Computer-Based Environment for Wastewater Treatment Plant Design

By J.-J. Kao,[1] E. D. Brill Jr.,[2] Member, ASCE, J. T. Pfeffer,[3] Member, ASCE, and J. J. Geselbracht[4]

Abstract: A prototype computer-based design environment was developed to facilitate wastewater treatment plant design tasks. The design environment includes several mathematical techniques, interactive graphic displays, and user-friendly interfaces. The mathematical techniques are mass and water balances for an analysis program for plant design and a rule-based system for evaluating the likelihood of sludge bulking. A processor is also used to check a given design using existing design standards. The interactive graphic displays and the user interfaces are intended to provide a user-friendly environment for manipulating data, models, and solutions. Sensitivity analyses can be performed for models as well as parameters. The features of the computer-based system are described, and suggestion for extensions are given.

INTRODUCTION

In analyzing wastewater treatment plant design (WTPD) problems, many parameters must be considered. Also, many physical or biological reactions are not well defined. Exact mathematical solutions are thus not available for such complex problems, and, as discussed below, a trial-and-error design procedure is usually used to ensure that effluent standards are met. The procedure is, however, time-consuming because complex design-related data and their interrelationships cannot be quickly perceived and evaluated. In the present research, a prototype design environment was developed to deal with these issues using several mathematical techniques, graphic displays, and an intelligent and user-friendly interface. The focus is not on using a computerized mathematical model or a set of them to obtain or analyze a solution. Rather, the emphasis is on illustrating a prototype computer-based system developed to facilitate design using various mathematical models and an interactive user-friendly interface. For example, it is possible using such a system to examine not only the sensitivity of a solution to the values of the parameters in a particular mathematical model of a unit process but also the sensitivity to the choice of a model for that unit process.

The base WTPD model and analysis program adopted in this research were modified from those developed by Tang et al. (1987). The base model is for a typical activated sludge wastewater treatment plant, including sludge processing and disposal. In addition to the individual unit process performance, the model considers the interactions among various unit processes. Fig. 1 provides a typical process flowsheet showing the unit processes and

[1]Assoc. Prof. and Dir., Institute of Environmental Engineering, National Chiao Tung Univ., Hsinchu, Taiwan, Republic of China.
[2]Prof. and Head, Dept. of Civ. Engrg., North Carolina State Univ., Box 7908, Raleigh, NC 27695-7908.
[3]Prof., Dept. of Civ. Engrg., Univ. of Illinois, Champaign, IL 61801.
[4]Consulting Engr., Black and Veach, Pleasant Hill, Calif.

Note. Discussion open until March 1, 1994. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on July 23, 1990. This paper is part of the ***Journal of Environmental Engineering***, Vol. 119, No. 5, September/October, 1993. ©ASCE, ISSN 0733-9372/93/0005-0931/$1.00 + $.15 per page. Paper No. 183.

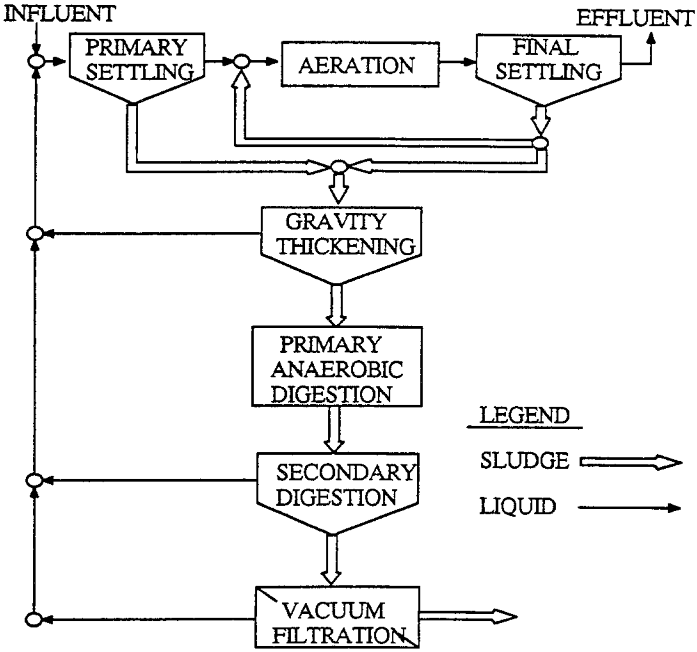


FIG. 1. Wastewater Treatment Plant Flow Diagram

various connecting flows. Several important unit processes can be included in the model, such as primary clarification, activated sludge with final clarification, gravity thickening of mixed primary and waste activated sludge, primary and secondary anaerobic digestion, vacuum filtration, and final sludge disposal via a sanitary landfill. The plant configuration can be dynamically changed during the design process, so that the final combination of unit processes may be different from the one shown in Fig. 1. Only the unit processes shown in Fig. 1, however, have been considered in the work to date.

The prototype design environment contains tools for preliminary design and analysis of wastewater processing plants. The design of any wastewater processing plant includes the selection of a process train, determination of mass and water balances, and facility cost estimation. One design procedure involves establishing influent and effluent conditions, selecting unit processes for an appropriate treatment train, applying appropriate performance models for the unit processes selected, setting up a mathematical model for the system, using the mathematical model to generate a few feasible alternatives, and comparing the alternatives with respect to cost and applicable design standards. Such a procedure is complex, time-consuming, and tedious. The computer-aided design environment presented facilitates the procedure by reducing the burden on a designer for tasks such as formulating a model, solving the model, and generating alternatives.

