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The Haztimator — Knowledge-Based Time and Cost Estimating of Hazardous Waste Remediation Projects[1]

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INTRODUCTION

This paper presents a new approach to conceptual cost estimating that will enable better cost control starting from the early stages of the design process. Our approach is based on the use of model-based reasoning tools to generate plausible alternative designs automatically at conceptual and preliminary stages of the design, with the limited amount of data available at those stages. We believe that these plausible detailed designs can be accurately estimated and then refined during later stages of design serving as "defending champions" against which every succeeding detailed design — or "challenger" may be compared. Further, the costs associated with these designs can be stored with semantic links to the design components in the design model, and can be refined as the design evolves. We claim that such an approach will have substantial impacts on the way that civil engineers can estimate future projects and control their costs.

This paper introduces a model-based design and cost estimating system, "Haztimator", which was implemented to apply this approach to the hazardous waste engineering domain. We will first describe the problems associated with the traditional approach to conceptual cost estimating focusing on the unique challenges of the Hazardous Waste domain. A section on Haztimator and its implementation environment will follow this introduction. Then, we will describe the potential implications of our approach on the design and project management process, and will provide some predictions about the impacts of design automation on the organizational structure of civil engineering firms. The final section of the paper will discuss possible future extensions to our proof-of-concept prototype.

BACKGROUND

Reliable cost estimates can be developed for many facilities, once the facility has been fully designed. However, the uncertainty associated with conceptual or preliminary design stage cost estimates is high. Cost estimates and designs do not evolve in parallel, limiting the value of the cost information in guiding the search for a feasible design solution, in organizing design activities, and in allocating time and resources to pursuing preferred alternatives in more detail.

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This mismatch between cost estimates and evolving designs is due to the traditional style of cost estimating that accompanies conceptual and preliminary stages of design. While design is an incremental synthesis or configuration task, conceptual cost estimating is viewed as a classification task (Amarel 1978 in Dym & Levitt 1991). Design as synthesis is a search, directed by constraints to arrive at a solution, by a process of assembling alternative candidate solutions from primitive elements, following a well-defined set of internal rules and structural constraints. It evolves by making incremental modifications to feasible alternatives and by eliminating certain alternatives as more information is made available. The discovery of what information is necessary to proceed is part of the design process.

On the other hand, conceptual cost estimating arrives at an estimated cost by associating the current solution with a class of past designs and adjusting the costs associated with that class of projects using a set of key parameters for comparison. For example, the cost of a plant might be estimated based only on its capacity using the 0.8 exponent rule to account for scale economies (Barrie and Paulson, 1992). Thus, an incremental change in a design is not usually reflected in a proportional change in cost unless it changes one of these key parameters. Since the level of detail and accuracy in our cost estimates do not match the level of detail in our designs, the two do not evolve in parallel. Consequently, cost control starts only after the detailed design stage of a project when detailed cost estimates based on quantity take-offs start to reflect the level of detail in the design solution. This is too late! A substantial amount of time and resources have already been spent in the design activity and commitments have been made. Changes based on cost considerations after this point will incur additional time and design costs to the project.

Further, when we approach conceptual cost estimating as a classification task, the information needs of a particular design alternative can not be evaluated since we can not compare the costs associated with getting a certain piece of information to the marginal utility of using that information in refining a design solution or its cost estimate. Especially, in those projects where the marginal value of information is a key ingredient in allocating resources to certain design activities, we need better estimates that are sensitive to incremental design refinements, and that can be used to determine the value of additional information.

Design follows the synthesize-analyze-evaluate cycle of problem solving, starting with an initial specification of requirements and evolving through several iterations in this cycle. However, routine design can be performed with a minimum number of iterations, if required heuristics can be used in structuring, and thereby simplifying the search for viable synthesis. Model-based systems provide effective representation and reasoning mechanisms that can enable the automation of routine designs by capturing these heuristics together with first principles to generate plausible solutions to routine design problems at early stages of a project. Formal symbolic models explicitly represent the structure and functional behavior of systems being modeled by using symbolic descriptions of a problem domain, description of the behavior of systems in that domain, and graphical presentation of the model and its behavior (Kunz 1988). The formal symbolic models can be complemented with mathematical models and heuristics when the structural or functional knowledge is incomplete or in the interest of efficiency (Kunz 1983 in Kunz 1988) as in the case of Haztimator.

When the design process is automated for routine design tasks, such designs can be used to estimate costs more accurately and control costs starting from the early stages of design. They can also be used to perform timely what-if scenarios, which would otherwise be unaffordable, to aid the selection of the most plausible alternative as well as to evaluate the value of information that would be used in refining certain alternatives. This would be a step in applying much needed utility theories to the design process (Simon 1984).

The application of utility theories in this context is two-fold. Model-based systems that can automatically generate alternative designs, estimate associated costs and select the alternative with the minimum cost with required functionality are the simplest form of utility maximization. Of equal if not more importance is the utility maximization that can be achieved by incorporating in the evaluation of each design alternative the value of additional information that can be used in refining that alternative. In Haztimator, each alternative's cost sensitivity to a set of site parameters can be automatically determined by what-if scenarios, and the value of refining the design using more accurate information on those cost sensitive parameters can be calculated in a matter of seconds. Thus, comparing the value of additional information (e.g., in terms of cost savings in the actual facility construction) for each design alternative against the cost of information gathering can aid in selecting the optimum alternative that maximizes the utility of the client.

Good design is not only the design that provides a feasible solution satisfying the given constraints, but also the design that makes best use of given resources, be it time, information, or money in **organizing** the process. Haztimator, through its generation of plausible alternative designs and their counterpart cost estimates, attempts to satisfy both of these requirements, especially the second one, by enabling the use of cost estimates to guide the process of design.

The hazardous waste remediation domain is one of the domains that can benefit most from this approach, due to the nature of both technological and site-related uncertainties and the high costs of information gathering (i.e., extensive site investigations) with which a hazardous waste remediation facility design needs to deal. Thus, after a first year project — "Conceptimator" —that applied the above approach to automating building foundation design, we decided to prove its feasibility in the hazardous waste domain in the "Haztimator" project.

THE HAZARDOUS WASTE ENGINEERING PROCESS

This section provides a technical introduction to the hazardous waste engineering process describing the actors and various stages involved in the process (Figure 1).

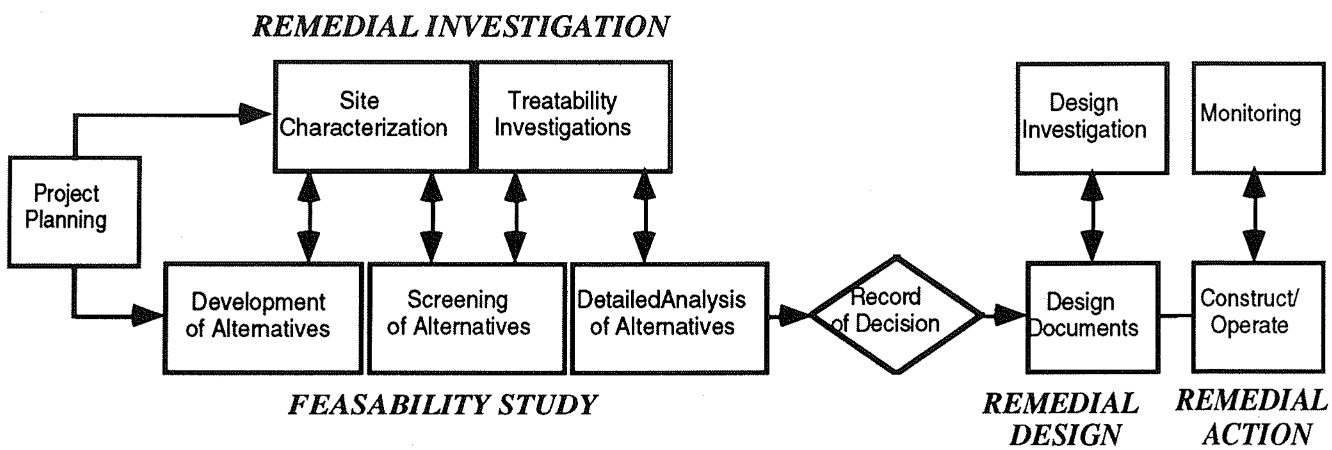


Figure - 1 Hazardous Waste Engineering Process

The project starts with a *Project Planning* stage in which roles are assigned to various participants — i.e., state and/or federal environmental agencies, potentially responsible parties if there are any, and one or more engineering & consulting firms that work on behalf of these governmental agencies and potentially responsible parties — for various stages of the project. Environmental engineering & consulting firms, appear in one of two client-consultant configurations; either with EPA or a public or private, potentially responsible party.

Once the *Project Planning* stage is complete and the engineering & consulting firm is assigned to the project, the first stage is referred to as *Remedial Investigation and Feasibility Study* (RI/FS). RI involves a set of in-situ and lab tests conducted on the contaminated site to determine the site and contamination characteristics. These tests may be conducted by either the engineering firm, the Client or the regulatory agency that requires the cleanup. The information collected in this stage constitutes the input to the *Feasibility Study*. The *Feasibility Study* (FS) involves the evaluation of available cleanup technologies based on this input, applicable standards and the relevant regulatory requirements. The RI and FS are complementary in nature. The data collected in the RI determines the applicable design alternatives, while the alternatives considered in the FS trigger further investigations depending on the sensitivity of the design alternatives to various measurable site parameters.

The product of the FS is a set of feasible design alternatives for the contaminated site. However, due to high institutional pressures, the process of evaluation is as important as this final selected set of alternatives. Thus, the intermediate stages of the FS — Development of Alternatives, Screening of Alternatives, and Detailed Analysis of Alternatives — need to be fully documented. This documentation is like a summary of the design team's task describing the alternatives reviewed and screened and justifying the selected alternative.

