide material and fuel consumption rates for individual periods. With these data, engineers can negotiate with the material and fuel supply companies to create better purchasing contracts. Also, budget planning results can be used as a reference point for further retrofitting studies.

Investment Decision Making

To improve the profitability of a production site, investments in production and utility systems improvements are regularly needed. A decision to make an investment should not be done without knowing its site-wide effect. In the Yokkaichi plant site, for instance, closing down a few aging process plants resulted in the surplus of medium pressure (MP) and low pressure (LP) steams. A new MP or LP condensing turbine is then proposed for increasing electricity generation (see Figure 1). Together with seasonal fluctuations in utility demands and prices, and electricity purchasing contract limitations, investigation of all design options becomes a very complicated task.

With a small modification to the site-model used for budget planning, we can effectively examine all the different scenarios and determine the best option for utilizing the steam.

Marginal value analysis plays a very important role in this study. Without MVA, an optimum solution can tell only the objective values or the profit of a new investment. Other potential modifications are hidden behind the solution. For instance, while examining the option of installing an LP or MP condensing turbine, in most cases, the MVs of high pressure (HP) steam are close to the value of MP, indicating an incentive to utilize the HP steam. This option was not considered at the beginning of the study but eventually became one of the most promising investment decisions to the utility plant.

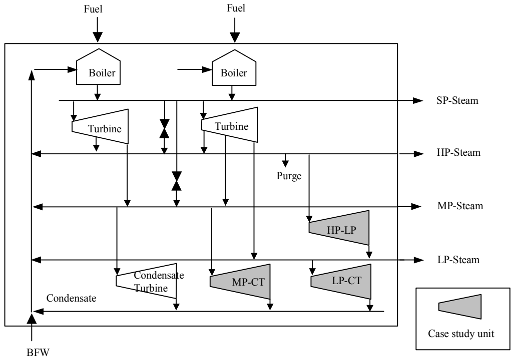

Figure 1. Simplified utility plant configuration

Utility Contract Optimization

Electricity is essential to sustain production at a chemical production site. Although a chemical site is usually equipped with its own utility plant for electricity generation, purchasing electricity from an external supplier(s) is needed for balancing demands at the plant site. To guarantee sufficient supply from the external supplier and to reduce the cost, a long-term electricity supply contract is signed between the company and the supplier. Once the contract is signed, it cannot be changed within the contract period. To minimize the adverse effect caused by the contract, the contract type and parameters have to be carefully selected or optimized with consideration of other site-wide constraints such as production targets, utility demands, equipment capacities, etc.

A long-term electricity supply contract could be very complicated. To make it simple, a contract normally consists of a fixed cost that is determined by the overall annual demand and the peak amounts during different seasonal and daily periods. Variable costs are applied for every unit of electricity intake but are varied according to the time and date in a pre-agreed price calendar. The upper and lower limits of electricity intake at each time interval are also defined in the calendar.

The site-model of the Yokkaichi plant site was again used for optimizing an electricity supply contract. This was one of the main considerations before making an investment decision about installing a new turbine. The scenarios of turbine selection, plant shutdown, etc., were taken into account when for optimizing the new electricity supply contract. Since additional electricity generation capacity was added by installing a new turbine, a contract for exporting electricity was also studied. Without a site-model ready for the calculation, the study could not be completed and nor would comprehensively cover all the possible scenarios.

Shutdown Maintenance Scheduling

Preventive maintenance is a typical management task that engineers regularly have to tackle. In fact, shutdown maintenance involves a lot of human and utility resources. As resources are limited, it is necessary to arrange the resource usage very carefully to guarantee feasibility of plant operations during the maintenance period. A well-planned shutdown maintenance schedule is therefore required.

As a plants' shutdown maintenance affects the overall site-wide material and energy balances, the maintenance schedule should be determined by considering all the plant and utility units in the site. Although this will increase the complexity of the problem, it also guarantees the overall feasibility as well as the profitability of the plant. With the help of a site-model, maintenance scheduling can be done effectively.

The scheduling procedure is divided into a two-step approach, namely long-term and short-term scheduling (Cheung and Hui, 2001). In the long-term scheduling, the combination of plant maintenance is determined for a two- to five-year time span. This schedule guarantees that periods between plant shutdowns are within the required frequency set by the government. Other site-wide or company-wide constraints such as inventory strategies, purchasing policies, manpower coordination among plant sites, etc., are also considered.

Based on the results from the long-term scheduling, the shutdown plant combinations in the pre-defined maintenance periods can be extracted for the second step, the short-term scheduling. Short-term scheduling schedules the detailed processes (shutdown, overhaul and startup) of the plant shutdown within a particular maintenance period. To indicate the plant status, binary variables are employed with careful formulations and the site-model formulates a MILP. This has been discussed by Cheung *et al*. (2002).

Fuel and Water Balances

The usages of fuel and water affect each other at a chemical production site. For example, reducing fuel consumption in water regeneration will result in more fresh water usage. Also, burning clean fuel can decrease water consumption for treating the flue gas. These relations seem to be obvious, but they are very difficult to optimize if we tackle them separately. Other similar trade-off problems can be easily found in a chemical production site. A site-model is again useful for obtaining the best trade-off among these flows.

Conclusions

The site-model is a general mathematical linear (or mixed integer) programming model. It includes all site components in one single model, such that all site-wide constraints can be considered simultaneously. With the technique of marginal value analysis, engineers can utilize the site-model to manage site operations more efficiently and accurately. Applications like budget planning, investment decision making, utility contract optimization, shutdown maintenance scheduling, fuel and water balances were successfully modeled for the Yokkaichi plant site of Mitsubishi Chemical Corporation in Japan.

Acknowledgments

The authors would like to acknowledge financial support from the Research Grants Council of Hong Kong (Grant No. 6014/99P) and financial and technical support from Mitsubishi Chemical Corporation, Yokkaichi Plant.

References

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

Cheung, K.Y., Hui, C.W. (2001) Total-Site Maintenance Scheduling. *Proceedings of 4th Conference on Process Integration, Modeling, and Optimization for Energy Saving and Pollution Reduction (PRES'01)*, Florence, Italy, 355.

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

Hui, C.W. (2000). Determining Marginal Values of Intermediate Materials and Utilities Using a Site-Model. *Computers and Chemical Engineering*, 24, 1023.

Hui, C.W. and S. Ahmad (1994), "Total Site Heat Integration Using the Utility System". *Computers and Chemical Engineering,*18, 729.

Hirata K., H. Sakamoto, L. O'Young, K.Y. Cheung, C.W. Hui, Multi-site Utility Integration – An Industrial Application, *ESCAPE-12*, May 2002, The Hague.