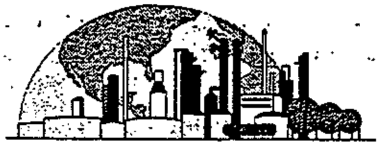
International Journal of Environmentally Conscious Design & Manufacturing, Vol. 4, No. 2, 1995
Printed in the U.S.A.



EXPERT SYSTEM SUPPORT FOR ENVIRONMENTALLY CONSCIOUS MANUFACTURING

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To achieve environmentally conscious manufacturing, engineers must evaluate and select materials and processes that minimize environmental impact. To support this task we developed a computer program, called EcoSys™, that assists manufacturing and environmental engineers in assessing the environmental consequences of their manufacturing decisions. First, this article describes the environmental philosophy that supports the decision making of the program, second, the use of artificial intelligence techniques, including rule-based search algorithms based on the analysis of manufacturing experts' protocols, and finally, the design and software system integration that makes up the program itself.

INTRODUCTION

Green design is now considered an integral component of an ideal product realization process. Unfortunately, the assessment of tradeoffs among economic, performance, and more recently, environmental attributes associated with competing processes or products is extremely challenging, particularly due to the many technical, societal, and cultural perspectives associated with environmental quality. To enable emerging concurrent design and agile manufacturing initiatives at both corporate and national levels, a tool for green design that incorporates these perspectives and provides timely design information and decision support is critical.

This article describes the development of EcoSys™, an information system and expert system that performs environmental impact analyses of product design and manufacturing processes. The goals of EcoSys™ are:

(1) to identify and quantify within the manufacturing process the relationships between product design and material consumption and waste generation, and

(2) to apply these relationships to compare the environmental consequences of competing product designs or processes.

The expert system addresses the issues associated with the increasing complexities of product design, and supports analyses according to a broad range of environmental views. Results of EcoSysä analyses provide decision support in a number of areas including comparative process and product assessments, process optimization (such as the incorporation of emerging *environmentally conscious manufacturing* technologies), and environmental needs assessments.

ENVIRONMENTAL LIFE CYCLE DECISION ANALYSIS MODELS

Currently within the manufacturing industry, *environmental quality* is a loosely and subjectively defined term. To conduct meaningful environmental assessments, one must have clearly defined and accepted metrics. Additional yet critical aspects of environmental models are to determine how environmental consequences can be reported in a true sense, other than by only the magnitude of some use activity (consumption or emission levels). Another important issue is how to compare the impact from very different manufacturing activities.

For instance, we can measure "tons" of carbon dioxide (CO_2) emissions from a coal fired plant, or "acres" of land consumed from a metal mining operation. These numbers are often cited as the "impact" of a particular process. The real impact, however, is in the degradation of our sustainability* as a result of the presence of additional CO_2 or absence of usable land. Furthermore, one might expect that the environmental consequences from CO_2 emissions and mining are numerous. The impact of either one might be directly comparable to that of the other, that is, each affects global CO_2 balance, or they might be very different. Unfortunately, defining "impact" and assigning judgments between dissimilar environmental impacts has historically been extremely difficult. This issue *must* be addressed if we are to have success in promoting effective environmental life cycle work.

A challenge for the environmental management community is to identify and quantify the relationships of material and energy consumption, and waste generation and management, with environmental quality. This systematic process, referred to as *valuation*, can be conducted using one of a number of techniques including monetization, direct comparison, and abstract comparison. The choice of method will influence to a great extent the framework for the analysis methodology. Only recently has the debate begun over which techniques are most appropriate for the valuation of life cycle inventories.[3]

We employ in our environmental modeling the principles of *life cycle analysis* as defined by the Society of Environmental Toxicology and Chemistry (SETAC)[4] and the Environmental Protection Agency (EPA).[5] Our approach is structured around what is termed the *product life cycle inventory*. It is important to note, however, that the analysis methodology presented in this paper does deviate substantially from the more traditional life cycle inventory guidelines. Although inventory data generated from the manufacturing phase of the product life cycle is explicitly considered in our analysis (in our case, manufacturing is the phase where the greatest degree of data precision can be maintained), full life cycle inventories are considered only in a more qualitative sense.

Traditionally, life cycle inventory has a very specific meaning. The inventory identifies and quantifies the inputs to industrial systems, such as resources and energy, and the outputs, such as air emissions, waterborne effluents, solid waste and other environmental releases incurred throughout the life cycle of a product or process.[4] Unfortunately, gathering and characterizing life cycle inventory data is fraught with problems. These include the tremendous breadth of direct and indirect material and waste streams associated with a single process or product, and the associated difficulties of determining appropriate system boundaries. Life cycle inventory concepts have been criticized because of the large economic burdens of "accurate" assessments. In response, the life cycle analysis community has developed strategies to address inventory issues, such as promoting industry averaged data, and in doing so has to now deal with significant concerns over data quality. Finally, the emergence of agile, or flexible, manufacturing has complicated the issues of performing inventory analysis. More often the processes once used to produce a single product are now being used to produce a wide range of products and have more sporadic duty cycles. Determination of life cycle inventories for these aggregates of products requires a methodology that accommodates the "many to many" relationships among products, processes, and materials.

The approach described here was adopted in response to the concerns of traditional life cycle inventory analysis, and also, in large part, because of the need for an environmental impact assessment methodology that goes well beyond the quantification of input and output streams. As an important further extension of the current state of life cycle analysis, we define *environmental impact analysis* models and have developed a prototype expert system to effectively present environmental information to the design and manufacturing community. This tool is not strictly an environmental compliance-driven process, but recognizes that problems associated with environmental damage extend well beyond the constants imposed by federal and local regulations. Beyond compliance, the possibilities for the creation and use of the concept of "green design" are exciting.

Beginning our effort to identify the criteria that effects

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*The term sustainability is defined by the World Commission on Environment and Development as "meeting the basic needs of all and extending to all the opportunity to satisfy their aspirations for a better life . . . [and] acceptance of consumption standards that are within the bounds of ecological possibility and to which all can aspire."[1] In addition, sustainability is also defined in economic terms as True, or Hicksian, income. Unlike traditional treatment of welfare (i.e., GNP), Hicksian income includes consideration of the depreciation of natural capital.[2]

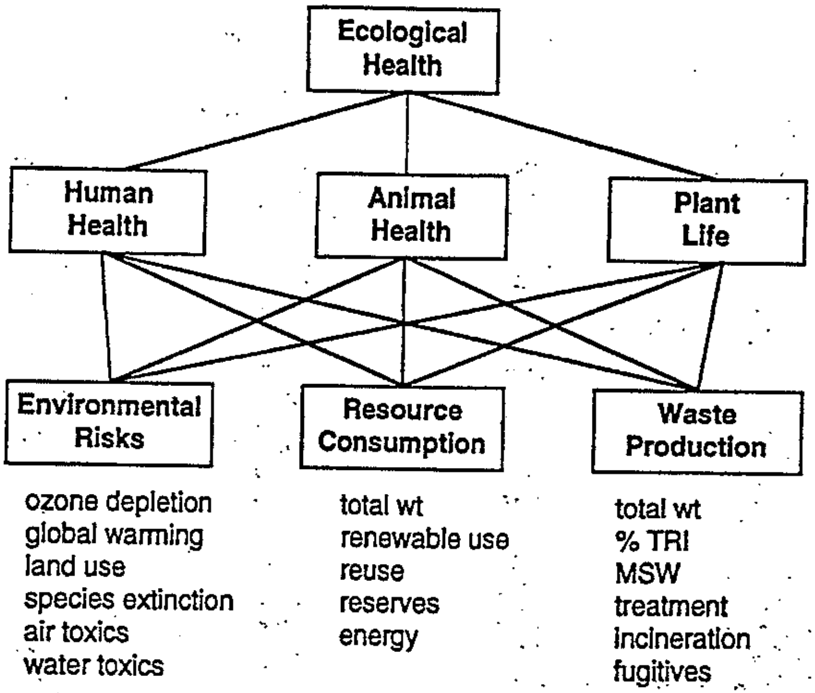

Figure 1. Environmental impact decision model derived from: (1) the Sandia Environmental Impact Metrics Stakeholder Panel,[8] and (2) the EPA Science Advisory Board study on risk.[9]