Once the final set of feasible technologies are determined they are submitted to the regulatory agencies with their documentation and made available for public comment. After this period of public comment, regardless of who the Client is, EPA decides on the best design alternative to be actually implemented. Thus, the EPA-approved design alternative and other related documents are summarized in the Record of Decision, and the environmental engineering group starts with *Design Investigation* (DI) and *Remedial Design* (RD) studies which are conducted in parallel.

Remedial Design involves the detailed design of the EPA selected alternative and its refinement with additional necessary information that is collected during Design Investigation. The detailed design documents are presented to the client in the form of performance specifications and/or detailed design drawings and are used as bid documents for the civil construction contractors that bid for the construction of the remedial facility. The design and consulting firm may assist the client in the evaluation of contractors' bids, the generation of construction contracts, and the subsequent inspection and monitoring of the *Remedial Action.*

Unique Challenges of Hazardous Waste Engineering

The major challenge that differentiates hazardous waste engineering from other branches of facility engineering — even conventional underground construction — is the unusually high degree of uncertainty associated with site characterization, particularly with site soils. Most decisions are based on incomplete information about the extent of contamination and its distribution in a site as well as the possible soil heterogeneities around zones of contamination. Performing enough site investigations to reach to a state of complete information is very costly if not impossible. Since the facility designed is not a "valued" product for the client, there is a strong tendency to minimize costs by reducing data collection resulting in the bare minimum of data usually being available. Thus, decisions are made with incomplete information at early stages of a remediation technology design, and modified continuously as more data are made available. These modifications last through the life cycle of the project until the start-up and operation of the remedial facility, and often during operation, as monitoring data is obtained.

Due to these uncertainties, the specifications presented with bid documents to the contractors usually take the form of performance specifications accounting for certain contingencies and leaving the design of various structures and equipment components to the contractors who will have more information about constructability issues. This results in a greater than usual asymmetry of information between the designer-owner and the contractor. The contractor has knowledge about the construction but is not familiar with the hazardous waste engineering issues. On the other hand, the designer has knowledge about, for example, process engineering considerations and constraints, but does not have enough expertise to translate the process diagrams into detailed specifications for physical structures. However, s/he needs to evaluate alternative bids provided by the contractors. This situation is very similar to the Engineering / Construction interface in other branches of facility engineering; however, it is more pronounced in this domain as most engineers in this domain tend to focus more on the constantly evolving new remedial technologies and their scientific basis, rather than on practical constructability issues. This puts the environmental engineer in a more disadvantaged position compared to his/her counterparts in other disciplines in terms of engineering-construction communication.

Our approach to conceptual stage design and cost estimating enables the generation of plausible detailed designs by both contractors based on performance specifications, and by designers based on limited site characterization data. It facilitates what-if scenarios to determine value of additional information, and enables continuous refinement to the conceptual stage detailed design as more information is made available. By enabling dual usage by contractors and designers it serves as a translator between design and construction.

PROJECT OVERVIEW

Knowledge Acquisition

For the prototype version of Haztimator, the remedial alternative selected for primary focus consists of two technologies: soil vapor extraction (SVE), followed by vapor-phase granular activated carbon adsorption (V-GAC). SVE technology is the current technology of choice for removing volatile organic compounds (VOC) and some semi-volatile organics (SVOC) from vadose zone soils (i.e., soils located between the land surface and the top of the groundwater table). As such contamination is frequently found at hazardous waste sites and at sites which have experienced gasoline or other hydrocarbon fuel spills, SVE has gained widespread use as a remedial technology. However, due to technical complexity of the problem, SVE system design is strongly dependent on expert knowledge and site-specific constraints.

As SVE itself results in the contaminants being transferred from the soil to a vacuum-induced air stream (see below for further description), the contaminant-laden air stream needs to be purified prior to atmospheric release. V-GAC is the current technology of choice for removal of relatively low mass/concentration loading of organic contaminants as frequently encountered in SVE operations. This conventional technology has been in widespread use for over 20 years, and its design is relatively straightforward.

Description of Remedial Technologies

The concept behind SVE technology is relatively straightforward to grasp. Figure 2 provides a schematic of typical major SVE system components. One or more "dry wells" (often referred to as vapor extraction vents) are sunk into the area of contamination. To these wells, one or more vacuum pumps (air blowers) are attached. When operated, the pumps creates a desired vacuum within the well and the surrounding soils. As a result of the reduced pressure field created, air flow is induced from the surrounding soils towards the well. As the targeted organic contaminants in the soil are volatile in nature, they will tend to volatilize from the soil into the passing air. The air is drawn through the vents to the surface where it is passed through a vapor treatment system (described below) prior to release to the atmosphere. The number of wells installed is based on an estimated "design radius" which represents the effective area of influence that the induced airflow passes through on its path towards an extraction vent.

Figure 2 goes in here

Optional SVE system components include 1) passive or active air injection vents used to enhance and control air flow through contaminated areas, 2) vapor/liquid separators, to remove entrained groundwater and/or condense water from potentially saturated airflow, thereby protecting the vacuum pump and increasing the efficiency of the vapor treatment system, and 3) an "impermeable" cap (constructed of low-permeability soil, plastic membranes, asphalt, etc.) to minimize water infiltration and/or to enhance and control air flow through contaminated areas.

V-GAC vapor treatment technology operates based on the natural physical process of adsorption whereby contaminant molecules are held (due to physical and/or chemical phenomena) at the surface of a solid (e.g., the carbon). Activated carbon is utilized as the adsorbent as it is a highly porous material (typically 60% porosity) with a large surface area (typically on the order of 1000 square meters per gram of GAC), properties which enhance potential adsorption of contaminant molecules as the air passes through the carbon. The carbon is placed in a granular form (typical diameter of 0.4 cm) in a contactor vessel through which the contaminant-laden air stream is passed, and 100% of the contaminant is removed. When the adsorptive capacity of the carbon is reached (referred to as the "breakthrough point"), it is removed for "regeneration" (thermally treated to remove and destroy adsorbed contaminants) and subsequently re-used.

Existing Systems

SVE is a relatively new remedial technology that has rapidly expanded in usage since late

80's. The USEPA included SVE under the Superfund Innovative Technology Evaluation (SITE) program (US-EPA, 1989a, 1989b). Because of its cost-effectiveness and ease of implementation, use of SVE has spread to an estimated hundreds if not thousands of sites, particularly for cases involving fuel spills from leaking underground storage tanks. As a result, the USEPA issued a reference handbook specifically for SVE (US-EPA, 1991a). The US-EPA also issued an interim guidance for conducting SVE treatability studies under CERCLA (US-EPA, 1991b). Several SVE vendors exist in the current marketplace, and at least one has secured a U.S. patent with regards to employment of the technology. Thus, it appears the technology will continue to be a "workhorse" for remediation of hazardous waste sites containing VOC-laden soil.

V-GAC was first used for vapor treatment in response to the German introduction of gas warfare in 1915 (Freeman, 1989). In the 1970's, the ability of GAC to remove a broad spectrum of toxic organics from both vapor as well as liquid streams was recognized, and GAC has since become a conventional treatment technology choice in cases of relatively low mass loading. Several GAC vendors exist in the current marketplace. Specifically with regards to SVE, V-GAC is recommended by vendor practitioners as the treatment technology of choice for VOC removal rates below 25 to 50 lbs/day (Trowbridge & Malot, 1990), a criteria frequently met at most sites.

State of Knowledge

Although a large number of field applications of SVE have been reported since the mid-1980s, design of full-scale systems have been empirical due to the varying subsurface conditions and complexities of the dynamic, interactive processes involved (Cho and DiGiulio, 1992). Experts on design exist in vendor and engineering firms. A pilot-scale system is recommended to obtain necessary design parameters before full-scale design and implementation (Cho and DiGiulio, 1992). The USEPA has recent guidance on conducting such a "treatability study" (USEPA, 1991b).

Since V-GAC is a conventional treatment technology that has been used over a relatively long time, a solid database of empirical performance data has been established. In addition, a theoretical model is available (Crittenden et al, 1988) which is employed by Haztimator. It's predictions correspond closely with available empirical data (Stenzel and Gupta, 1985). Further, this model is utilized by the USEPA (USEPA, 1988).

Technical Complexity of the Problem

For SVE/V-GAC system design, the following three parameters are required: (1) Extracted Air Flow Rate which affects vacuum pump and V-GAC unit sizing; (2) Design Radius which affects number of extraction vents required; (3) Extracted Air Contaminant Concentration

Profile which determines V-GAC unit sizing and determines required system operation or remediation time.

The technical complexity that hinders estimation of the above critical parameters is due to: (1) Dynamic, unsteady-state operation; (2) Real-world variability of the subsurface environment; and (3) Mass transfer limitations.

As a result of such technical complexity, it has been asserted that it is doubtful a predictive mathematical model can be developed that is applicable to a wide variety of field situations (Stephanatos, 1990). Indeed, the USEPA notes that a limitation to SVE is the inability to accurately predict cleanup times via mathematical models (USEPA, 1991b).

Evaluation/Selection of SVE Models

For SVE, required parameter prediction can be split into two parts: (1) Air Flow Rate / Design Radius Prediction; and (2) Extracted Air Contaminant Concentration Profile With Time Prediction. With respect to air flow rate and design radius predictions, two types of models were noted, a simple analytical model (Johnson et al, 1990), and various sophisticated numerical models (Krishnayya et al., 1988; Massmann, 1989; Kuo et al., 1991). These models were evaluated versus heuristically-derived values based on the predominant soil type found at a particular site. The heuristic approach was ultimately adopted for use in Haztimator based on the following limitations noted with the mathematical models: (1) The predictions of Simple Analytical Models are inconsistent with field-observed values due to the inherent variability in subsurface conditions; (2) The Sophisticated Numerical Models require site-specific information normally not readily available, have limited validation against field-observed results, and the numerical solutions have large computer memory requirements. These limitations are worthy of noting, as the increased benefit of numerical model solution is unknown.