Moreover, this design environment increases the power of the traditional trial-and-error procedure. Trial and error is tedious if each trial takes a long time to set up and finish, but it would be more powerful if it were necessary only to press several buttons to finish a trial with the results presented immediately to the designer. This design environment provides almost real-time responses to the designer, allowing the designer to easily generate alternatives, to compare alternatives under different design conditions, and to significantly shorten the time required to analyze the design of a wastewater treatment plant.

Several techniques, multiple graphic displays, and a user interface (with a pointing device, a computer mouse) were used to develop the design environment. The techniques include mass and water balances (Kao et al. 1990), and a rule-based technique for predicting likelihood of sludge bulking (Geselbracht et al. 1988). Also, a processor is provided for checking a given design to see if it meets existing design standards. The numerous graphic displays provide comfortable interfaces for data manipulation, and the user interface is designed for engineers who are not necessarily computer experts.

In the following sections, the conventional design process for a WTPD problem is described and the potential use of a computer-based design environment such as that presented here is discussed. Next, functions and options provided by the design environment are described along with some illustrations of their potential uses.

WASTEWATER TREATMENT PLANT DESIGN APPROACH

It is desirable to design a process flow diagram and to size units so that the complete system is efficient and performs reliably. A conventional approach for designing an activated sludge process is described in the wastewater engineering text led by Metcalf & Eddy, Inc. (*Wastewater* 1979). The design is initiated by specifying the influent conditions as well as two process design variables [sludge age and mixed liquor volatile suspended solid concentration (MLVSS)] and the return sludge concentration. Thus, from a design point of view, the problem is already solved; all that remains is to use these variables to calculate the resulting state variables, such as treatment efficiency, the reactor volume, and sludge wasting rate. Aeration volume is conservatively determined based on the soluble 5 day biochemical oxygen demand (BOD_5) removal required under the condition of high effluent suspended solids. Checks are then conducted on the resulting hydraulic retention time and the volumetric loading rate. The text guides the user in selecting those design variables by providing recommended ranges. It also warns of other factors that must be considered during the design, including cost. Unfortunately, the nature of the interactions among the design variables and the resulting cost and reliability of the design is not explicit.

A possible approach using the prototype design environment is as follows. The first step is to specify the influent conditions and effluent requirements for which the plant must be designed. Next, the average influent conditions are used with acceptable average loading criteria to determine unit process sizes. Those loading criteria may come from applicable state or regional design standards or from the consulting firm's standard practice. Next the performance in terms of water quality of the resulting design (i.e., a set of specific unit sizes) can be estimated under peak loading and adverse temperature conditions. For this task, the analysis program can be used to solve the process models and mass balances rapidly and to estimate the cost. From this point on, the designer can use the prototype iteratively to delete processes or to change unit process sizes using professional judgment to see the effect on cost and performance.

J. Environ. Eng. 1993.119:931-945.

DESIGN ENVIRONMENT

The complexity associated with developing a design environment is caused not only by the potential mathematical difficulty of obtaining a numerical solution (for cases such as those shown in the references listed later), but also by the difficulty of presenting design data logically, manipulating different design conditions, and generating good alternatives in an interactive process. Before a solution is selected by a decision maker, these tasks are expected to be implemented iteratively. The goal of the prototype is to demonstrate a system for use in the creative design of wastewater treatment plants in which the engineer can apply professional judgment as well as use the computer-based analyses. Other than mathematical techniques such as those described by Tang et al. (1987), Geselbracht et al. (1988), and Kao et al. (1990), graphic displays and user interfaces are the other important components that should be carefully designed in building such a system. The general characteristics of components are briefly discussed as follows.

Graphic Displays

The purpose of the graphic displays in the prototype is mainly for visual presentation of information. Attributes of a given WTPD such as cost are usually important for a decision-making problem. The display of attributes, however, may be difficult. For example, the display of cost curves may be difficult because the curves are exponential and might cover a wide range of design parameter values. Although semi-log plots can be used to represent cost curves, determining the approximate value of cost from such a plot may be difficult. In this work, the cost curves are presented in normal scale so that the approximate cost associated with a design parameter value can be easily seen. Similarly, the presentation of a configuration, such as a wastewater process flow diagram, and results, such as a set of numerical output data, also require appropriate presentations. The goal of using graphic displays for attributes, configurations, and results is to present them in a manner that supports quick evaluations.

User Interface

The user interface is a key component of the current prototype. A design engineer may be reluctant to use a system that is computationally efficient but that has a poor interface. Characteristics of a good user interface (Kao 1990) are: (1) Simplicity of learning; (2) minimal possibility of making mistakes; (3) flexibility in modification of models and data; (4) efficiency of data organization or solution management; and (5) clarity of instructive feedback.

In the prototype, a menu-driven interface with a pointing device for making selections was developed. Such an interface is expected to require less learning time. Several functions that could be executed by simply pushing a button were developed to implement WTPD modification tasks. A nonintrusive and intelligent feedback system including error messages, warning messages, help messages, a beeper, valid action response messages, and graphical displays was developed to help a designer explore good alternatives. Graphic objects for physical objects such as unit processes are also used as an interface for information retrieval.

Numerous checks are made while a problem is being solved. For example, the aeration tank volume is determined as the minimum volume that satisfies the maximum loading and minimum detection time values. If the volume violates the minimum loading rate or maximum detection time, there is no solution for those design conditions. In instances where the design proves infeasible or a violation of a design condition or standard has occurred, a warning message will be shown on the screen. The user interface not only provides an easy-to-use design environment, but also serves as an intelligent assistant for the designer.