environmental quality at the process and product levels, we first selected a number of designers, manufacturers, environmental safety and health (ES&H) personnel, and environmental technology staff, and assessed their knowledge of environmental criteria. We solicited perspectives from industry, universities, and the EPA. Results of these assessments, obtained through a survey and a panel session, were applied in our development of environmental impact decision models that support life cycle analysis.[6] These models, based on the application of the *analytic hierarchy process*, or AHP[7, 8] can be represented in a tree-like structure consisting of goals, objectives, criteria, and alternatives. The basic features of the models are illustrated in Figure 1.

Although there seemed to be a general consensus on criteria to include in an environmental impact model, there was significant disagreement among experts regarding the relative importance of the various criteria within the model. We believe this observation to be an indication of the more subjective nature of environmental impact analysis. To address this dilemma, we constructed a set of models, each supporting significantly different views. These models, based in part on Colby's different views of environmental management,[9] recognize the evolving perspectives associated with environmental quality. Colby proposes five alternative models of the relationship between economic growth and the environment. These define a diverse range of views of environmental quality and ecological health:

(1) *Frontier Economics*: This view focuses on economic growth and a free market economy with little regard to environmental consequences.

(2) *Environmental Protection*: Here the environment is viewed as an economic externality that must be safeguarded through laws and regulations. The primary issue in this view is that humans simply produce too much waste. This highly anthropocentric view focuses on pollution prevention and waste minimization.

(3) *Resource Management*: In this view the environment is again an economic externality, but it must now be internalized in measures of economic performance. The problem in this view is that humans are managing resources poorly. This view recognizes that consumption as well as waste generation affects environmental quality, but is still concerned primarily with effects related to human health.

(4) *Eco-Development*: This view stresses the co-evolution of man and ecosystems on an equal basis. This view suggests that, at present, the scale of economic growth is inconsistent with the long-term coexistence of man with nature.

Table I
Weighting factors for Impact Analysis Model Objectives and Criteria

	Environmental Protection	Resource Management	Eco-Development
Objectives:			
human health	1.000	0.667	0.333
animal health	0.000	0.167	0.333
plant life	0.000	0.167	0.333
Criteria:			
global risk	0.250	0.333	0.667
waste production	0.750	0.333	0.167
resource consumption	0.000	0.333	0.167
Sub-criteria:			
ODP[1]	0.080	0.108	0.171
global warming	0.061	0.088	0.140
land use	0.031	0.051	0.140
species extinction	0.030	0.047	0.125
air toxics	0.009	0.019	0.049
water toxics	0.009	0.019	0.049
total waste produced	0.265	0.100	0.045
qty TRI[2]	0.160	0.100	0.052
% MSW[3]	0.030	0.013	0.006
% incineration	0.081	0.026	0.013
% treatment	0.084	0.030	0.016
qty fugitive	0.160	0.063	0.044
total resource consumed	0.000	0.100	0.045
non-renewable use	0.000	0.066	0.026
non-reuse	0.000	0.040	0.025
reserves	0.000	0.058	0.026
energy	0.000	0.072	0.028

(5) *Deep Ecology*: This view focuses on harmony with nature, and emphasizes drastic reduction in human population and the scale of economic growth.

We feel that the most relevant views, based on the current climate in the environmental policy arena, are the *Environmental Protection, Resource Management,* and *Eco-Development. Deep Ecology,* although it evolved as a reaction to *Frontier Economics*, did in fact provide a significant awareness that resulted in the formulation of these other more practical views. Based on this assumption, we generated three decision models consistent with these three intermediate positions. Criteria selected for inclusion in these models are based on (1) environmental risk, (2) waste production, and (3) resource consumption, with each model viewing the relative importance of these criteria differently. Sub-criteria under risk were assigned in part following the findings reported by an EPA Science Advisory Board[10] study on risks associated with global environmental problems. Issues including global warming, ozone depletion, land use, and species extinction were identified by the EPA Science Advisory Board as posing the greatest threat to environmental quality. Therefore, these criteria were given greater weight in our models. Other elements of risk considered include air and water toxics. For waste production, issues such as the quantity, the percentage hazardous, the route of disposition, and fugitive emissions are addressed. For resource consumption, the models include quantity, energy, renewable materials use, and reuse.

Table I lists the strawman weights assigned for each criterion and sub-criterion for each of the three models. Weights were assigned through our own interpretation and extension of Colby's work. The differences between each view can be understood by examining the relative distribution of weights. For example, at the *Environmental Protection* view considers only human health as its primary objective with no weight given to plants and animals. On the other hand, the *Eco-Development* model views human health, animal health, and plant life as equally important. At the subcriteria level, the *Environmental Protection* view considers total waste production and hazardous waste production (qty TRI, materials on the SARA in Toxic Release Inventory list) as the most important criteria. Products or technologies that produce less overall waste than others will be viewed favorably from this viewpoint. In contrast, the *Eco-Development* view considers the quantitative aspects much less impor-

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[1] Ozone Depletion Potential

[2] Toxic Release Inventory hazard designation

[3] Municipal Solid Waste

tant relative to the more global environmental risks associated with global warming, ozone depletion (ODP), land use, and species extinction. Products or technology alternatives that yield lower global risk will be viewed favorably in this view, potentially even in cases where more waste is produced. The goal in our implementation of these models was to remain consistent with Colby's definitions and to provide the user with a choice regarding the most appropriate view—decision-makers are free to compare and contrast the advantages and disadvantages of each approach relative to the policies of their own organization. In addition, recognizing the continuum on which the spectrum of environmental management views can exist, EcoSys permits the user to create unique distributions of weights.

Application of the Environmental Life Cycle Impact Analysis Model

Application of environmental impact analysis requires a careful integration of the models described above with the information in the product inventory. This integration is accomplished in part by the definition and construction of a *product/process hierarchy*. Figure 2 illustrates the features of such a representation and defines the boundaries of the product life cycle information relevant to this type of analysis. Figure 2 shows that *products* are derived from *processes*. Input values for processes can be product-specific and process-specific *materials*, and/or lower level products (subassemblies, connectors, housings, and so on). Lower level products are derived from other materials and/or other lower level products. Ideally, the hierarchy is complete once all product subassemblies and product specific materials have been broken down into their most basic constituent sets of processes and materials. At this point, all leaf nodes (nodes without "children," or lower level features) are defined as materials.

The focus of environmental impact analysis is the *process*. The fundamental assumption is that environmental impacts result directly from human activity (processing) rather than from the materials or products themselves. The process defines what materials are required, and in what quantities. The impact from a product results from a unique combination of processes.