With respect to prediction of extracted contaminant concentration profile over time, three types of models were noted; a simple equilibrium-based analytical model (Johnson et al, 1990), several equilibrium-based numerical models (Baehr et al., 1989; Stephanatos, 1988; Wilson et al., 1988), and several sophisticated numerical models directly incorporating mass transfer limitations (Brusseau, 1991; Gierke et al., 1992). For the equilibrium-based models, mass transfer can be accounted for via use of "effective" input parameter values which approximate mass-transfer limited conditions. The simple, equilibrium-based analytical model using a heuristically-derived efficiency term to account for mass-transfer limitations was ultimately adopted for use in Haztimator.

Computer Implementation

Design++ Environment

Haztimator, like its predecessor Conceptimator, is implemented using Design++ , a design configuration system implemented as a high-level object-oriented design automation language built on Lisp. Design++ has interfaces to AutoCAD to display and manipulate geometric data, and to ORACLE and other SQL data bases to access and query external sources of data.

Two key features of the Design++ implementation environment are (1) Component Libraries; and (2) Product Structures. Design++ enables the designer to create libraries of objects i.e., reusable descriptions of the behavior of physical and conceptual components of an engineered system. These generic components are then assembled into a product structure by the designer, to define a generic legal configuration for all of the possible systems of a given type (e.g., SVE systems) that can be generated from these components.

Design++ Libraries Design++ libraries are organized as abstraction hierarchies that consist of data structures called components which designate concepts and physical objects in the real world. Object classes closer to the root of the hierarchy are more general than the object classes located closer to the leaf nodes. Design++ libraries make use of inheritance rules in storing data about objects they designate in the world, by each object subclass inheriting attributes from classes that precede it on the path to the root of the hierarchy. The values of the object attributes may be static or may be determined at run-time. In the latter case, the designer needs to define the procedure or the relation which should be used in determining the value of an attribute in the form of a rule attached to the object's attribute. Rules (Figure 3) use as constraints the attribute values of the component in question, the relations the component has with other components in the design solution, as well as the attribute values of those other components with which the component has relations. Object attributes may have restrictions on the type of values they accept (referred to as their value-class), or default values in case there is not enough information to determine a value for their instances.

Figure 3 goes in here

Design++ Product Structure The product structure is a text file which pre-defines a generic legal configuration for possible designs that can be generated using the library components as primitives. It consists of a nested list of generic components from the component libraries where each list has a part-of relation with the list it is nested in. Product structure is one of the strengths of Design++. It simplifies the search for a feasible design solution and can easily be specified for routine designs. It is flexible enough to allow slightly different configurations for a class of facilities by the use of rules which determine (1) The membership of possible components in a specific design solution; and (2) The number of components that should be included in a certain sub-assembly that is part of the design solution. Secondly, it is used as a structure to relate various components to each other using their relative positions in the part-of hierarchy to calculate their attribute values for a specific design. For example, the diameter of any collection pipe, that is part-of a vapor extraction system can be calculated based on the maximum flow rate that the extraction system needs to sustain.

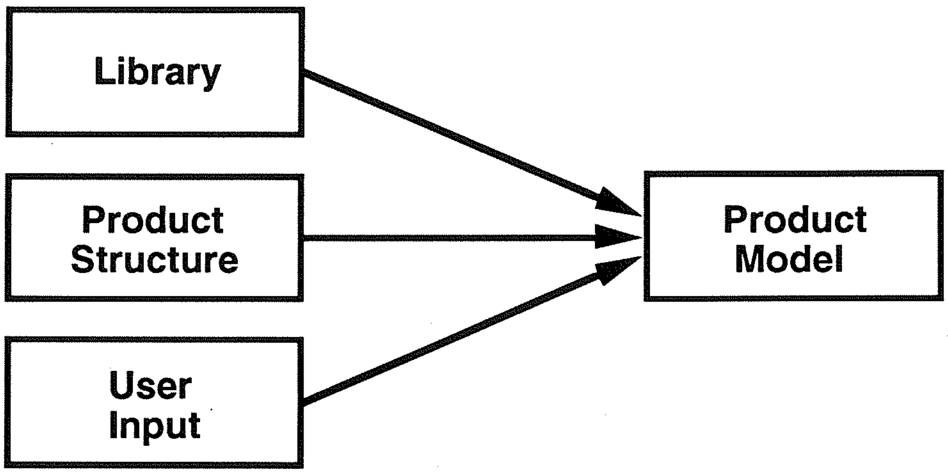


Figure 4 - Design++ Product Model Creation

Design++ Model A Design++ model, as it will be referred to in the following sections, is a specific instance of the product structure, fleshed-out to meet the requirements of the current design problem. It is created from client input for a particular design case using the rules stored in the library components that make up the product structure to determine attribute values of each component instance, and its relations with other components.

Haztimator Library

The Haztimator library (Figure 5) consists of two generic classes of objects at the root level: (1) Assemblies which refer to concepts used and functional sub-systems created during the design process; and (2) Parts which designate primitive physical components with geometric attributes that make up the functional systems.

Under assemblies, we describe the soil and site conditions by storing data in objects such as *hazardous_waste_site*, *operable_unit, soil_strata*, and *contamination*. Object classes such as *control_variables* (e.g., *soil_vapor_extraction_control_variables*) are used to calculate and store design parameters that drive the design of remediation systems. Examples of such parameters stored in control variables are attainable air flow rates per unit screen, allowable design radius to place vents in an extraction system, and removal rate for vapors. Another major class of concepts represented in the Haztimator library describes the evaluation processes used in choosing between different remedial actions (e.g., *treatment_eval, containment_eval*) and between different technologies (e.g., *excavation_eval, soil_vapor_extraction_eval*) to carry out a selected remedial action approach. The attribute rules in these objects evaluate the soil and site conditions, and the various design parameter values calculated based on these conditions and stored in control variables, to determine the effectiveness and feasibility of alternative remedial action approaches and alternative technologies. Pilot studies are also represented in the library to store any information that may help the evaluation of different alternatives. Also under assemblies we store information about system level parameters of designed systems such as *extraction_vent_system*, or *injection_vent_system.*

Figure 5 goes in here

Under generic class parts we have those classes of objects that describe a set of possible physical components that may be used in a remediation design. These components (e.g., *extraction_vent*, *collection_pipe*, *screen*) have geometric attributes describing their shapes, and dimensions, as well as their design locations in a 3-dimensional coordinate system. Most of the attribute values stored at the system and concept level in the assembly objects are used in calculating the dimensions and positions of these components in a given design. Also the cost attributes (e.g., material cost, labor cost, soil disposal cost) are all calculated and stored at this level using cost estimating rules reflecting the amount of detail represented in our design solutions.

Haztimator Product Structure

The Haztimator product structure is shown in Figure 6. As can be seen in the figure, the product structure starts from a root node representing the *hazardous_waste_site*'s general characteristics. A site can be composed of one or more *operable_units* (i.e., self contained contamination zones that may be treated as separate entities). Each operable unit's characteristics are stored in objects such as "n" number of distinct contaminated *soil_strata*, contaminated with one or more of the contaminants shown in the figure. The response action for each *operable_unit* will be evaluated based on these soil and site characteristics and will determine the inclusion of other more detailed level evaluation processes (i.e., *soil_treatment_eval, ground_water_treatment_eval*) in the design. At lower levels in the part-of hierarchy we see legal components of an *extraction_vent_system* such as a run-time calculated number of *extraction_vents* each with a *screen*, a *valve*, a *joint* and a *connection pipe*. Each of these physical objects, when instantiated in product models, will have their dimensions and relative locations calculated by the rules attached to them, based on their relative positions in this part-of hierarchy.

Figure 6 goes in here.

Haztimator Input

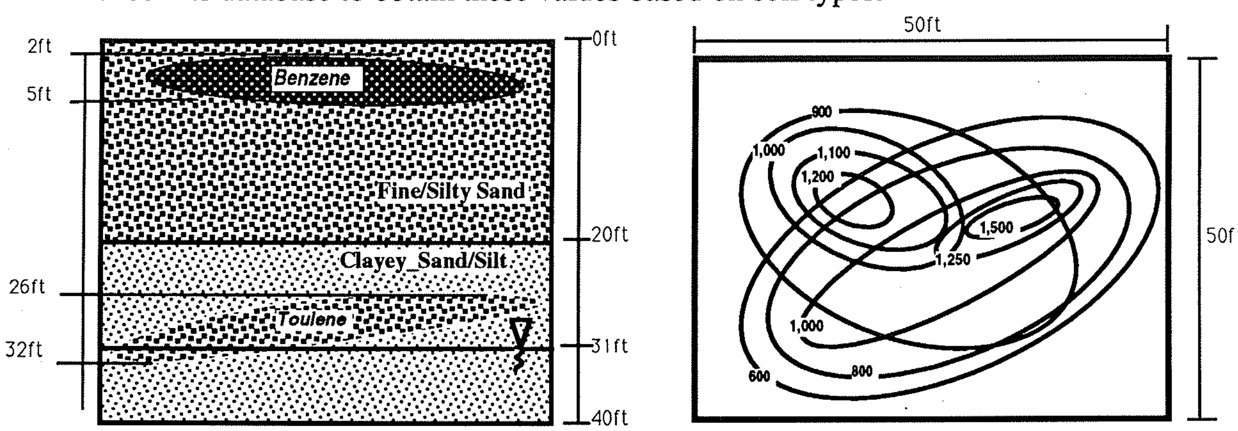
Figure 7 shows a simplified soil cross-section and contamination contours of a site for which Haztimator could generate a remedial technology design. The basic input to the system consists of:

(1) The distinct layers of soil found on site with their depths and thicknesses;

(2) The contaminants detected in each soil layer and the extent of contamination for each layer;

(3) The detailed percent distribution of contaminant concentrations derived from contours if information exists, or average concentration for each contaminant found in various soil strata;

(4) If there are any pilot studies, then soil permeabilities, attainable air flow rates and required radius of influence obtained in these studies; in case of no pilot studies the system will check its database to obtain these values based on soil types.