CAPABILITIES

The current prototype is functional on Apollo workstations and allows the user to:

- Specify a process flow diagram graphically
- Specify unit process sizes
- Construct interactively an activated sludge system model of any combination of a given set of unit processes, solve the mass balances, and estimate the cost and the likelihood of bulking for that treatment scheme
- Change interactively baseline model parameters, process performance models, and plant design conditions (flow, waste strength, and so forth)
- View details of mass balances throughout the plant and details of capital and operating and maintenance (O&M) costs for the system with data presented in either a tabular or graphical format
- Display output data graphically
- Save and load a large number of design cases (limited only by computer disk space)
- Receive further explanation regarding the values of model parameters and the conditions under which they were developed

The prototype was first developed on an IBM PC AT. Since the IBM PC AT has limited capacity and screen resolution, this version was complex to use and was thus converted to an Apollo workstation environment. The workstation features at 1,280 by 1,024 screen resolution on a 19 in. monitor and the Domain operating system with several powerful graphical packages and processors. The user interface of the prototype on the Apollo workstation is much simpler and easier to use. The program for the interface was written with DIALOG (*The DOMAIN* 1987) and GMR2D (*Programming* 1985). The user controls program flow with the computer's mouse. Menu options are presented as a set of boxes on the screen.

DEMONSTRATION AND DISCUSSION

The prototype is an interactive system. Although the following demonstration illustrates how the system works, it is much easier to understand from a videotape or a live demonstration. A detailed demonstration of the prototype is provided by Kao et al. (1990); a series of 43 different screens are given to demonstrate the potential uses of such a system. The following description presents only key features of the prototype using graphical illustrations.

Create, Configure, and Open Designs

Creating a new design is achieved by typing a new design name in a name field. After typing a name, a default set of unit processes will be shown.

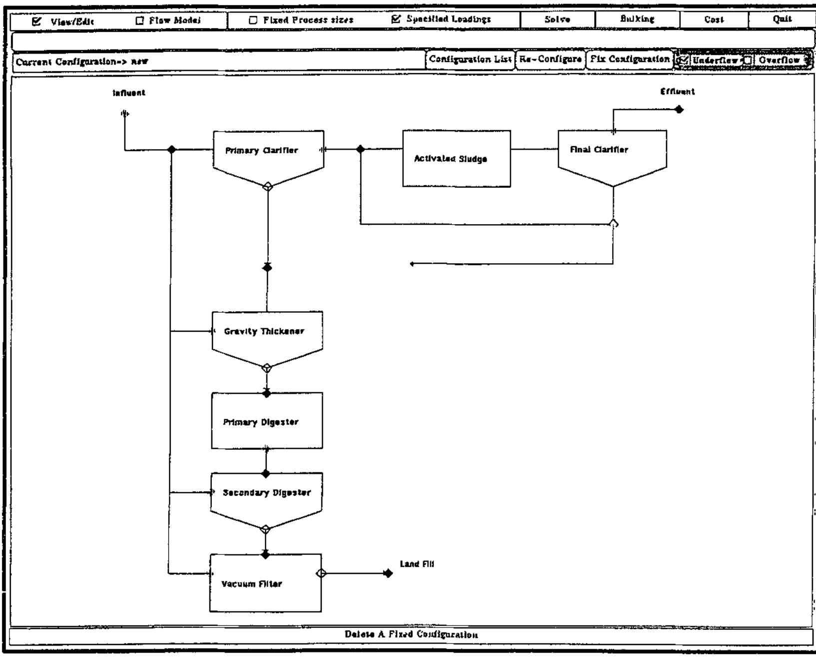


FIG. 2. Configure Design Screen

Once on the screen with the default set shown, the user can easily configure the process schematic by interactively clicking the mouse button on a process and drawing the flow lines to another process. Although a designer can create a process schematic composed of any combination of the unit processes, the schematic may be infeasible based on design constraints or mass and flow balance conditions. In Fig. 2, a process schematic would be established after drawing (by moving the mouse) the underflow line from the final clarifier to the gravity thickener.

This interactive approach of using the mouse to specify flow linkages is convenient for establishing a process schematic. The designer can open an existing design by typing the appropriate name in the name field. A list of design names can be shown by selecting the option "Configuration List" for review. Each time the designer types a new name, a new design is created. After the option "Fix Configuration" is selected, the design will be stored in a file. Those unit processes that do not have any linkage to or from any other process will be automatically deleted. Thus, no options are needed to save and delete individual processes.

View and Edit Design Parameters

The characteristics of design parameters and results obtained from analyzing a design are shown in several forms. A form can be selected for viewing and editing by clicking the mouse cursor on the desired position in the process schematic. For example, by clicking "Activated Sludge," the form for parameters and attributes for activated sludge will be displayed as shown in Fig. 3. The editable fields are highlighted by using bold character display (see the numbers on the lower right of the form shown in Fig. 3).