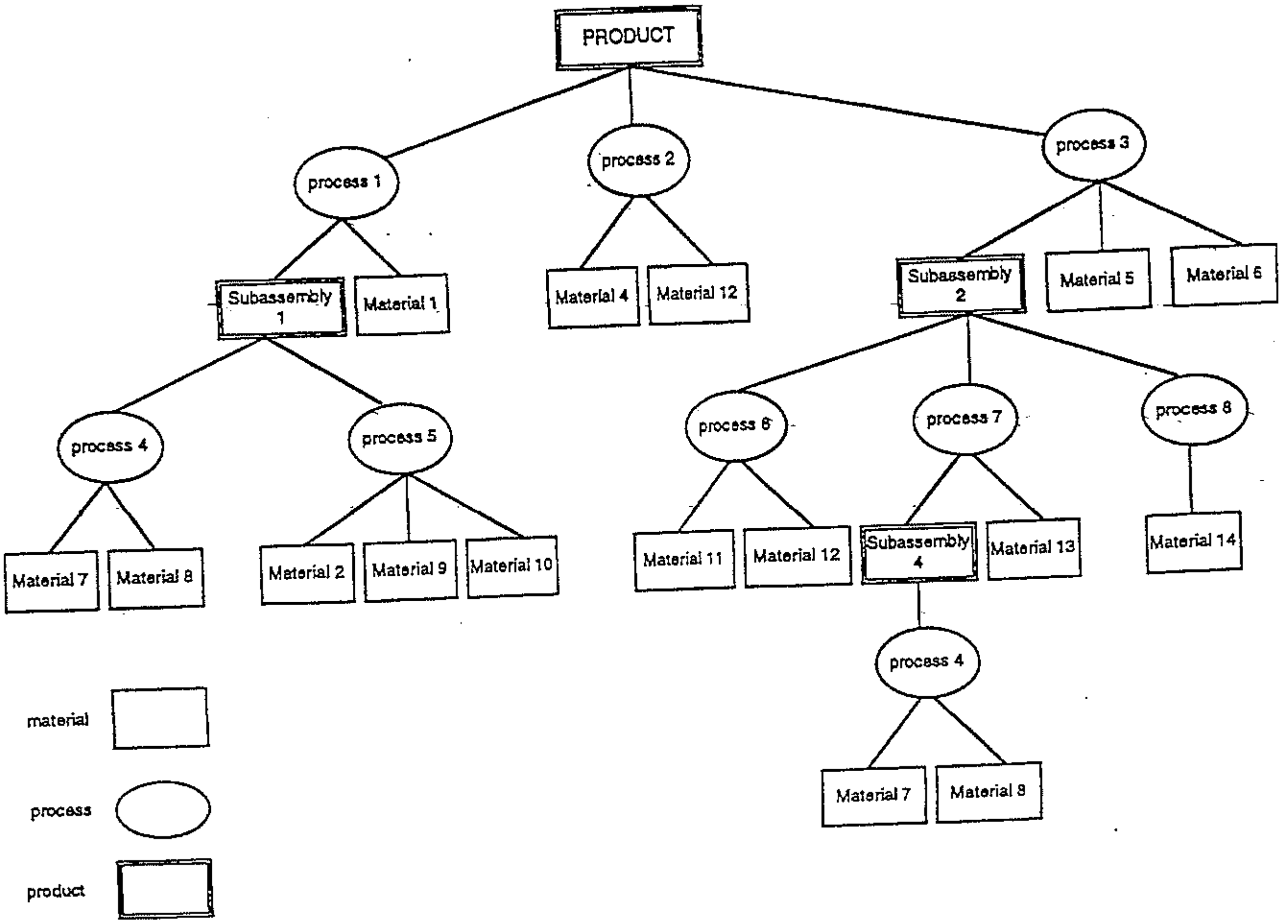

Figure 2. Product and process hierarchy.

or even more generically, "events," experienced during the life cycle of that product. Changing the materials used in the product or in the processes will alter the relative environmental impact. Despite this assumption, the basic building blocks for a process are, of course, materials. Materials, although they are viewed as not having direct environmental impacts, do have what we term *environmental attributes*. Consistent with the environmental impact models described above, attributes of materials include a percent hazardous (TRI), a disposal option (landfills, incinerate, treat), whether they are a renewable or nonrenewable resource, reuse or recycle, reserves index, energy consumption, and risks associated with ozone depletion, global warming, land use, species extinction, and air and water toxics.

The Environmental Impact Rating System

We constructed a materials library to assign values to each of the environmental attributes for a set of selected materials. For *Ozone Depletion Potential (ODP)* relative values are applied where available (ODP is typically reported relative to CFC-11, which is given a value of 1.0). For *disposal option*, the material is given a designation for the most common (or actual) route of disposition. For all other attributes, we adopted a rating system that assigns a value of "1" if the material has *low* impact for that attribute, "5" for a *moderate* level of impact, and "9" for *high* impact. The rationale for our use of such a discontinuous rating scale is that these values are often derived from limited and sometimes conflicting literature sources, rather than from detailed life cycle studies. As more and more studies are completed, these data will be modified and be made more consistent with a true life cycle perspective.

The material library database is used to construct the process definition. From the life cycle inventory, we generate mass balances for material use in and out of processes. To define the process, the appropriate material data sets are retrieved from the library, and are assigned quantities into the process and quantities out of the process (qtyin and qtyout). There is also a measure of quantities emitted in an uncontrolled manner, termed fugitive (fugtvs). Quantities are used to derive: (1) the total quantity of materials consumed by the process, (2) the total quantity of waste produced by the process, and (3) the weighted averages of the environmental attributes for the process. To define the product, all of the processes applied are then summed. This summation is conducted in much the same manner as summing the materials that constitute a process.

Application of environmental impact attributes to materials, as just defined, results in an impact analysis methodology that deviates from more traditional life cycle analysis guidelines. Rather than conducting full life cycle inventory assessments of all materials used, we are providing inventories only for manufacturing. The choice of environmental attributes was selected to permit the creation of a qualitative life cycle *perspective* without the need to collect complete life cycle inventory data. Again, while a broader set of inventory data can be used to help generate the ratings, this data is not explicitly required. Our approach will support the evolution of a more "graded" analysis methodology, where a high degree of data certainty is maintained within appropriate system boundaries (in this case, manufacturing). As customer-supplier relationships evolve, the EcoSys™ framework will support detailed analyses upstream and downstream.

THE REPRESENTATION OF KNOWLEDGE AND DESIGN OF SEARCH IN ECOSYS

The goal of EcoSys™ is to build a program that assists the human expert in making supported, environmentally sensitive decisions in product design and manufacturing processes. Understanding this complex task involved the knowledge extraction process from individuals[11] and was performed on a number of experts in three distinct domains: the environment, design, and manufacturing. The system must have the environmental models available to support decisions in the design of products or processes. This was accomplished through interviews with environmental experts and the results were described in the previous section.

The second part of the solution involved a great deal of interaction with manufacturing engineers and product designers. In the past, design and manufacturing were two very distinct steps in the product realization process. We needed to understand this decoupling before

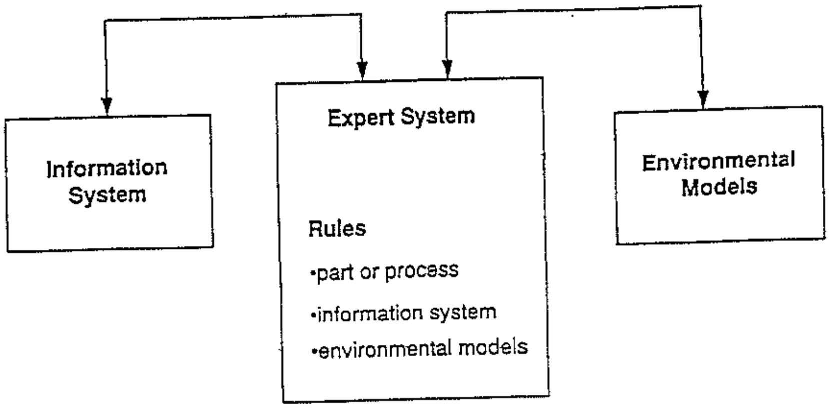

Figure 3. Expert system rules link the information system and environmental models.