CONTAMINATED SOIL CROSS-SECTION ***CONTAMINATION CONTOURS*** ***based on boring logs (ppm)***

Figure 7 Haztimator Input: Contaminated soil cross-section and Contamination contours

The required input to generate a design varies depending on the available information specifically the existence of pilot studies, soil borings and other site investigation data. If there is information available, the system takes this into account and the generated design will be more accurate. However, if the information does not exist, Haztimator will use data in its database to make appropriate assumptions and will still generate a plausible design that can be refined as more information becomes available. This flexibility can enable the designer to play what-if scenarios and determine the value of additional information. For example, if there are not enough boring-logs to accurately define the contamination contours, one design model can be generated and costs estimated using average contaminant concentrations that are known today. Then the designer can try a number of additional models using more detailed information about alternative possible contaminant concentrations and compare the costs of these additional models. If the estimated costs of these models differ significantly from the costs of the model generated with the default information, this difference can guide the designer to invest in further site investigations, rather than proceed with design based on the current data. This kind of sensitivity analysis can be performed to determine the marginal value of additional information of several kinds which, in turn, can guide the organization of the design process and the allocation of resources.

Haztimator Process

Generation of the Haztimator design solution is directed by the product structure which defines the space of legal solutions. To flesh-out the skeleton provided by the product structure, the system first performs an initial screening of alternative remedial actions (i.e., containment, treatment, no_action) and determines the set of possible technologies (e.g., soil vapor extraction and removal by excavation for soil treatment remedial action) that may be used in accomplishing the selected remedial action. It includes these technologies as alternatives in the product model.

In the second stage, the various technology parameters are calculated to determine the effectiveness of each technology and are used in the generation of physical designs, capital and operating cost estimates, and cleanup-time estimates as well as contaminant removal rate curves (if applicable) for each alternative. The system finally chooses the most attractive feasible alternative from both a technical and an economic perspective, and generates a three dimensional system layout in AutoCAD. Figure 8 summarizes the Haztimator reasoning process.

This model can be used as a "defending champion" to evaluate future design alternatives in terms of their technical adequacy. More importantly, it can be used as a new and powerful cost control tool enabling the designer to isolate and control the cost effects of any modification to the "defending champion" design.

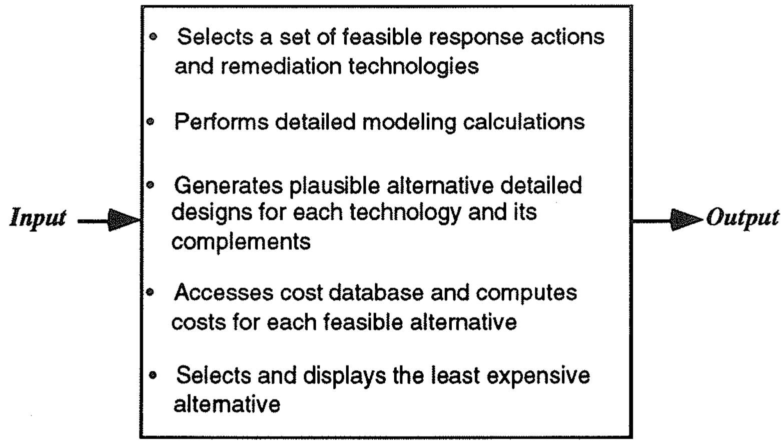


Figure 8 - Haztimator Reasoning Process

Haztimator Output

Haztimator produces as output (Figure 9) a design model as seen in Figure 10, an interactive AutoCAD model (Figure 11) of the site layout, and a cost estimate that reflects capital and operational costs at both individual item (e.g., vent, pipe) and aggregate (e.g., extraction vent system) levels.

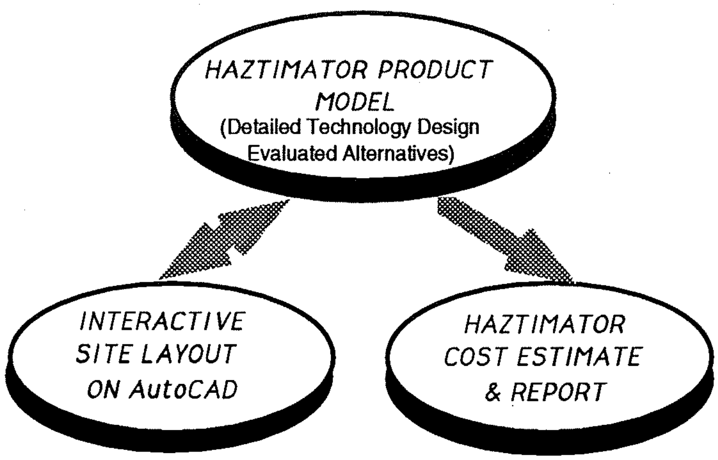


Figure 9 - Haztimator Output

The interactive nature of both the design model and the AutoCAD drawing give the designer the necessary level of autonomy over the design decisions. The designer may change the location or dimensions of various structures in the AutoCAD drawing and these changes will automatically be reflected in the revised design model, and cost estimates. Or provided with new information, s/he can change the attribute values of various soil-strata or contaminants represented as part of the site information in the design model (e.g., the extent of contamination in a certain soil layer) and can automatically see the effects of this change in the design in the form of a new alternative being evaluated or a different site layout and cost estimate being generated for the same remediation technology. The designer can also easily modify the underlying technology assumptions as more scientific information is obtained about the performance of various remediation technologies. The interactive nature of the system supports a high level of human-machine cooperation in producing optimum designs.

Figure 10 goes in here.

Figure 11 shows a site layout for a soil vapor extraction system that consists of several vertical extraction vents, collection pipes, vacuum source, an air water separator and a carbon unit. The upper rectangular block delimits the volume of excavation necessary to clean up the upper soil layer. The designer may modify the dimensions of the excavated volume as well as its shape as more accurate site information is obtained about the extent of contamination in the first layer. Similarly changes to the model to reflect the vertical extent of contamination in the second soil layer or its concentration will lead to automatic changes in the depth of vertical vents and possibly the capacity or the number of carbon units to clean up the vapors. All these changes will automatically be reflected in revised estimated costs for the clean-up solution.

Figure 11 goes in here.

IMPLICATIONS OF OUR APPROACH

Cost Control Implications

Tools like Haztimator can enable designers and owners to have better control over cost implications of their decisions. Linking costs to design components provides designers with on-line access to the cost implications of their decisions. Designers can make changes to their designs or their assumptions in the light of such on-line cost feedback. Both construction and design costs can be controlled, starting from the conceptual and preliminary stages of design. Early feedback to designers on the cost implications of their decisions will enable designs to stay within pre-determined budgets and designers to investigate those alternatives that minimize cost from the beginning. This will avoid future increases in budgets to meet the actual costs discovered during detailed design.

We argue that this is especially important in the hazardous waste engineering domain. where costs must be known early in the process to appropriate private or public funds for clean-up programs. Design costs can also be minimized using this approach. By eliminating alternatives in the early stages of the project that would very likely prove to be infeasible from a cost perspective at the detailed design stage, designers will reduce the amount of resources and time spent in non-value adding design activities.

Tools like Haztimator can also be used to perform what-if scenarios or sensitivity analysis by varying the design input variables and determining the solution's sensitivity to each input variable in terms of cost. This type of analysis can help in deciding whether to invest more resources in gathering additional information at conceptual stages of the design and, if so, to determine what the value of information is for a given design solution. This is especially important during the Remedial Investigation and Feasibility Study stages of the hazardous waste engineering process, where engineers need to decide whether to make more costly site investigations or to refine their design based on available information.

Communication Implications

Engineering - Construction Communication => Constructability Improvements

Having plausible detailed designs starting from the early stages of the design can facilitate communication between engineers and contractors. Such designs have the level of detail with which contractors can reason about constructability issues. This allows early constructability feedback to the engineer who is not familiar with construction during the preliminary design stage . A change made to a process diagram or to an initial assumption by the designer can be input to and detailed by the system, serving as a translator for communication between the engineer and the contractor. Thus, the performance specifications that are provided with bid documents can be supplemented by electronic detailed designs which facilitate both the engineering/construction communication and the engineering evaluation of contractor bids.

Engineering-Regulatory Agency Communication => Regulatory Decision Making Quality

The implementation of this approach in a model-based tool enables the easy storage and retrieval of all alternatives that were eliminated, along with the ones that were qualified during the RI/FS. This makes the technology selection rationale more explicit and better documented, and can provide regulatory agencies with better decision criteria in preparing the Record of Decision.

Project Structure Implications

This approach to conceptual design and cost estimating may lead to the elimination of the preliminary design stage and to a leap from conceptual to detailed design for routine design problems, or at least to a much shorter preliminary design stage, since many issues will be resolved by the use of tools like Haztimator. In the hazardous waste engineering domain this would mean shorter Remedial Investigations and Feasibility Studies making alternative technology designs available to regulatory agencies with their associated costs in a more timely manner.