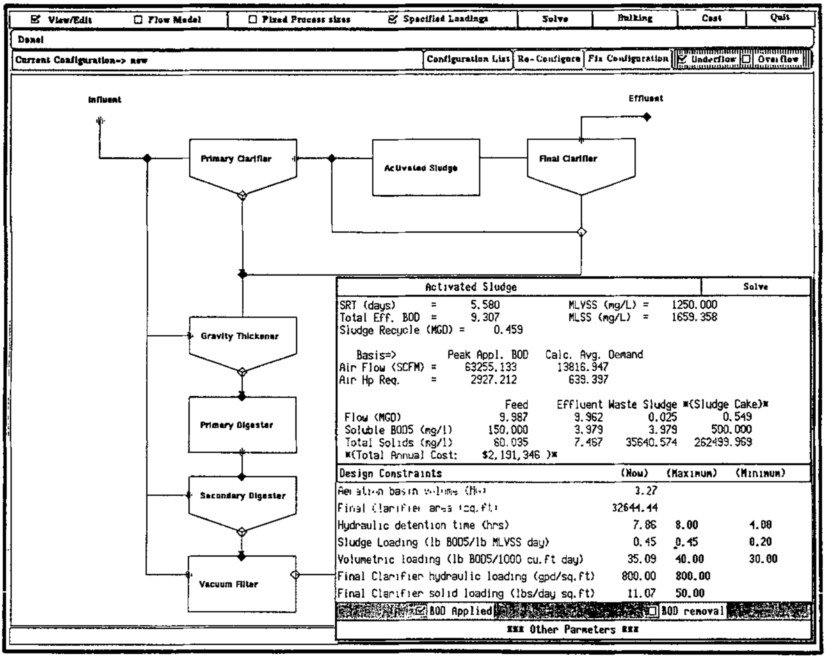


FIG. 3. Edit Parameter Values and Solve Design Screen

To edit, the designer can click the mouse on a desired field. Then, a small triangular cursor will be shown to indicate the typing position (see beside "0.45" for maximum sludge loading in the form shown in Fig. 3). The designer can then enter a new number into a desired field. Similar operations can be used for editing input and viewing output forms for the primary clarifier, thickener, digesters, and so forth. The input (editable) fields are highlighted by bold character displays, and the output fields are those numbers that are not highlighted; it shows the information that is not editable and only for reference purposes.

In cases where the information for a unit process exceeds the display capacity of the screen, it is divided into two separate windows, one containing output and frequently used input fields and the other containing the less frequently modified parameters (Fig. 4). The second window can be shown by selecting a menu option (e.g. "Heat Balance Parameters") on the first window. Using the "form fill-in" approach demonstrated before, the design parameters related to a specific unit process can be easily examined and modified.

In the PC version of the prototype, a menu system with up to four levels of pop-up windows was used. Although each screen provides clear information for an individual part of the design, it is not easy for the user to recall the entire system from this limited information. The screen size of an Apollo workstation monitor is suitable to hold most of the desirable information, but there are several complexities associated with such a presentation: (1) It may be difficult to handle too much information if it is shown at the same time; (2) the display of detailed information about each component, such as a unit process, would reduce the room available for other

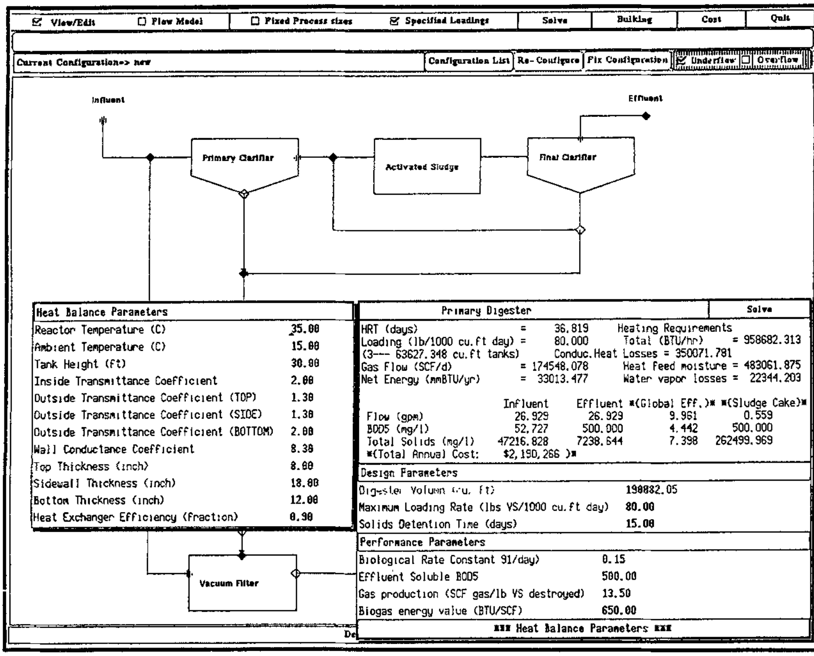


FIG. 4. Display Information Screen

information, e.g., the plant layout; (3) the designer usually does not need all of the information simultaneously; and (4) the design screen may become complicated and the response time when changes are made interactively will be increased. Thus, a decision was made as a compromise between clarity and simplicity: a menu system with up to two levels of pop-up windows was used for the current WTPD prototype. The second level of pop-up windows shows infrequently examined or less important attributes of a design. When a second level pop-up window is needed, it is displayed beside the first level pop-up window instead of erasing the first one (Fig. 4). The designer, therefore, still has a chance to examine all related information at the same time, while simplicity of usage, display, and response is maintained.