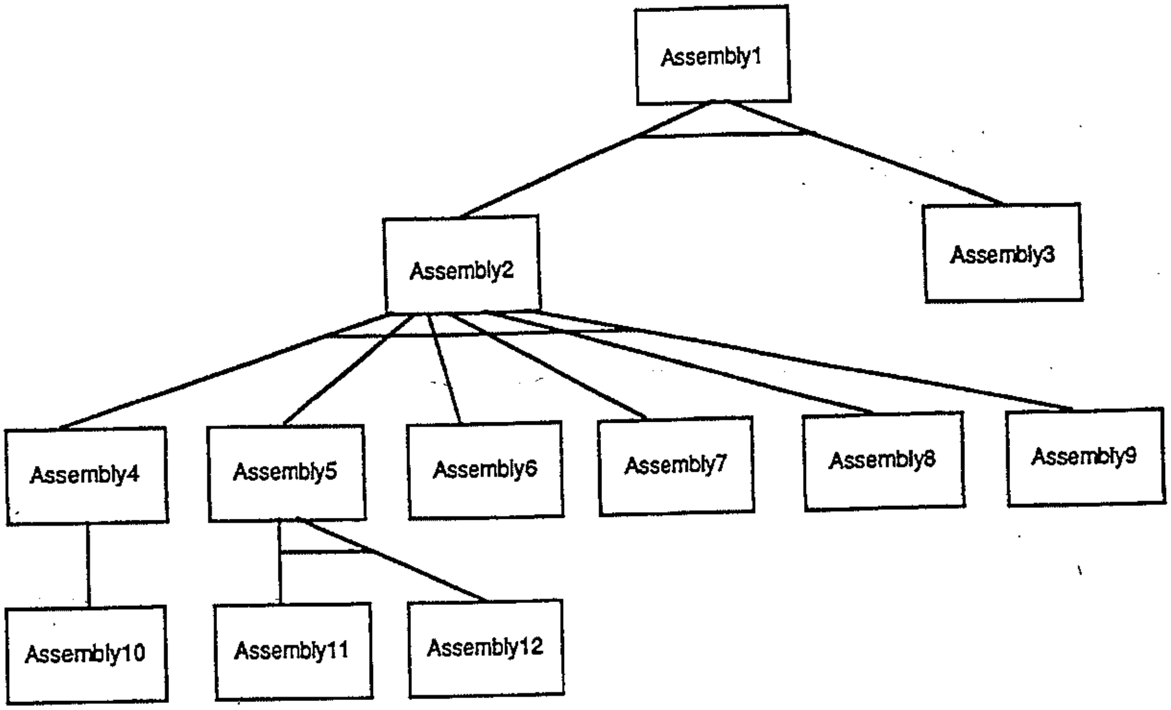

Figure 4. A typical product flow diagram for manufacturing.

we could integrate the two sequential steps into a product/process structure as described in the next section. The third part was the reasoning steps that allowed the human expert to tie all this information together. The part and process information was gathered together in a database along with environmental information about materials. We next describe how we captured the reasoning that brought the system together.

To be successful, it was necessary to understand how the human expert attempts to solve this complex task. To accomplish this we set up interview sessions with human environmental and manufacturing experts. During these sessions we asked the experts to talk through their problem solving processes for a number of typical problems. The audio taped interview sessions were fairly relaxed with experts asked to go through typical situations. We also asked several different experts to go through the same situations to see the different ways human experts focused on similar problems. The program designers were the interviewers and were initially rather naive about the entire process. An important component of these interview sessions was for the human expert, in the context of describing their solutions, to indirectly instruct the EcoSys™ designers.

Traditionally, the representation for product structure is in the form of some type of flow diagram similar to that of Figure 4. These diagrams are similar to organizational charts that outline the hierarchy of employees at a work place. At times, they are difficult to read when long lines connect the boxes with no apparent order for their composition. The hierarchical relationships are sometimes confusing since boxes may be connected horizontally as well as vertically. Based on our analysis of the reasoning of human experts, and the natural decomposition of this expertise into *if. . . then . . .* rules, we selected an alternative representation to the flow diagram, that of the *and/or* tree. These trees not only clearly define the hierarchical relationships within a product structure but can also represent alternative ways to construct the product. (The reader is asked to make a clear distinction from the decision analysis tree presented in Figure 1.) The product structure in Figure 4 is shown as an *and/or* tree representation in Figure 5. This is actually an *and* tree because there are no alternative choices in this particular fabrication process. Everything is *and*ed together to make the final product. (We recommend Luger and Stubblefield[12] for descriptions of artificial intelligence (AI) data structures, including *if. . . then . . .* rules, *and/or* trees, and *data* and *goal driven* models of state space search.) Figure 6 shows an *and/or* tree that includes process information with product structure. The processing nodes are shown enclosed in rectangles with rounded corners, with materials shown as a single box and assemblies shown as double boxes. This is done for illustrative purposes only. Notice the *or* branch under Assembly5 where this assembly can be made by either Process6 or Process6A

Our expert system traverses this tree in a *depth-first*

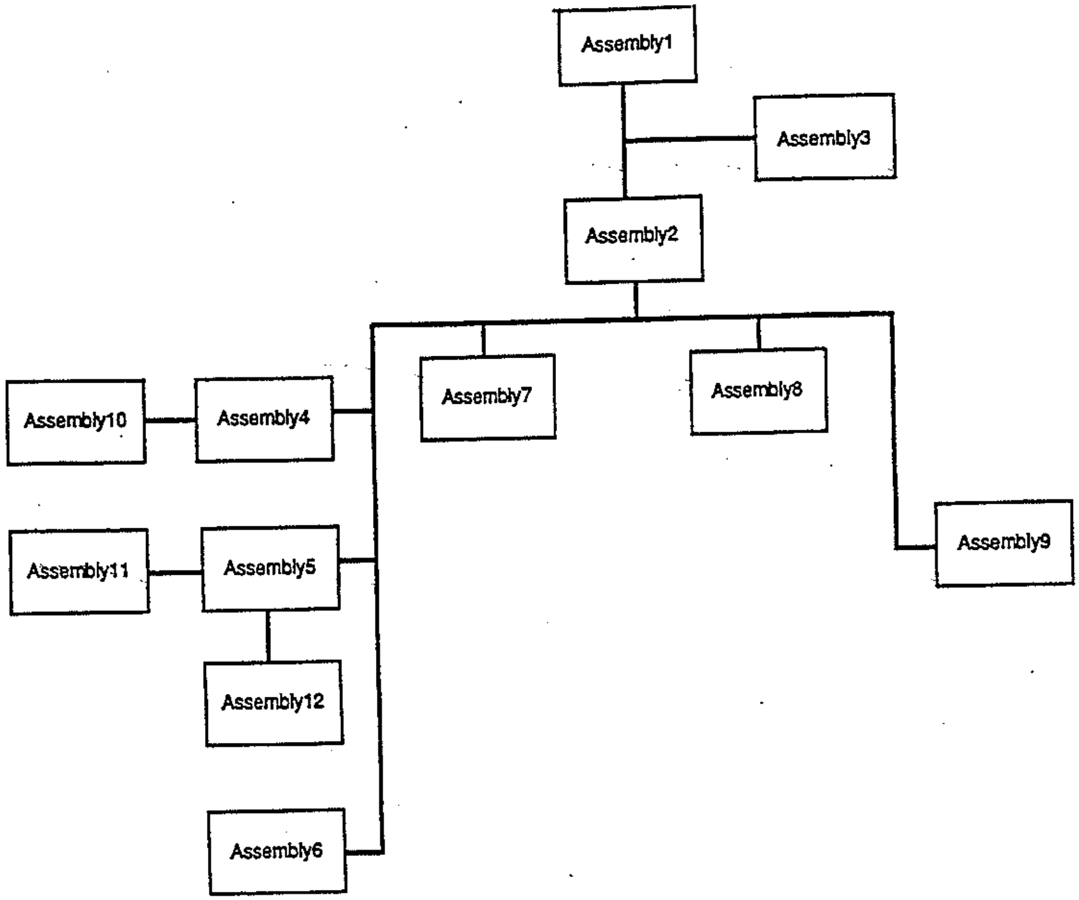

Figure 5. Product structure of Figure 4 represented as an *and/or* tree.