Organizational Implications of Design Automation & Decision Support Systems

This section provides an overview of the organizational issues related to the use of information systems, design automation and decision support being one example. In this section we make some speculations supported by organizational literature about possible implications of such tools for engineering organizations. These and other speculations related to the influence of information processing tools on organizational structure, and decision and control mechanisms of engineering organizations are investigated as part of the first author's ongoing research.

Effects at different organizational levels

Organizational level

Pfeffer and Leblebici evaluate the match between a given task environment and an organizational structure in terms of the control requirements of the task and the control capacity provided by structure (Pfeffer and Leblebici 1977). In this perspective any information system that will provide better means of control will relax the other aspects of the organization set up for control. Tools like Haztimator actually do the task of the performers automating the quantitative and some qualitative processes that lead to decisions. They also store, integrate, and reason with a vast amount of technical knowledge that would otherwise be in different specialists. The use of such tools in project-group decision making implies process control on the group's task through formalization of decision criteria in computer's knowledge base. Thus, looking from control perspective these types of decision support tools used by professionals may lead to further decentralization. In a matrix structure, such a system would allow specialists from different functional groups to perform with minimum upward referral to the functional manager for technical problems related to their discipline.

But at the same time, these tools would make the decisions easier and would reduce the necessary information to perform the task. This would change the one to one mapping between the task and the individual or organizational level that possesses the knowledge to perform the task (Huber 1990). This may mean more decentralization in centralized organizations, and less decentralization in already decentralized ones as it will lead to a more uniform distribution of information and autonomy throughout the organization. In either case, these tools would reduce the number of organizational levels involved in authorization.

Depending on how much of the task is automated these tools may either reduce differentiation or improve the information processing capacity of differentiated organizations by reducing the need for coordination. The first case would hold if the automation is high and the decision support tool provides both differentiation and integration through analysis and synthesis of project decisions and handles most of the interdisciplinary interdependencies. However, this level of automation is not feasible and achievable in a very complex and unstable task environment such as the hazardous waste engineering domain. Thus, the second case is a more likely one where these tools support the task of the professional, improve its efficiency and accuracy and also provide interfaces to tasks of other professionals supporting the interdisciplinary communication. Thus highly differentiated structures could increase their information processing capacities through the use of such tools.

Organizational Memory. Technical decision support tools expand the organizational memory of the professionals performing the task (Huber 1990). They make more, better quality, and easily accessible organizational and technical knowledge available to professional decision makers. They reduce the negative impacts of experienced personnel turnover which is especially important in newly developing domains where expertise is rare. And they also supplement the skills of the specialist working in project teams making the specialty knowledge available and not confined to the individual's own experience and skills. All these factors would increase the quality of decisions.

New technology and legitimacy New technologies are accepted and utilized in organizations to the extent that they (1) improve technical efficiency; and (2) contribute to institutional legitimacy and reputation (March and Sproull 1990). The early adopters of a technology are driven more by technical efficiency while late adopters are after legitimacy or conformity. Information technologies and decision support tools are particularly valuable if competitors do not have it, thus those organizations that are early adopters who use it for technical efficiency have a higher competitive advantage.

Subunit Level

At the subunit level Huber hypothesizes that decision support tools can reduce the size and heterogeneity of decision units in our case project groups (Huber 1990). The existence of a tool with the expert knowledge may reduce the number of specialists necessary as official members of the project team. This reduction in number may make decision making easier. However, Huber also says that these tools can enable more and a variety of people participating in decision making. This is true in that such systems will enable the knowledge of several professional experts to be made available through the system to the current users. Thus reducing group size will not reduce the richness of information media. Finally such systems can reduce the frequency and duration of meetings as most of the problems will be solved through man-machine or group-machine interaction, where the machine will provide a wide range of information which would otherwise be communicated during meetings. However, for all these to happen the subunit task has to be redesigned to revolve around the use of this tool and its utilization.

Limitations and Future Extensions

Haztimator is a prototype system implemented to investigate the feasibility of using "Conceptimator" approach in the hazardous waste domain. In the future, it can be expanded to other types of removal and treatment technologies that are relatively well known, supplemented with additional cost and design information to widen its scope of application.

Developing system interfaces to geographic information systems for site characterization such as "Consolve" can make more accurate 3D site characterization data available to Haztimator and can enable more sophisticated spatial reasoning which will improve the quality of the design solutions.

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Figure 2 - Typical SVE system crossection

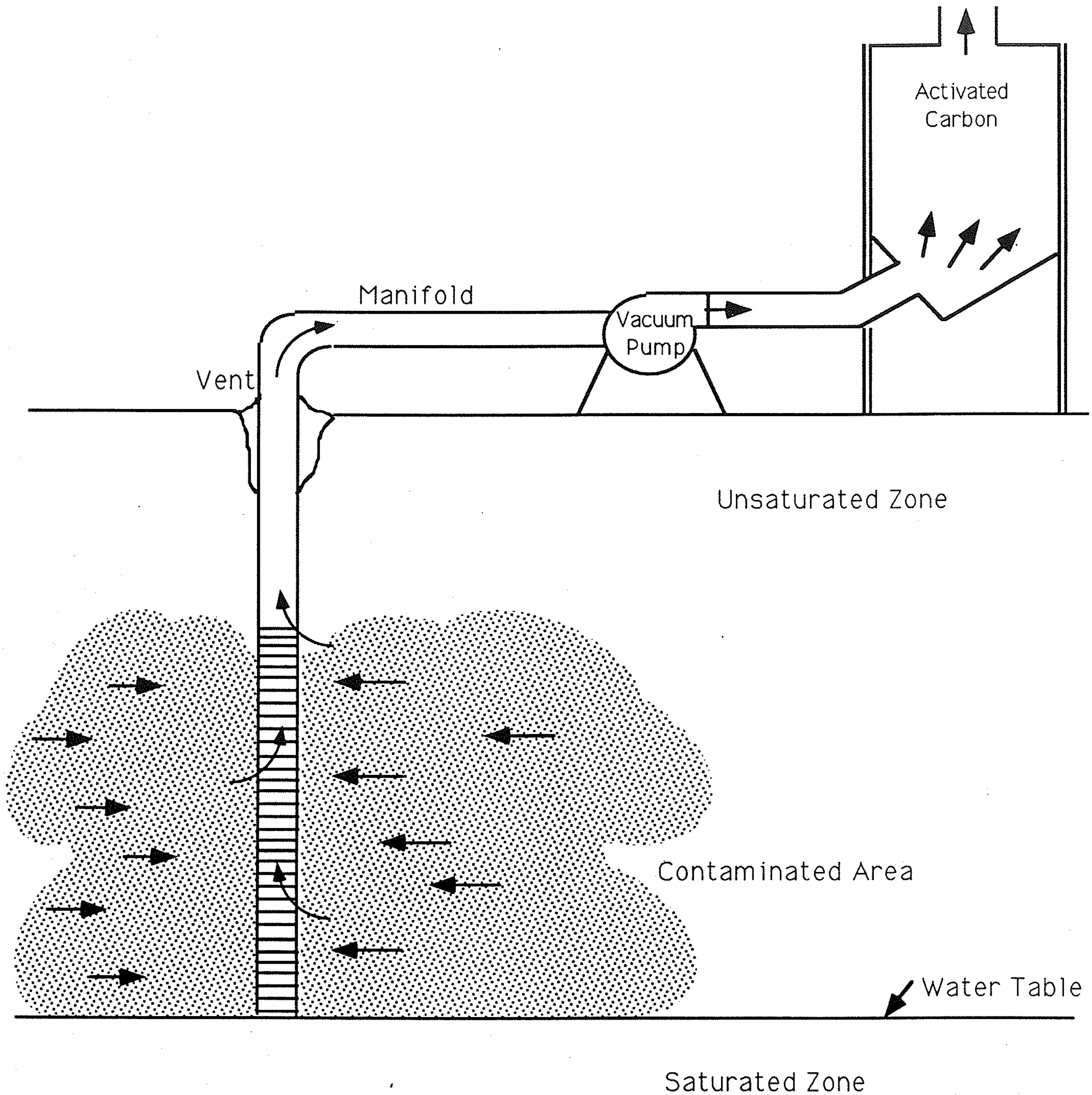
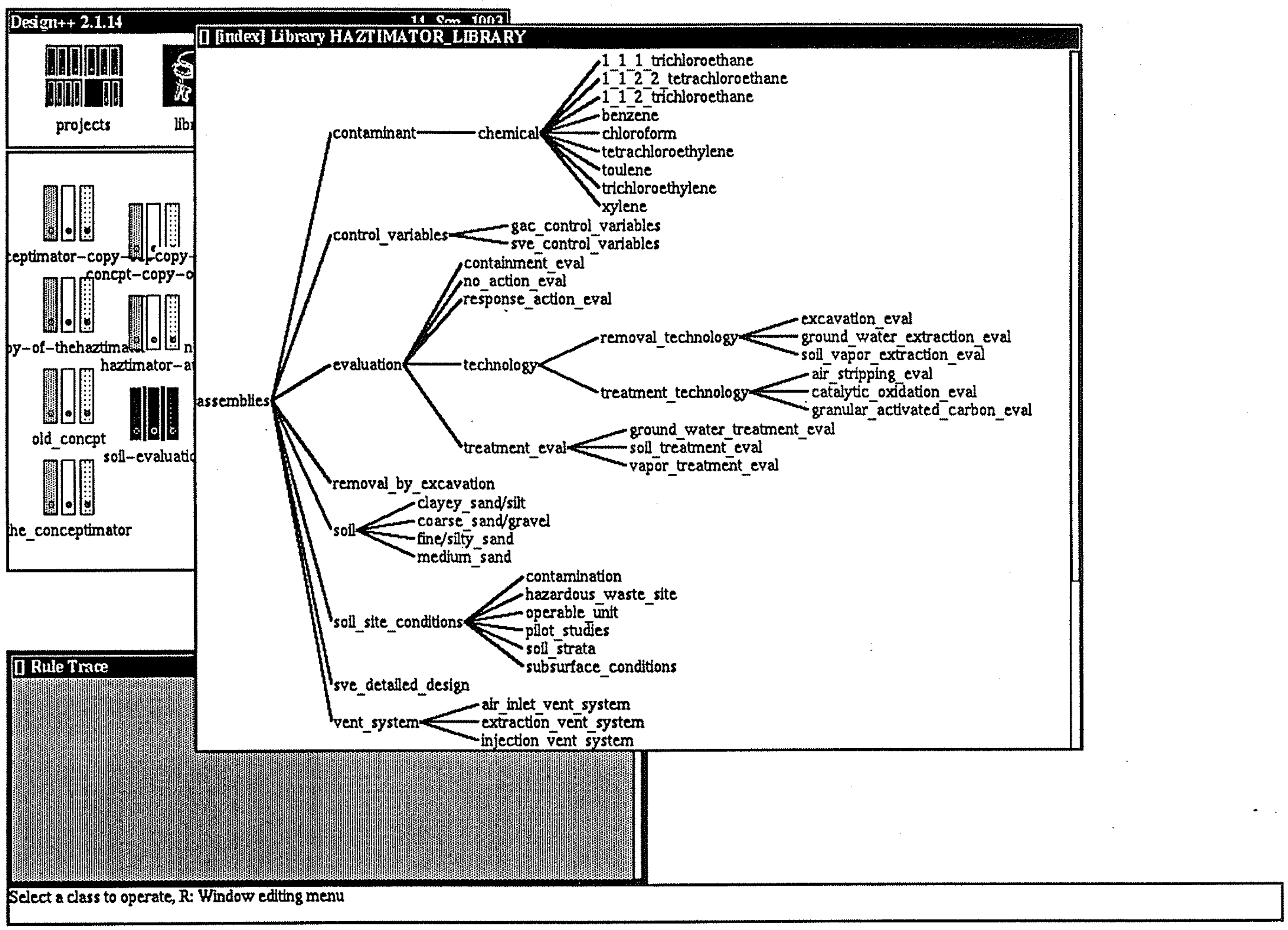