Sometimes, of course, a user makes mistakes. Mistakes that result in an infeasible design are hard to prevent, but many other mistakes can be minimized. For example, the layout of menu items was arranged to avoid inadvertent selection of wrong menu items. Two possible methods, fixing sizes or loadings, can be used by the engineer for the WTPD problem. Each method has a different set of editable parameters, but both sets are important for a design and should be displayed. In the prototype, the parameter fields of the fixed set are turned gray with a dotted parameter name [see "Digester volume (cu ft)" in Fig. 4] and cannot be selected. The fields are still available to the designer, but the chance of inadvertently selecting inappropriate items is significantly reduced.

Review of Process Performance Models

A variety of process performance models is available in the prototype. This flexibility is considered important for allowing the engineer to explore the impact of research results or specific plant operating data on the design and performance of a plant. Those performance models are presented to the user on a two-dimensional plot of the performance parameter (solids concentration, fraction removal, etc.) versus a significant design parameter (overflow rate, underflow rate, and so forth). All of the available models for a given process are plotted on the same scale. The user selects one of the models, that curve is highlighted, and an abstract of information (under what conditions the model was developed, the equation form of the model, etc.) is presented. This type of presentation provides background information and allows comparisons. Many of the models, however, have more than one dependent variable and thus the plot does not show all of the relationships. For example, in the case where the overflow solids concentration model for the final clarifier depends on overflow rate, unit feed rate, and feed solids concentration, a two-dimensional plot requires two of these variables to be fixed.

A variety of process performance models from the literature is available in the prototype for these unit processes: primary clarifier, final clarifier, gravity thickener, and secondary digester. The performance models can be displayed by first selecting the option "Flow Model" and the flow type (under- or over-flow solids), and then clicking the mouse on the desired unit process. For example, if the designer wants to specify a performance model for the primary clarifier in the design, by clicking the mouse on "Primary Clarifier" and "Flow Model," a pop-up window will display six primary clarifier overflow models (Fig. 5); the Voshel and Sak (1968) model was selected, and the description and associated curve are highlighted. Of course, it would be possible to rerun a given analysis using other primary

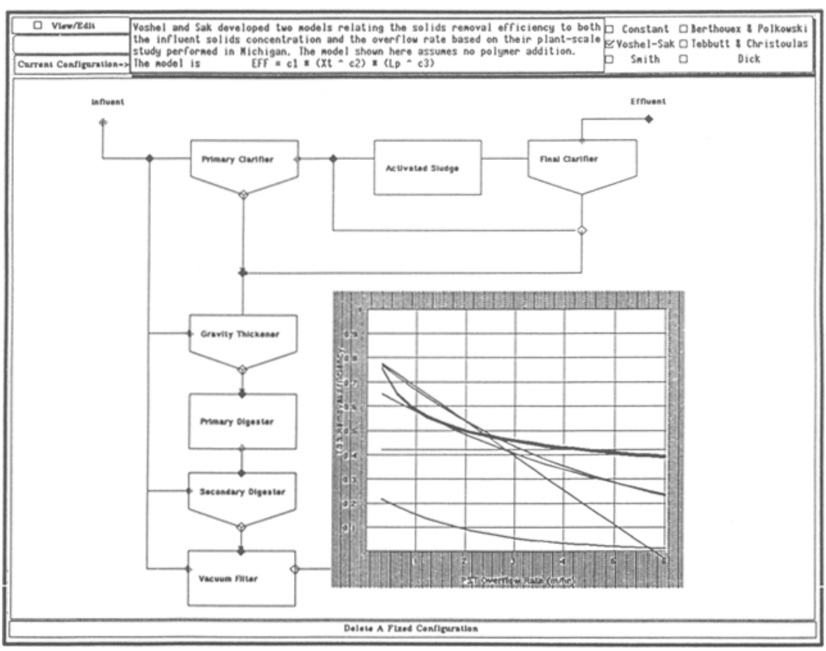


FIG. 5. Review Flow Models Screen

clarifier models to examine the sensitivity of the results. There are also multiple models in the prototype system for the final clarifier, gravity thickener, and secondary digester.

Solve Design Model and Present Results

After the values of all design parameters are determined and all performance models are selected, the designer can solve the design model by selecting the option "Solve" on either the top row of the screen or the top right corner of an editing window (Fig. 3). Although the "Solve" option is duplicated, the icon in the editing window makes it easy to see changes immediately after modifications are made to the design parameters; this interactive ability makes it possible to explore alternative designs readily. The designer may want to change the value of a design parameter. For instance, the maximum for sludge loading may be increased from 0.45 to 0.5 kg BOD_5/kg MLVSS day. A new solution can be readily obtained by re-solving. The cost of the new solution decreased from $2,191,346 (Fig. 3) to $2,190,266 (Fig. 4). Since the interactive response time is quick, the conventional trial-and-error procedure can be used more efficiently.

After creating a feasible design, the designer may want to examine the likelihood of experiencing an operational problem such as sludge bulking [using the method described by Geselbracht (1988)]. By selecting the Bulking option on the top row, a pop-up window will be shown (Fig. 6) to provide an estimate of the likelihood of bulking based on design conditions.