manner to propagate and combine information used in the analysis of the product. The *or* branches represent alternative parts or processes and our analyses compare alternatives to determine the optimum combination according to our different environmental criteria. The human experts of the early interviews felt very comfortable with this automated reasoning process and felt it reflected their reasoning processes in fairly complete detail. To support this approach, we use the M.4 software product from Cimflex Teknowledge,[13] a rule language that captures the constraints in the *and/or* tree that reflect the product and processes we desire to analyze. A typical rule has the format:

IF(A and B and C) THEN D

This is a simple inferential rule that states if A, B, and C are true then D is true. The rule representation maps directly to the and/or tree. For example, the rule that represents the "pretin" manufacturing process is:

IF (solder and flux and TCE) THEN pretin

There is a separate rule for every node in the tree that has sub-nodes. The leaf nodes of the tree are database entry points for product and process information. This way, the entire *and/or* tree structure that represents the product and process is represented as a set of rules that ultimately connect the environmental constraints of product and process. Constraint analysis across this data structure is known as a state space search.

We used goal driven search of the state space as we noted in the previous section. Goal driven search is appropriate for this problem because the types of questions we have with respect to environmental models are goals to be satisfied. For example, if we want to assess assembly A with the Resource Management model, we present the goal. "What are the environmental constraints on manufacturing Assembly A according to this model" to the expert system.

The architecture of the Ecosys™ system is seen in Figure 7. The environmental and inventory information that the expert system manipulates resides in an ORACLE[14] relational database. It consists of seventeen tables that are joined in various ways to provide usable information for the expert system. There are two main

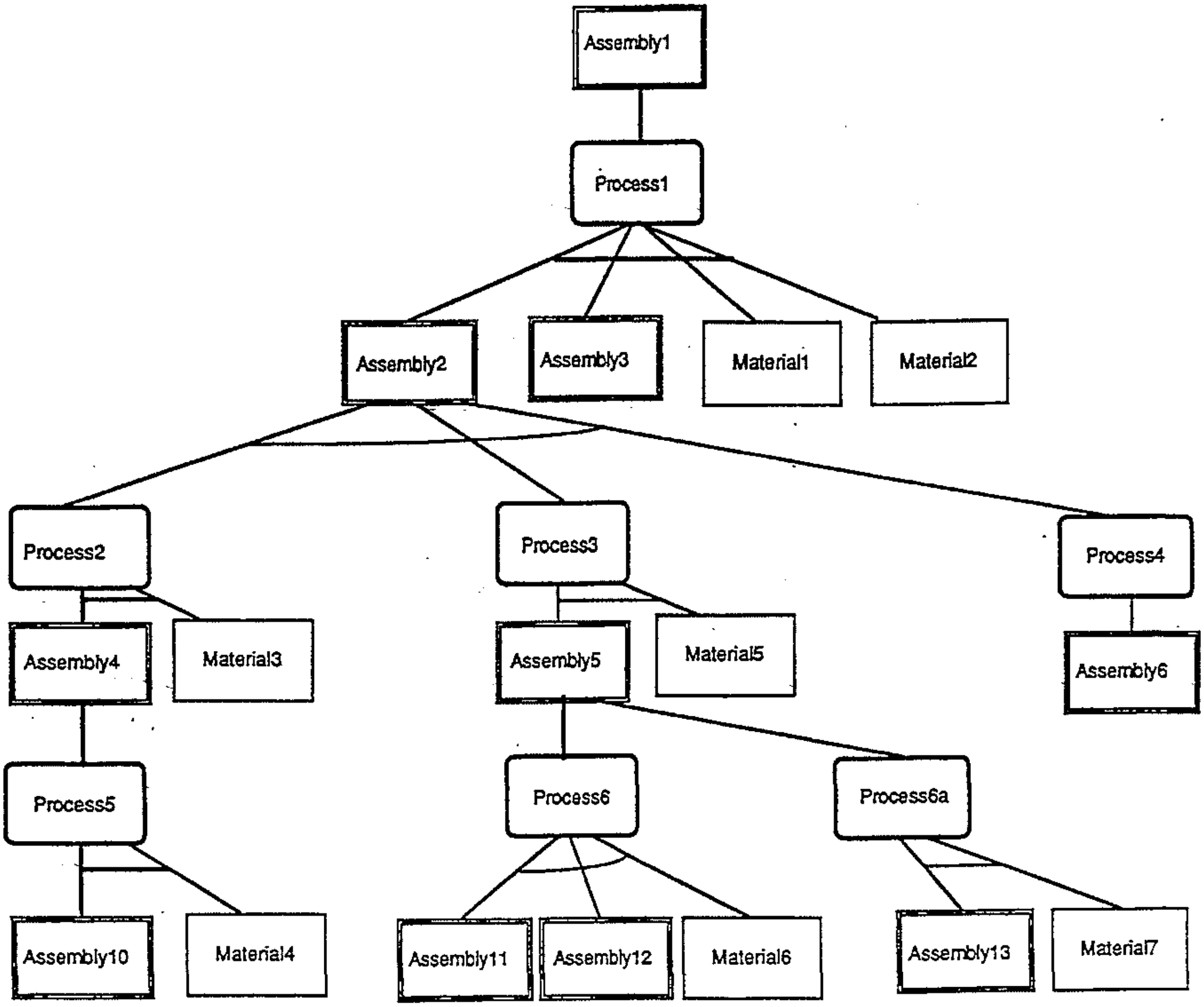

Figure 6. *And/or* tree showing processes and assemblies; and branches are joined by a horizontal line.