Activated
Carbon
Manifold
Vacuum
Pump
Vent
Unsaturated Zone
Contaminated Area
Water Table
Saturated Zone

Figure 3 - D++ Rule Example

Figure 5 - Haztimator Component Libraries


Design++ 2.1.14
projects
[] [index] Library HAZTIMATOR_LIBRARY
assemblies
contaminant
chemical
1_1_1_trichloroethane
1_1_2_2_tetrachloroethane
1_1_2_trichloroethane
benzene
chloroform
tetrachloroethylene
toulene
trichloroethylene
xylene
control_variables
gac_control_variables
sve_control_variables
evaluation
containment_eval
no_action_eval
response_action_eval
technology
removal_technology
excavation_eval
ground_water_extraction_eval
soil_vapor_extraction_eval
treatment_technology
air_stripping_eval
catalytic_oxidation_eval
granular_activated_carbon_eval
treatment_eval
ground_water_treatment_eval
soil_treatment_eval
vapor_treatment_eval
removal_by_excavation
soil
clayey_sand/silt
coarse_sand/gravel
fine/silty_sand
medium_sand
soil_site_conditions
contamination
hazardous_waste_site
operable_unit
pilot_studies
soil_strata
subsurface_conditions
sve_detailed_design
vent_system
air_inlet_vent_system
extraction_vent_system
injection_vent_system
old_concpt
the_conceptimator
[] Rule Trace
Select a class to operate, R: Window editing menu

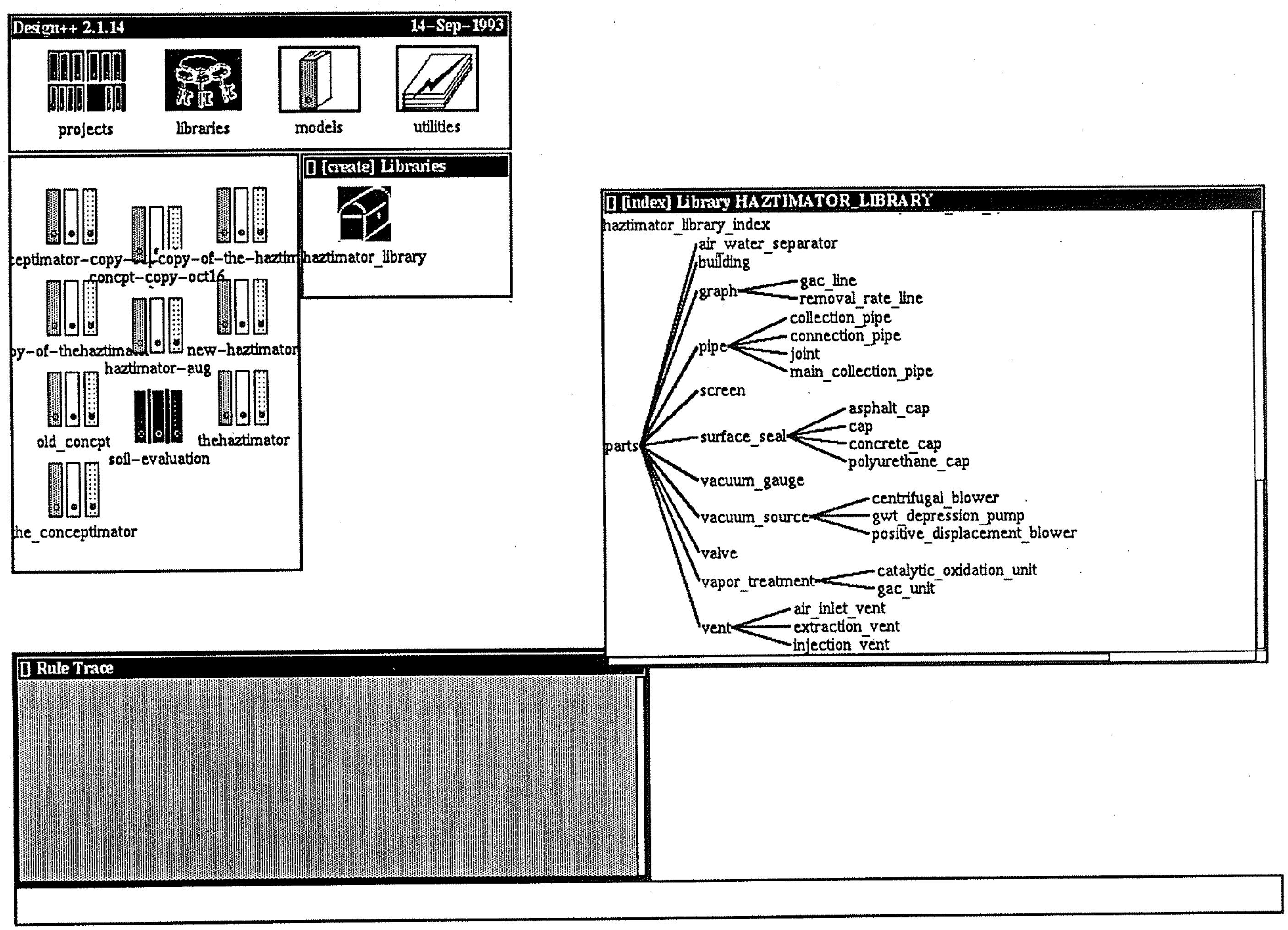
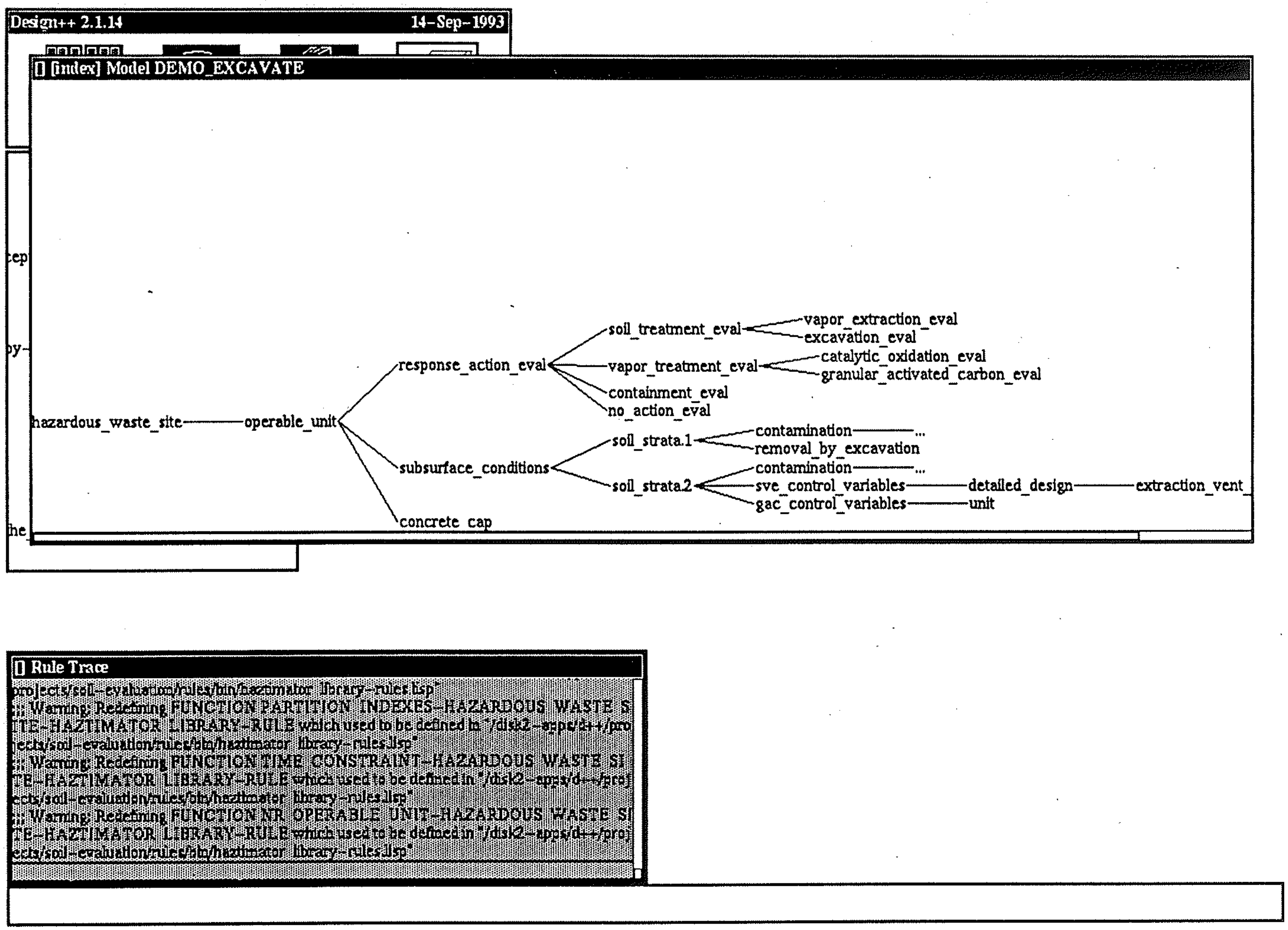