For each unit process, two major parameters—size and loading—are interrelated. For the same performance, there may be different combinations of values of the two parameters. In the prototype system, either of

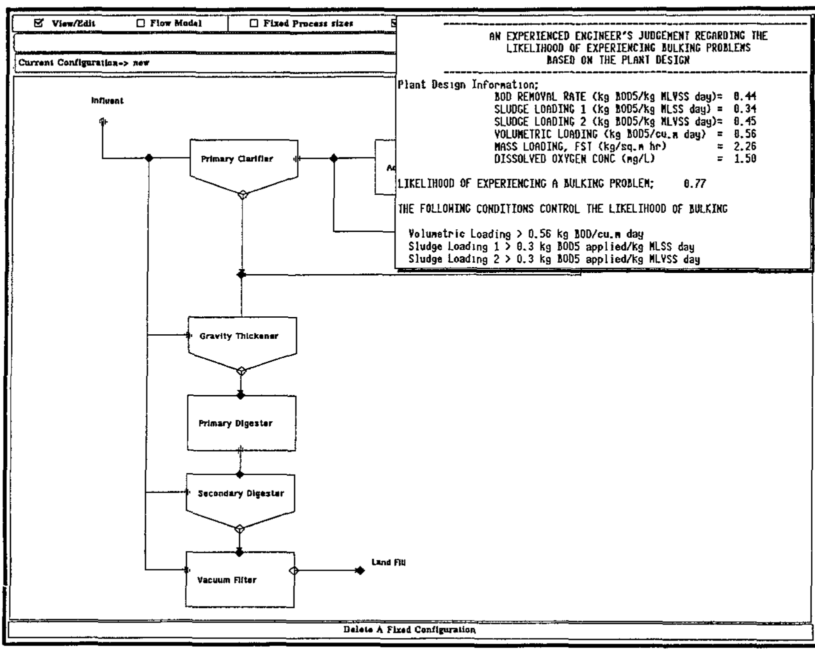


FIG. 6. Examine Sludge Bulking Likelihood Screen

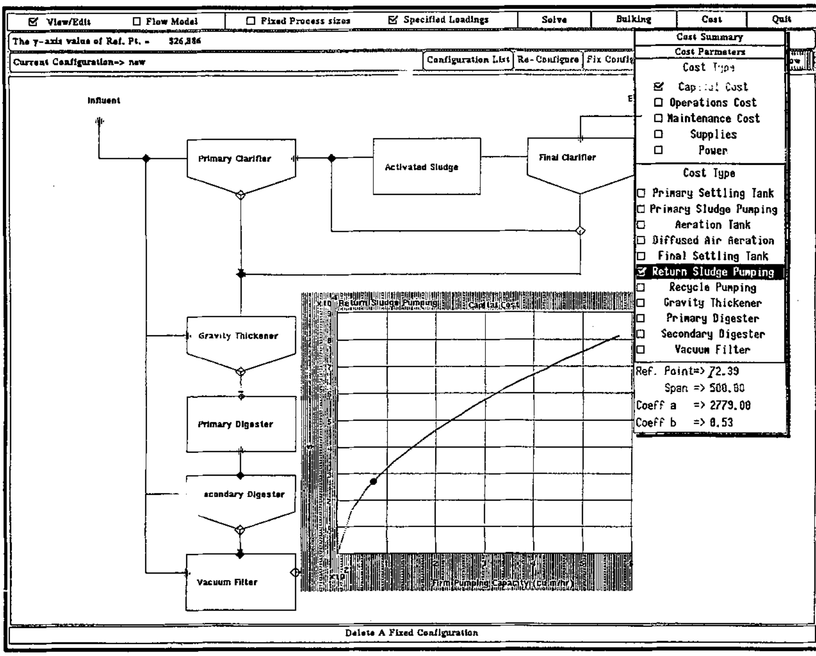


FIG. 7. Examine Cost Information Screen

the two values can be selected to be used in solving the design models; the other is then implied. The two options are shown on the top row of Fig. 3. Each option has a group of editable fields. If the fixed sizes option is selected, all fields related to the fixed loadings method will not be highlighted (and vice versa); see, for example, the gray texts in the editing window of Fig. 3.

Examine Cost Information

The cost equations have been modified to utilize a generic function. Generally, the cost equations are nonlinear curves of the form

$$\text{Cost} = a(X)^b \qquad (1)$$

where a and b = modeling parameters; and X = relevant sizing variable. The prototype allows up to five different curves for each cost function. Each curve is used for a different range of values of X and has a different set of values for a and b. Default values are provided for cost parameters (e.g., a and b), but the user can change these values.

The cost-related information includes a cost summary table, cost parameters, cost curves, and cost coefficients. The cost-summary table can be displayed by selecting the suboption "Cost Summary." Cost parameters (average wage rate, electricity cost, capital recovery factor, methane value, and sludge disposal cost) can be modified from a pop-up window shown after selecting the suboption "Cost Parameters." Five types of cost information are provided in this prototype: capital, operations, maintenance, supplies, and power. Other than specific unit processes, there are several other components in a design (e.g., return sludge pumping) that affect the