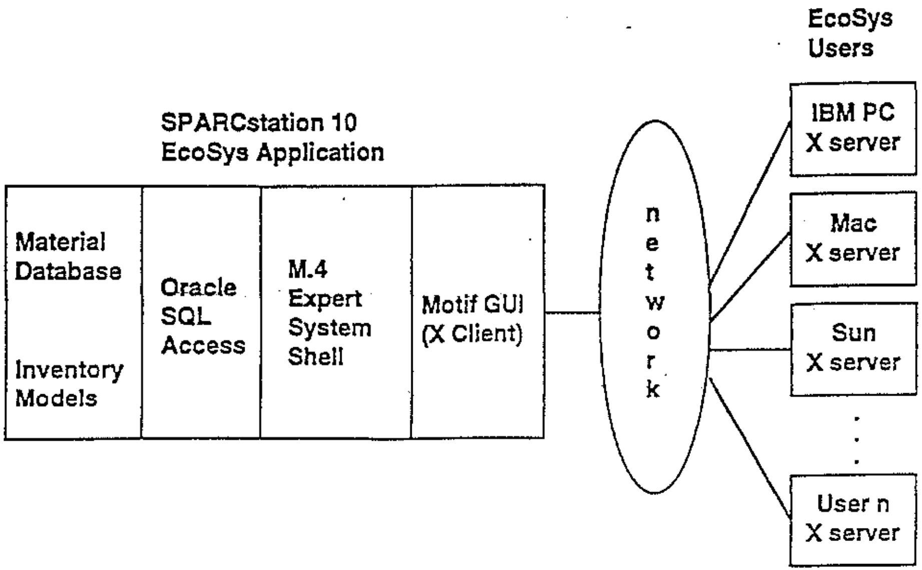

Figure 7. The EcoSys™ system architecture.

access procedures that the expert system uses. One procedure retrieves environmental impact information for materials including indices for land, water, and air, global warming, recyclability, and reusability. The other procedure provides life cycle inventory information, such as quantities of materials that are used in a manufacturing process. These access procedures are invoked through the expert system rules. They are simple procedures that contain Standard Query Language (SQL) statements that manipulate the tables and retrieve the requested data. The *and/or* tree is traversed in a depth-first manner whereby the information is propagated through the tree to arrive at the desired node for the type of analysis chosen by the user.

The decision analysis module is based on the application of the Analytic Hierarchy Process or AHP. The environmental impact model is represented in a tree-like structure consisting of goals, objectives, criteria, and alternatives. The expert system is the heart of EcoSys, encoding the product/process tree of the manufactured product. It has access procedures to the environmental and inventory data and encodes the environment decision analysis models and is called from a graphical user interface. The graphical user interface is written in Motif, a widget set for the X-window system,[15] and consists of various windows and menus to set control parameters. The core of the interface is the product/process tree browser. The browser allows the user to analyze any node in the product-process tree, not just the entire product. This allows the user to compare and contrast the environmental impact of two or more product subassemblies or manufacturing subprocesses.

From a functional point of view, the user interface controls the rest of the underlying modules, beginning with the expert system that manipulates information from the information sources according to the rules defined by the decision analysis module. These results are then reported back to the user and the system waits for more instructions.

EcoSys™ runs on a server machine, currently a SPARC station 10, with users remotely accessing the system from their personal computers, be they PCs, Apple Macintoshes, or other SPARC stations. The only requirement for the user or client machine is that it have an X-window terminal emulator with access to the network where the server machine resides.

The most important criterion for the expert system was that it must be easily embeddable and able to integrate the three major components: the user interface, the expert knowledge, and an information system. M.4 was designed exactly for that purpose. It also is primarily a backward chaining system which perfectly implemented our goal driven search strategy. It has a powerful knowledge representation language with full pattern matching capabilities. It also has a full object system that we plan to use for information views in later versions of our program.

EXAMPLES OF ECOSYS™ ANALYSES

EcoSys™ can model static or dynamic products or processes. That is, the information pertaining to particular products and processes that currently exist at a manufacturing facility can be stored statically in a database for retrieval and analysis, or the analyst can dynamically define their own through interaction with EcoSys™. A process engineer might, for example, want to evaluate a new process in comparison to an existing one. Likewise, a product designer may want to examine the environmental impact of a slight change to the product design. In these cases EcoSys™ presents the user with a series of data entry screens to design the new manufacturing process or product. The examples that follow are taken from an existing information database of a manufacturing facility.

EcoSys™ has three methods of analysis; material analysis, data summation, and impact analysis. At the most detailed level is material analysis where the user may want to examine information pertaining to specific materials. The user simply accesses the materials library. When this is done, an alphabetical list of all the materials in the database appears in a window of the browser. Any number of materials can be selected for analysis. The environmental information from the database for all the materials selected is presented in the results window. As an example, four different materials were selected and the information appears as shown in Table II. Information from the materials database is useful for examining attributes such as the percent TRI, the typical route of disposition, and ratings for the various impact criteria.

Data summation, a second type of analysis, is used to collect information for any number of operations or components. The summed information includes the inventory of all materials and/or subassemblies required for the specified node(s) of analysis. If a single operation is to be summed, just the immediate materials involved in the process are combined. In contrast, if the user selects a component to be summed, all information down to the leaves of the tree is combined. In both cases, summing means that the total mass of materials consumed and wastes produced is collected and the material environmental information is presented as a weighted average. If a list of operations is to be summed, the individual operations are first combined and then a sum of all the operations is performed. Table III shows the results from summing four operations.

Key information is obtained from a data summation analysis. First, there is an important distinction between the information presented for materials and the information presented for data summation of an operation or a component. In the former case, there are factors assigned for the percentage of the material that creates a toxic release, and factors for the route of disposition of waste, where the possibilities are industrial solid waste, incineration, or some "other" treatment. When applied in the context of an operation, these factors are converted into quantities to determine (I) the quantity of material consumed by the operation, (2) the quantity of waste generated, (3) the amount of the waste that is hazardous, and (4) the amounts of waste that are disposed through other various routes. An additional feature specific to operations is the quantity of waste released in an uncontrolled manner, termed "fugitive."

The most common data summation analysis is performed on a single component or product. The component is analyzed by summing all the operations that are performed to make the component. If an operation includes another component, it is likewise summed. This continues until the leaves of the tree are reached for the component. If more than one component is selected, the summation is done for each component on the list and the analysis concludes with a grand total sum of all components selected. Table IV shows the summation results for a single component, Printed Wiring Board 1 (PWB1), a major subassembly. In this respect, data summation is somewhat analogous to more traditional process waste assessments. However, rather than reporting quantities

Table II
Examples of Specific Material Information from the Database

Type	Name	ID	TRI	ISW	Incin	Treat	ODP	ReNu	ReUs	ReSe	Eng	Glob	Land	Spec	Air	Water
material	sodium_car	4553052	0.00	0.00	1.00	0.00	0.00	9.00	9.00	5.00	5.00	5.00	5.00	5.00	1.00	1.00
material	sufuric_ac	4528351	0.93	0.00	0.00	1.00	0.00	5.00	5.00	5.00	5.00	9.00	5.00	5.00	9.00	9.00
material	boric_acid	4528010	1.00	0.00	1.00	0.00	0.00	9.00	5.00	5.00	5.00	1.00	5.00	5.00	5.00	9.00
material	solder	8330203	1.00	1.00	0.00	0.00	0.00	9.00	5.00	5.00	5.00	1.00	5.00	5.00	5.00	9.00

Table III
An Example of Data Summation Across Four Operations

Type	Name	ID	Qty In	Qty Out	Qty Fug	TRI	ISW	Incin	Treat	ODP	ReNu	ReUs	ReSe	Eng	Glob	Land	Spec	Air	Water
total	chemical_c	397348-40	1033293.0	1040663.0	95.0	2468.5	2593.0	34.0	1038036.0	0.00	1.02	1.02	5.00	1.01	1.01	1.01	1.01	1.02	1.02
total	laminate_r	397348-50	49.0	14.0	0.0	14.0	14.0	0.0	0.0	0.00	9.00	9.00	5.00	5.00	5.00	5.00	5.00	5.00	1.00
total	brown_oxid	397348-150	151973.0	152377.0	770.0	927.1	555.5	52.0	151769.5	0.00	1.15	1.14	5.00	1.08	1.01	1.08	1.08	1.08	1.15
total	machine_so	397349-130	1110.0	876.0	259.0	855.0	55.0	820.0	0.0	0.02	9.00	8.78	5.00	4.99	8.49	5.00	5.00	8.74	4.54
*** Grand Total ***			1186425.0	1193930.0	1124.0	4264.5	3217.5	906.0	1189805.5	0.00	1.05	1.05	5.00	1.02	1.01	1.03	1.03	1.03	1.03