Design++ 2.1.14
14-Sep-1993
projects
libraries
models
utilities
[] [create] Libraries
haztimator_library
old_concpt
soil-evaluation
thehaztimator
he_conceptimator
haztimator-aug
new-haztimator
concpt-copy-oct16
[] [index] Library HAZTIMATOR_LIBRARY
haztimator_library_index
parts
air_water_separator
building
graph
gac_line
removal_rate_line
pipe
collection_pipe
connection_pipe
joint
main_collection_pipe
screen
surface_seal
asphalt_cap
cap
concrete_cap
polyurethane_cap
vacuum_gauge
vacuum_source
centrifugal_blower
gwt_depression_pump
positive_displacement_blower
valve
vapor_treatment
catalytic_oxidation_unit
gac_unit
vent
air_inlet_vent
extraction_vent
injection_vent
[] Rule Trace

Figure 6 - Haztimator Product Structure

```
(hazardous_waste_site
 (:n operable_unit
     (response_action_eval
      (:n soil_treatment_eval
          (soil_vapor_extraction_eval)
          (excavation_eval))
      (:n ground_water_treatment_eval)
      (vapor_treatment_eval)

      (containment_eval)
      (no_action_eval)
      )

     (:n building)
     (subsurface_conditions
      (:n soil_strata
          (:n pilot_studies)
          (contamination
           (:n trichloroethylene)
           (:n tetrachloroethylene)
           (:n 1_1_1_trichloroethane)
           (:n 1_1_2_trichloroethane)
           (:n 1_1_2_2_tetrachloroethane)
           (:n benzene)
           (:n toulene)
           (:n xylene)
           (:n chloroform))
          )
      )
     )
 )

(operable_unit
     (:n asphalt_cap)
     (:n concrete_cap)
     (:n polyurethane_cap)
     )

(vapor_treatment_eval
 (:n air_stripping_eval)
 (:n catalytic_oxidation_eval)
 (:n granular_activated_carbon_eval))

(soil_strata
 (:n removal_by_excavation)
 (:n sve_control_variables
     (sve_detailed_design
      (extraction_vent_system
       (:n extraction_vent
           (screen)
           (valve)
           (joint)
           (connection_pipe
            (:n collection_pipe
                (:n main_collection_pipe
                    (:n air_water_separator
                        (main_collection_pipe)
                        )
                    )
                )
            )
           )
       (:n CENTRIFUGAL_BLOWER)
       (:n POSITIVE_DISPLACEMENT_BLOWER )
```

```
        )
      )
    )
 (:n gac_control_variables
     (:n gac_unit)
     )
 )
```

Figure 10 - Haztimator SVE Design Model



Design++ 2.1.14
14-Sep-1993
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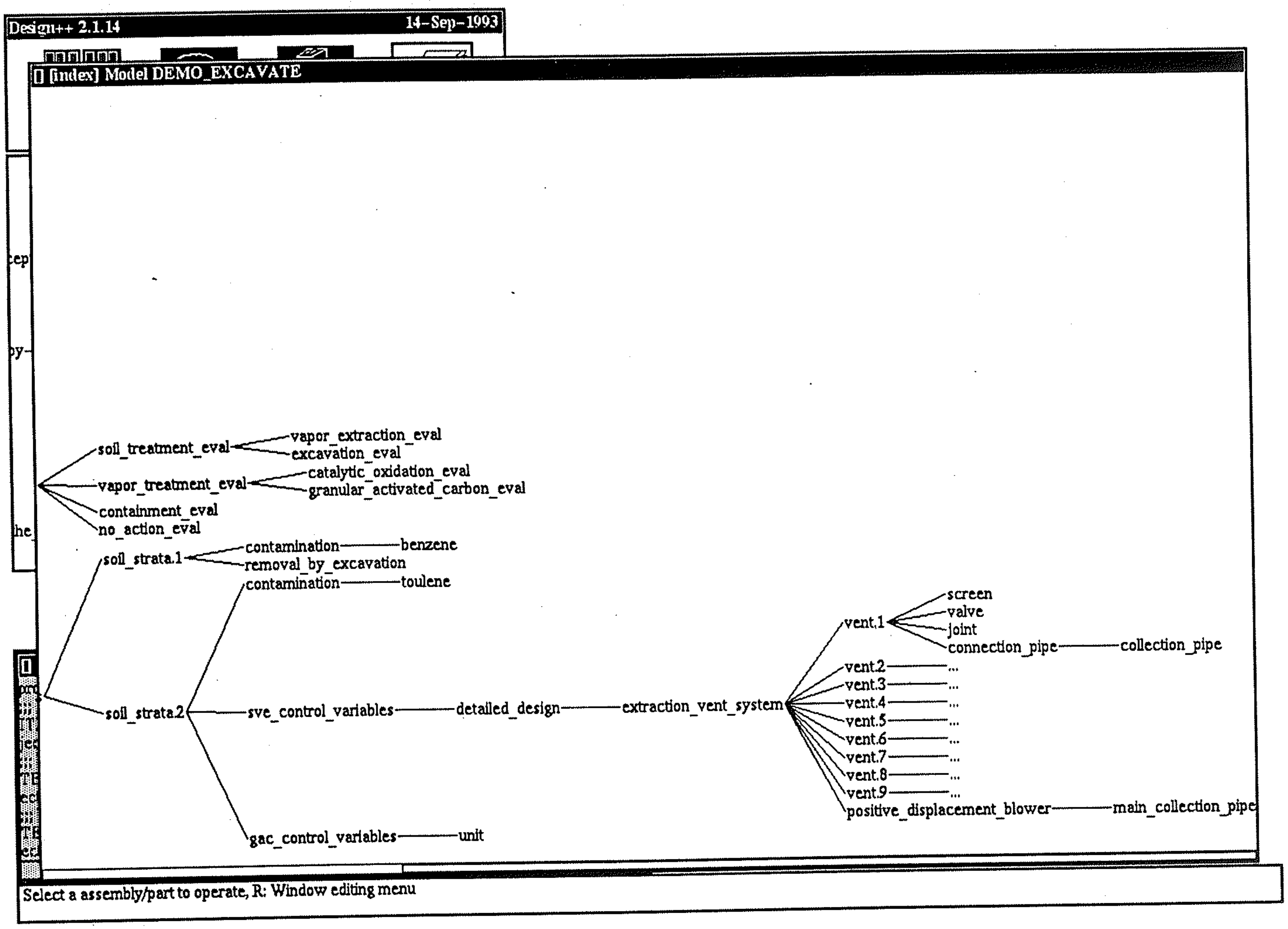
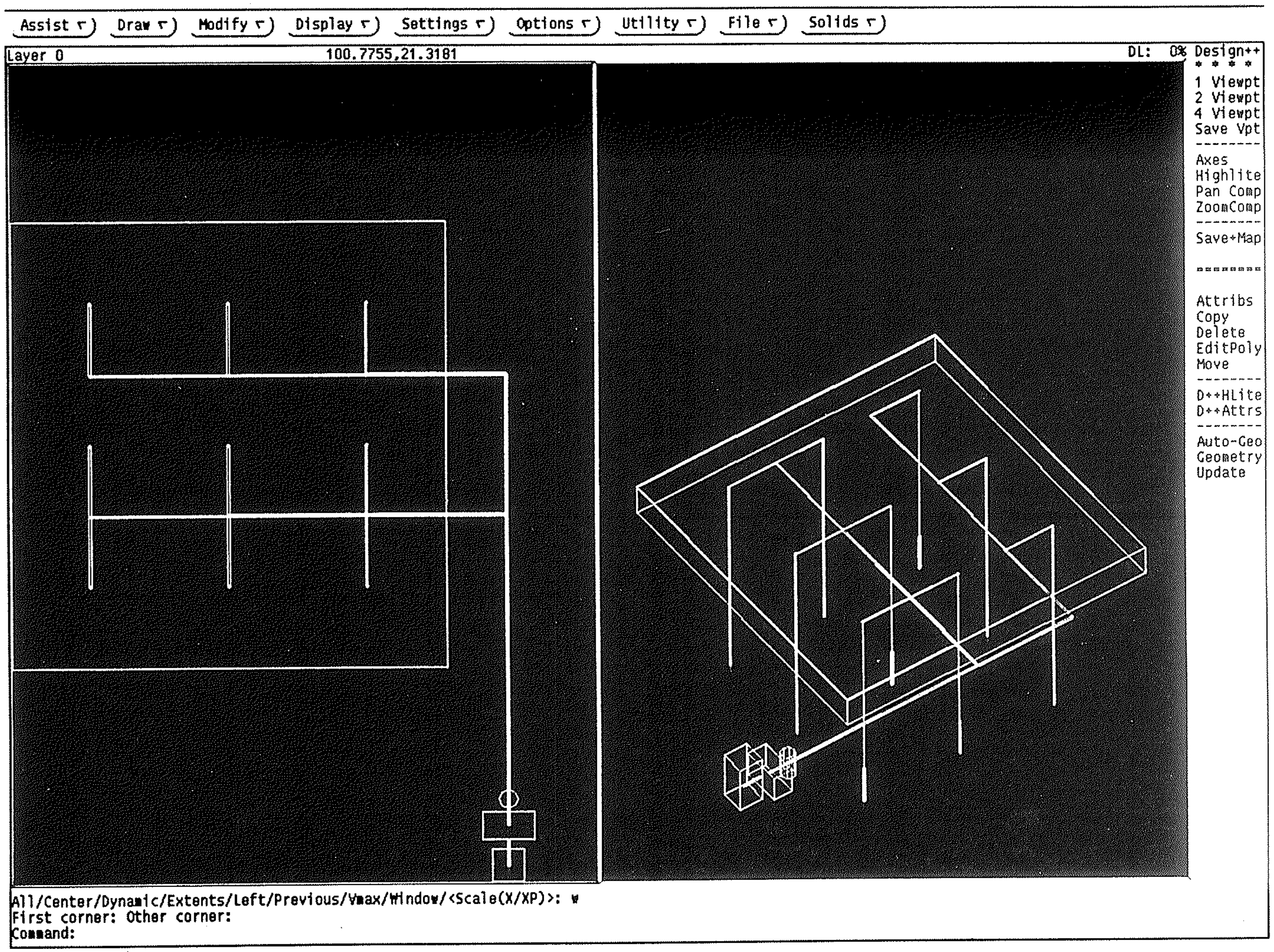
hazardous_waste_site
operable_unit
response_action_eval
subsurface_conditions
concrete_cap
soil_treatment_eval
vapor_treatment_eval
containment_eval
no_action_eval
vapor_extraction_eval
excavation_eval
catalytic_oxidation_eval
granular_activated_carbon_eval
soil_strata.1
soil_strata.2
contamination
removal_by_excavation
sve_control_variables
gac_control_variables
detailed_design
unit
extraction_vent_
[] Rule Trace
projects/soil-evaluation/rules/bin/hazimator library-rules.lisp"
;;; Warning: Redefining FUNCTION PARTITION INDEXES-HAZARDOUS WASTE S
ITE-HAZTIMATOR LIBRARY-RULE which used to be defined in "/disk2-apps/d++/pro
jects/soil-evaluation/rules/bin/haztimator library-rules.lisp"
;;; Warning: Redefining FUNCTION TIME CONSTRAINT-HAZARDOUS WASTE SI
TE-HAZTIMATOR LIBRARY-RULE which used to be defined in "/disk2-apps/d++/proj
ects/soil-evaluation/rules/bin/haztimator library-rules.lisp"
;;; Warning: Redefining FUNCTION NR OPERABLE UNIT-HAZARDOUS WASTE SI
TE-HAZTIMATOR LIBRARY-RULE which used to be defined in "/disk2-apps/d++/proj
ects/soil-evaluation/rules/bin/haztimator library-rules.lisp"