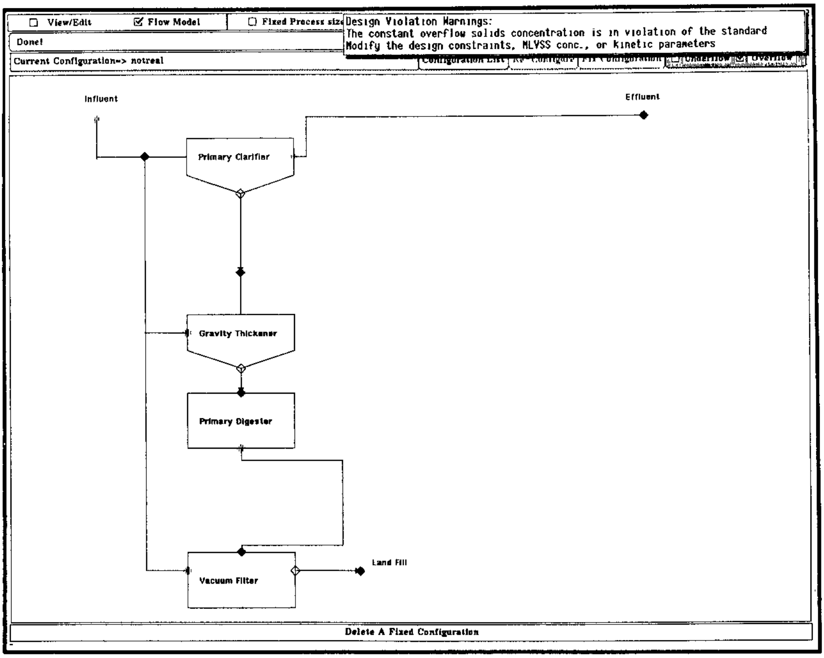


FIG. 8. Report Design Violation Screen

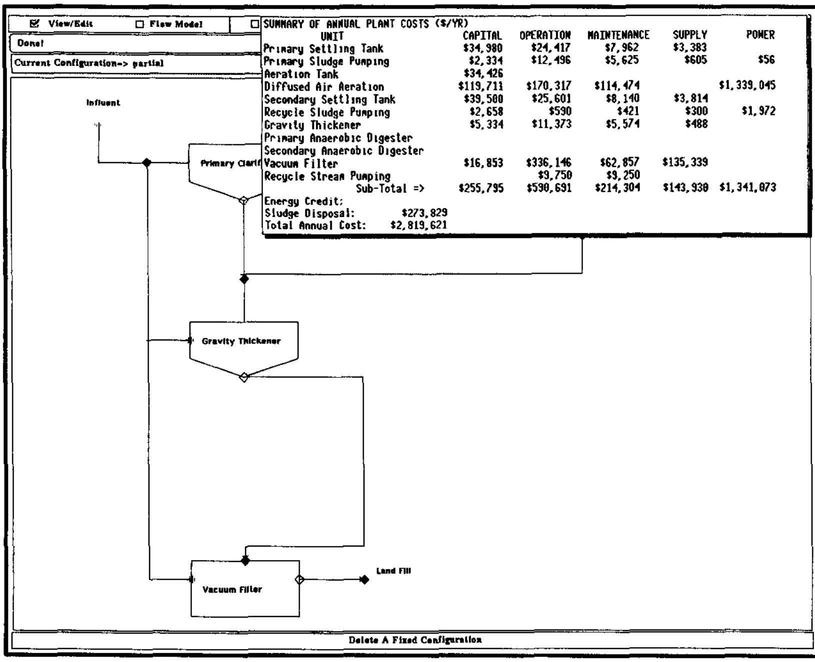
cost. Instead of using the configuration as the interface for displaying cost curves, a list is provided and selections are implemented by a checkbox approach.

A normal scale plot is used to show the cost curve. Fig. 7 shows the capital cost for return sludge pumping. By using the normal scale instead of semi-log plot, the cost curve can be easily understood and used by the designer. On the curves, the cost associated with the value of a design parameter in the current solution is indicated by a circle and shown in the message area. The parameter value is shown in the field "Ref. Point = >." For example, Fig. 7 shows the capital cost ($26,886) of return sludge pumping with a pumping capacity of 72 m^3/h, which is indicated by a circle on the curve and shown in the message area.

The range of parameter values to be displayed can be specified by the designer in two data fields: one for a reference point and the other for a spanning range (see field "Span" in Fig. 7). The designer can select a desired range by entering values into the two fields, and a cost curve, centered at the reference point and spanning backward and forward by the span range specified, would then be shown along with the cost associated with the reference point. The flexibility of showing different ranges of the cost curve and the cost for a particular parameter value may be useful for the designer in selecting an appropriate design under a cost constraint.

Report Design Violations

After a design is solved and the solution has been checked against the design conditions or standards, a pop-up window with a warning message would show if any violation(s) occurs. Although only one example, Fig. 8,



UNIT	CAPITAL	OPERATION	MAINTENANCE	SUPPLY	POWER
Primary Settling Tank	$34,980	$24,417	$7,962	$3,383	
Primary Sludge Pumping	$2,334	$12,496	$5,625	$605	$56
Aeration Tank	$34,426				
Diffused Air Aeration	$119,711	$170,317	$114,474		$1,339,045
Secondary Settling Tank	$39,500	$25,601	$8,140	$3,814	
Recycle Sludge Pumping	$2,658	$590	$421	$300	$1,972
Gravity Thickener	$5,334	$11,373	$5,574	$488	
Primary Anaerobic Digester					
Secondary Anaerobic Digester					
Vacuum Filter	$16,853	$336,146	$62,857	$135,339	
Recycle Stream Pumping		$9,750	$9,250		
Sub-Total =>	$255,795	$590,691	$214,304	$143,930	$1,341,073
Energy Credit:					
Sludge Disposal: $273,829					
Total Annual Cost: $2,819,621					

FIG. 9. Cost Summary Screen

is used to illustrate this ability, this kind of warning message may frequently appear in a design session using the prototype. This feedback capacity is very important for guiding the designer to a sound design.

Compare Designs

Comparison of designs can be implemented using cost-summary tables or the graphical schematics of the process train. By comparing cost tables, the effect of deleting or adding a unit process on the cost can be observed; an example of a table that includes the total system cost as well as the cost of individual unit processes is shown in Fig. 9. Also, the duplicate "Solve" option can be used to compare the results obtained from using different values of a design parameter. Detailed examples are provided by Kao et al. (1990).

CONCLUSION

A prototype design environment has been developed for a WTPD problem. The prototype is intended to demonstrate the potential effectiveness of such a system for implementing WTPD tasks. The features of the prototype are demonstrated. The prototype monitors options selected by the user and performs appropriate calculations or actions and displays results. The menu options are designed to be as simple as possible; most are shown in one window. To avoid confusion, at most two levels of pop-up windows are shown on the screen. The second level of pop-up windows shows parameters that are infrequently modified.

The feedback system provided in the prototype is intended to show how intelligent assistance can be provided to a designer in a design session. Such a system can be expected to shorten the time for producing a feasible design and to provide functions to assist in the exploration of better designs. For instance, a design engineer could readily perform sensitivity analyses using different models of a given unit process as well as different values of parameters in one particular model. The ability of such a system to solve a mass balance on combinations of unit processes included in the system is potentially a great aid to the designer.

Since the design environment is a research prototype, a number of changes or extensions are needed to make it more complete, more robust, and more efficient. For example, other user-friendly features such as cut-and-paste of unit processes included in the flow diagram may be used. Of course, there is always a trade-off between capability and simplicity. How to provide the maximum capability while maintaining simplicity is a key research issue in developing a computer-based system. Several suggestions for improvements or potential extensions of the prototype or new techniques are:

- Explore ways to present characteristics of a given WTPD problem or solution
- Overcome the numerical difficulties that occurred in solving highly nonlinear WTPD models and improve computational efficiency so that formal optimization techniques can be applied within the system
- Extend the WTPD model to include a wider variety of unit processes
- Provide flexibility in selecting a graphic object to express an attribute or real object, in adding attributes to the prototypes, and in arranging the display and layout of menu items or models
- Provide easy-to-learn tutorials, such as the one developed for IDEAS (Brill et al. 1989, 1990)
- Include an object-oriented database system for information and knowledge which is appropriate for such a creative design problem (see Kao, 1991)

Certainly, there are many other potentially useful extensions of the prototype. To provide an additional capability might, however, increase the complexity of using it. As discussed by Kao (1990), issues such as capability, simplicity, clarify, modularity, etc., must be considered carefully in developing a computer-based system. These issues are usually in conflict with each other. Before extensions of such a system are made, these issues should be evaluated carefully to ensure that the benefits justify the complexity.

ACKNOWLEDGMENT

The writers thank Mr. Paul Clinebell, Zurheide-Hermann Inc. Consulting Engineers, Champaign, Ill., and Mr. Jon C. Liebman of University of Illinois at Urbana-Champaign for their reviews of the prototype design environment and valuable suggestions. We also thank Mr. James G. Uber of University of Cincinnati for discussions about mathematical issues and graphical presentations of the research. We are also grateful to the Water Resources Center, University of Illinois at Urbana-Champaign, for its financial support under Grant No. S-144-ILL.

APPENDIX. REFERENCES

Brill, E. D. Jr., Hopkins, L. D., Flach, J. M., Hariharan, Kao, J.-J., Morgan, R. D., and Uber, J. (1989). *Experimental evaluation of modeling-to-generate-alternative approach.* National Science Foundation, Washington, D.C.

Brill, E. D. Jr., Flach, J. M., Hopkins, L. D., and Ranjithan, S. (1990). "MGA: A decision support system for complex, incompletely defined patterns." *IEEE Trans. on Systems, Man, and Cybernetics*, 20(4), 745–757.

The DOMAIN/Dialogue user's guide, No. 004299, Rev. 01, Apollo Computer Inc., Chelmsford, Mass.

Geselbracht, J. J., Brill, E. D. Jr., and Pfeffer, J. T. (1988). "Rule-based model of design judgment about sludge bulking." *J. Envir. Engrg.*, ASCE, 114(1), 54–73.

Kao, J.-J. (1990). "Computer aided systems for environmental engineering decision making," PhD dissertation, Univ. of Illinois at Urbana-Champaign, Ill.

Kao, J.-J. (1991). "A conceptual object-oriented database for wastewater treatment plant design." *Proc., 7th ASCE Nat. Conf. for Computing in Civ. Engrg.*, ASCE, New York, N.Y., 259–267.

Kao, J.-J., Pfeffer, J. T., Brill, E. D. Jr., and Geselbracht, J. J. (1990). "Workstation environment for wastewater treatment design using AI and mathematical models." *Res. Rep. 213,* Water Resources Center, Univ. of Illinois at Urbana-Champaign, Ill.

Programming with Domain 2D graphics metafile resource, No. 005097, Rev. 00, Apollo Computer Inc., Chelmsford, Mass.

Tang, C. C., E. D. Brill Jr., and Pfeffer, J. T. (1987). "Comprehensive model of activated sludge wastewater treatment system." *J. Envir. Engrg.*, ASCE, 113(5), 952–969.

Voshel, D., and Sak, J. G. (1968). "Effect of primary effluent suspended solids and BOD on activated sludge production." *J. Water Pollution Control Fed. Part 2*, 40(5), 203–212.

Wastewater engineering: treatment/disposal/reuse. (1979). Second edition, McGraw-Hill Book Co., New York, N.Y.

J. Environ. Eng. 1993.119:931-945.