Table IV
Data Summation For Component Printed Wiring Board 1

Type	Name	ID	QtyIn	QtyOut	Qty Fug	TRI	ISW	Incin	Treat	ODP	ReNu	ReUs	ReSe	Eng	Glob	Land	Spec	Air	Water
operation	wet_blast	397348-30	197501.0	197501.0	0.0	0.0	84.0	0.0	197417.0	0.00	1.00	1.00	5.00	1.00	1.00	1.00	1.00	1.00	1.00
operation	chemical_c	397348-40	1033293.0	1040663.0	95.0	2468.5	2593.0	34.0	1038036.0	0.00	1.02	1.02	5.00	1.01	1.01	1.01	1.01	1.02	1.02
operation	laminate_r	397348-50	49.0	14.0	0.0	14.0	14.0	0.0	0.0	0.00	9.00	9.00	5.00	5.00	5.00	5.00	5.00	5.00	1.00
operation	develop_re	397348-80	6332.0	6364.0	0.0	3153.5	6291.0	57.0	0.0	0.00	9.00	9.00	5.00	5.00	1.05	5.00	5.00	1.01	1.00
operation	copper_etc	397348-100	450973.0	454928.0	580.0	904.6	0.0	0.0	454475.0	0.00	1.02	1.02	5.00	1.01	1.02	1.01	1.01	1.02	1.02
operation	strip_resi	397348-110	162520.0	162736.0	0.0	2867.5	5380.0	0.0	157356.0	0.00	1.27	1.27	5.00	1.14	1.00	1.14	1.14	1.00	1.01
operation	brown_oxid	397348-150	151973.0	152377.0	770.0	927.1	555.5	52.0	151769.5	0.00	1.15	1.14	5.00	1.08	1.01	1.08	1.08	1.08	1.15
operation	lamination	397348-180	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	9.00	9.00	5.00	0.00	0.00	5.00	5.00	0.00	0.00
operation	wet_blast	397348-260	39500.0	39501.0	0.0	0.0	17.0	0.0	39484.0	0.00	1.00	1.00	5.00	1.00	1.00	1.00	1.00	1.00	1.00
operation	chemical_c	397348-220	207659.0	208133.0	19.0	370.3	519.0	7.0	207607.0	0.00	1.02	1.02	5.00	1.01	1.00	1.01	1.01	1.01	1.01
operation	permangana	397348-270	36215.0	36215.0	235.0	810.1	0.0	128.0	36087.0	0.00	1.27	1.28	5.00	1.14	1.06	1.14	1.14	1.14	1.27
operation	electroles	397348-280	155928.0	155929.0	577.0	1180.1	144.0	109.0	155676.0	0.00	1.13	1.13	5.00	1.08	1.05	1.08	1.08	1.09	1.15
operation	flash_copp	397348-290	14328.0	14222.0	880.0	8756.4	1079.4	1301.0	11841.6	0.00	5.48	6.34	5.00	5.00	5.49	5.03	5.00	6.87	8.63
operation	laminate_r	397348-320	14.0	14.0	0.0	0.0	14.0	0.0	0.0	0.00	5.00	9.00	5.00	5.00	1.00	5.00	5.00	1.00	1.00
operation	wet_blast	397348-300	39500.0	39501.0	0.0	0.0	17.0	0.0	39484.0	0.00	1.00	1.00	5.00	1.00	1.00	1.00	1.00	1.00	1.00
operation	chemical_c	397348-310	208133.0	208133.0	19.0	494.0	519.0	7.0	207607.0	0.00	1.02	1.02	5.00	1.01	1.01	1.01	1.01	1.02	1.02
operation	develop_re	397348-340	154965.0	16641.0	0.0	627.0	1260.0	11.0	15370.0	0.00	1.07	1.07	5.00	1.31	1.00	1.03	1.03	1.00	1.00
operation	pattern_pl	397348-360	24963.0	24963.0	1020.0	2005.5	0.0	9.0	24954.0	0.00	1.87	1.87	5.00	1.72	1.72	1.72	1.72	2.29	2.43
operation	strip_resi	397348-370	32542.0	32545.0	212.0	568.5	1074.0	0.0	31471.0	0.00	1.27	1.27	5.00	1.14	1.00	1.14	1.14	1.00	1.01
operation	pumice_scr	397348-380	3806.0	3806.0	0.0	114.2	3806.0	0.0	0.0	0.00	9.00	9.00	5.00	5.00	1.00	5.00	5.00	1.00	1.00
operation	copper_etc	397348-390	90987.0	90987.0	116.0	211.6	0.0	0.0	90987.0	0.00	1.03	1.03	5.00	1.02	1.02	1.02	1.02	1.03	1.03
operation	solder_coa	397348-420	57975.0	567600.0	116.0	784.6	832.0	518.0	566250.0	0.00	1.19	1.18	5.00	1.01	1.01	1.02	1.09	1.02	1.02
operation	hand_debur	397348-460	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
operation	aqueous_cl	397348-470	24368.0	24368.0	0.0	4990.8	0.0	0.0	24368.0	0.00	5.10	5.10	5.00	3.05	1.00	3.05	3.05	1.00	3.05
operation	aqueous_cl	397348-500	24368.0	24368.0	0.0	4990.8	0.0	0.0	24368.0	0.00	5.10	5.10	5.00	3.05	1.00	3.05	3.05	1.00	3.05
total	pwb1	397348	3117893.0	3501509.0	4639.0	36239.1	24198.9	2233.0	3474508.0	0.00	1.17	1.48	5.00	1.09	1.03	1.10	1.10	1.65	1.10

Table V
Material Summation for a Given Process—Flash Copper

Type	Name	ID	Qty In	Qty Out	Qty Fug	TRI	ISW	Incin	Treat	ODP	ReNu	ReUs	ReSe	Eng	Glob	Land	Spec	Air	Water
material	pc4_cleane	4702967	4672.0	4672.0	612.0	0.2	0.0	0.0	1.0	0.00	5.00	9.00	5.00	5.00	1.00	5.00	5.00	5.00	9.00
material	copper	003	0.0	1.0	0.0	0.0	1.0	0.0	0.0	0.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
material	e_339	4702866	247.0	247.0	0.0	0.1	0.0	0.0	1.0	0.00	9.00	9.00	5.00	5.00	1.00	5.00	5.00	5.00	9.00
material	anodes	4520005	107.0	0.0	0.0	1.0	0.0	0.0	0.0	0.00	9.00	1.00	5.00	5.00	1.00	9.00	5.00	1.00	5.00
material	hci	4528071	2.0	2.0	0.0	0.4	0.0	0.0	1.0	0.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	9.00	9.00
material	copper_sul	4702865	1348.0	1348.0	0.0	0.2	0.8	0.0	0.2	0.09	9.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	9.00
material	sodium_per	4553285	1301.0	1301.0	268.0	1.0	0.0	1.0	0.0	0.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
material	sulfuric_ac	4528351	6651.0	6651.0	0.0	0.9	0.0	0.0	1.0	0.00	5.00	5.00	5.00	5.00	9.00	5.00	5.00	9.00	9.00
total	flash_copp	397348-290	14328.0	14222.0	880.0	8756.4	1079.4	1301.0	11841.6	0.00	5.48	6.34	5.00	5.00	5.49	5.03	5.00	6.87	8.63

Table VI
The Comparative Environmental Impact of Several Processes

Type	Name	ID	Qty In	Qty Out	Qty Fug	TRI	ISW	Incin	Treat	ODP	ReNu	ReUs	ReSe	Eng	Glob	Land	Spec	Air	Water
total	chemical_c	397348-40	1033293.0	1040663.0	95.0	2468.5	2593.0	34.0	1038036.0	0.00	1.02	1.02	5.00	1.01	1.01	1.01	1.01	1.02	1.02
total	laminate_r	397348-50	49.0	14.0	0.0	14.0	14.0	0.0	0.0	0.00	9.00	9.00	5.00	5.00	5.00	5.00	5.00	5.00	1.00
total	brown_oxid	397348-150	151973.0	152377.0	770.0	927.1	555.5	52.0	151769.5	0.00	1.15	1.14	5.00	1.08	1.01	1.08	1.08	1.08	1.15
total	machine_so	397349-130	1110.0	876.0	259.0	855.0	55.0	820.0	0.0	0.02	9.00	8.78	5.00	4.99	8.49	5.00	5.00	8.74	4.54

Impact Analysis

Name	Environmental Protection	Resource Management	Eco Development
chemical_c-397348-40	0.455	0.325	0.196
laminate_r-397348-50	0.083	0.184	0.277
brown_oxid-397348-150	0.217	0.150	0.125
machine_so-397349-130	0.245	0.341	0.401

for a single process or facility involving a large number of different products, data summation is a report of quantities associated with a single product exposed to a large number of processes.

To get more detailed information on an operation displayed as a result of a data summation, the user simply selects any operation and a material list including quantity information is presented for that operation, as shown in Table V.

The results from data summation may be applied in a number of ways. Most significantly, tabular results from data summation permit the user to easily compare a large number of operations against very specific user-selected criteria. For instance, one might ask which operation used to produce PWB1 produces the greatest amount of a toxic release chemical (TRI, maximum in that column is the *flash copper* process), or, which operation produces the greatest quantity of fugitive stack emissions (*pattern plate*, under Qty Fug). Similarly, the user can determine what types of toxic chemicals are used in the process (see Table V for the *flash copper* process).

Environmental Impact information, a third type of analysis, is an extension of data summation, in that the summation is performed first and that information is used by the impact analysis models to calculate the relative environmental consequences of the items selected for analysis. The user selects any number of operations or components or both to compare. It generally makes more sense to compare operations to operations and components to components but the flexibility exis to compare operations with components. Table VI show the comparison of the environmental impact for fo operations. Figure 8 shows the results in a bar grap form. In this case these operations are not similar competing; EcoSys™ supports analysis of like or unli processes or products—this feature is a reflection of t broad range of motivations of users for applying a t like EcoSys™. (A more typical scenario might invol analyzing three different soldering operations to det mine the one with the least environmental impact.) T results shown above illustrate the implications of diff ent environmental views when conducting environmen assessments. According to the Environmental Prot tion view, the chemical cleaning process has the high relative environmental impact by nearly a factor of t In the Resource Management case, chemical cleaning nearly equal to machine soldering. In the Eco-Devel ment view, soldering has nearly twice the impact of other process.

Presentation of the tabular data summation res may then be used to gain an understanding for the tre observed from the impact analyses. For example, as s in Table VI, chemical cleaning yields orders of ma tude more waste than the other processes. Environmental Protection view weighs waste pro tion heavily, so this result is not surprising. On the c hand, environmental attributes for chemical clea such as global warming and land use have low va

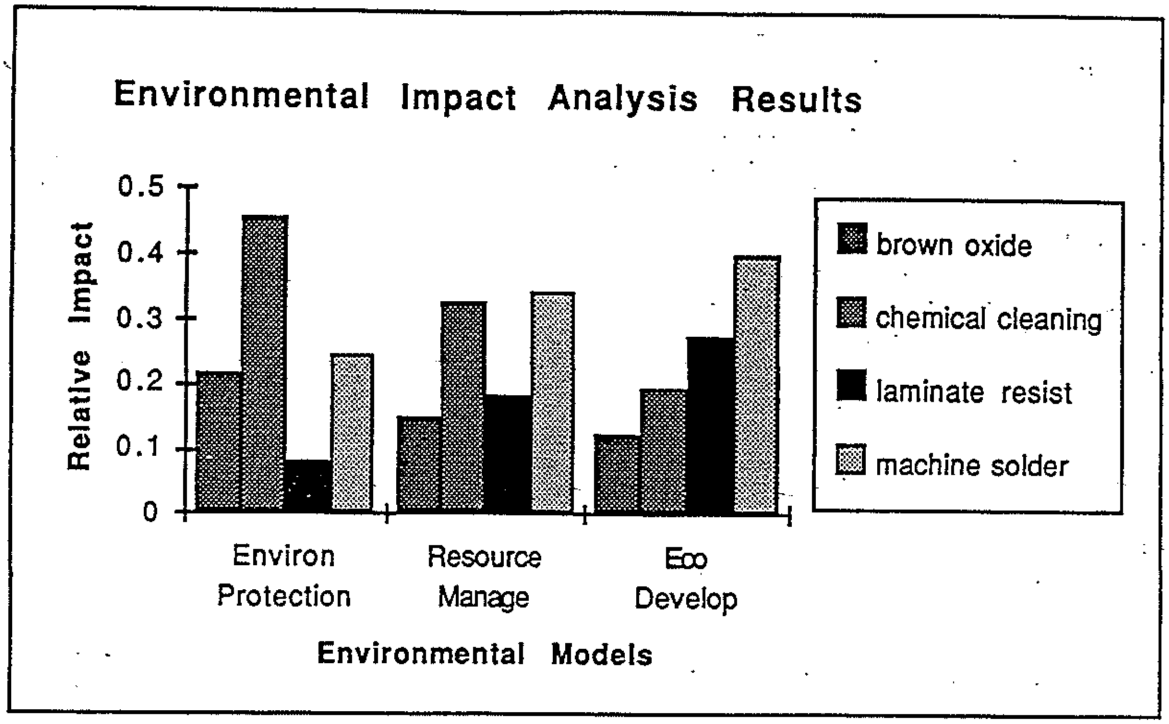

Figure 8. The results of an impact analysis shown in bar graph form.

These attributes are weighed higher in the Eco-Development model, contributing in the low relative impact of chemical cleaning according to this view.

SUMMARY

EcoSys™ is an automated assistant for manufacturing engineers attempting to design and fabricate products under environmental constraints. We discussed the details and use of the environmental models available for the human experts. We also showed how interviews with human manufacturing experts led to the design of a goal-driven rule based reasoning system to support the problem solving. Finally, we offered a number of examples that detailed the types of analysis possible with EcoSys™. Our ongoing work, while engineers continue to use the first version of our system, is (1) to increase the precision of the environmental attributes database and (2) to extend the product—process database to support a wider set of product analyses. Based on feedback from our current users, we are also continuing to improve the X-window user interface.

ACKNOWLEDGMENTS

This work was conducted at Sandia National Laboratories and supported by the U. S. Department of Energy under contract No. AC04-76DP00789. We would like to thank the staff at Sandia National Laboratories for providing environmental specifications for the products and process of the system. Ron Hall and Larry Claussen, also of SNL, provided the information system design as well as Oracle expertise. Gregory Gershanok of the University of New Mexico provided help in building the graphical user interface in Motif. Bruce Gockel from the AlliedSignal manufacturing facility in Kansas City provided process inventory and product data. Everett Heinonen of New Mexico Engineering Research Institute helped coordinate the EcoSys™ project.

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