Design++ 2.1.14
14-Sep-1993
[] [index] Model DEMO_EXCAVATE
soil_treatment_eval
vapor_extraction_eval
excavation_eval
vapor_treatment_eval
catalytic_oxidation_eval
granular_activated_carbon_eval
containment_eval
no_action_eval
soil_strata.1
contamination
benzene
removal_by_excavation
soil_strata.2
contamination
toulene
sve_control_variables
detailed_design
extraction_vent_system
vent.1
screen
valve
joint
connection_pipe
collection_pipe
vent.2
vent.3
vent.4
vent.5
vent.6
vent.7
vent.8
vent.9
positive_displacement_blower
main_collection_pipe
gac_control_variables
unit
Select a assembly/part to operate, R: Window editing menu

Figure 11 - Haztimator SVE system layout in AutoCAD


Assist
Draw
Modify
Display
Settings
Options
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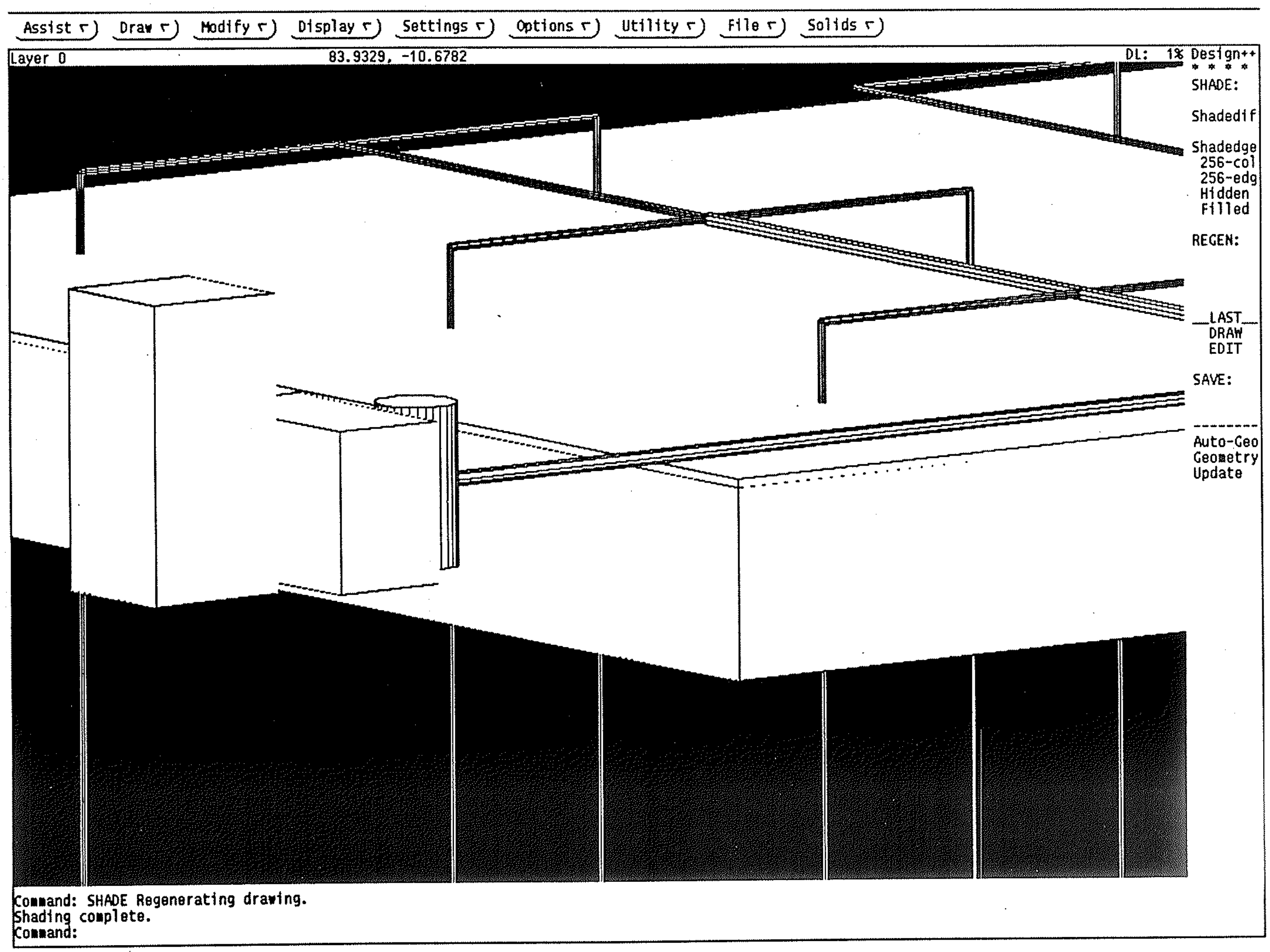
File
Solids
Layer 0
100.7755,21.3181
DL: 0%
Design++
1 Viewpt
2 Viewpt
4 Viewpt
Save Vpt
Axes
Highlite
Pan Comp
ZoomComp
Save+Map
Attribs
Copy
Delete
EditPoly
Move
D++HLite
D++Attrs
Auto-Geo
Geometry
Update
All/Center/Dynamic/Extents/Left/Previous/Vmax/Window/<Scale(X/XP)>: w
First corner: Other corner:
Command:


Assist
Draw
Modify
Display
Settings
Options
Utility
File
Solids
Layer 0
83.9329, -10.6782
DL: 1%
Design++
* * * *
SHADE:
Shadedif
Shadedge
256-col
256-edg
Hidden
Filled
REGEN:
__LAST__
DRAW
EDIT
SAVE:

Auto-Geo
Geometry
Update
Command: SHADE Regenerating drawing.
Shading complete.
Command: