AN OPTIMIZATION FRAMEWORK FOR FACILITY LIFE CYCLE ANALYSIS OF CONSTRUCTION MATERIALS TO MINIMIZE ENERGY AND ENVIRONMENTAL IMPACTS

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ABSTRACT

This study provides a framework to minimize natural resource impacts, limit ecological damage from manufacturing, and limit energy use from selection of various construction materials during the design decision process. The nature of the process views the facility component through its life cycle, extending the concept to material extraction from the ground, and further incorporating "end of life" disposal actions for bulk and hazardous waste items. By making planning and architectural design decisions based on standardized scores, the designer will be able to make the best choices for construction over the life cycle of the facility.

The framework is based on the ecological damage models used by EPA and some DOD agencies for resource extraction from the earth. The BTU input into the manufacturing process and transportation are included. The BTU utilization over the occupied life cycle of the facility is included. Finally the costs of disposal and possible environmental damage are also noted in the final score. Legal constraints are also to be included in the data base, which is anticipated to run on a PC environment, with reference data eventually stored on CD-ROM format.

In order to make the data framework usable to the architecture and engineering workplace at the decision level, the references are structured to the Construction Specifications Institute 16 division format for materials and products in the construction scenario. By identifying the materials and products in much the manner an automated construction estimator would, the evaluator will get a scored printout with materials ranked to life cycle ecological and environmental cost.

For instance, marble sheathing on a facade may include only resource extraction and finishing BTUs over the entire life cycle with little environmental damage. However an air conditioning unit may have impacts in terms of extensive energy use during the life cycle and disposal problems in terms of CFCs in the ozone layer, and lubrication oils disposal at the end of the life cycle. Although the designer may not have good alternatives for air conditioning equipment, the rank order of the design impact can be seen in the overall scores. Similar factors incorporating environmental trade-offs could be developed inclusive of the cost of hazardous waste disposal actions. In this manner, the overall economic, social, and energy life cycle costs of construction materials and assemblies could be evaluated in an automated decision format.

This study demonstrates that data components and structures are available to accomplish the concept as a design tool. However, the framework is not yet detailed enough to translate all variables into an accessable design instrument.

I. INTRODUCTION

A. Background

The United States is facing a major problem with solid and hazardous waste in landfills. Some components of this problem have been addressed through recycling, substitution of various types of materials, and also through an effort at creating biodegradable materials. The United States faces further problems in ecological management of its natural resources, and in increasing energy use. Many of these problems are associated with the manner in which our material culture has developed, and the transformation process of our manufacturing industry. We imply that the design and selection of materials has not been thought of in terms of energy and life cycle ecological management for the entire product life, through disposal and remanufacture.

Furthermore, the energy used in the manufacture of certain products has not been evaluated wholistically in terms of energy conservation and impacts on natural resources. The final product, at the end of its useful life, is disposed of, and can present problems both of hazardous waste and lost opportunities for recycling. This particular scenario then begins to suggest that many of our environmental and energy problems are linked to the way in which we review the manufacture, construction and disposal of our material civilization. The creation of various products in our society are not evaluated in terms of the overall life cycle from raw material to final disposal, particularly those items associated with buildings and civil projects. The entire national construction industry could serve as a basis for an alternative and innovative approach to this problem. Buildings, dams and other engineered and architecturally constructed items are essentially "products" and need to be looked at in the context of their impact on the environment and energy utilization. There is no tool or data base, however, which allows the engineer a life cycle viewpoint of components, or aids in decision-making in the selection process.

This long range point of view suggests that individual products or construction edifices should be designed cognizant of their impact on resource management, ecological systems, energy utilization, and recycling potential. This point of view implies that one might begin to evaluate the materials which go into buildings and structures from various alternatives during the design decision process. It furthermore suggests that rethinking of some of the ecological and environmental considerations may be necessary for individual building components.

However, a quick review of the literature reveals that this particular concept has no comprehensive basis in any piece of literature. The only near-term relevant study which has been done was sponsored in 1972 by DOE[1] and evaluates the BTU content of various building components in their manufacturing process. Another study by NBS[2] focuses on the economics of resource use, and postulates RIF's, (Resource Impact Factors) for manufactured goods. Since then, however, we have had ecological balance, health parameters, and hazardous waste integrated into our thinking. The problem of tracking environmental damage and impact for products is not new to science. It has been known as "green engineering" or sometimes concurrent engineering. Work has been done at MIT, Carnegie Mellon, and the University of Florida to name a few. At the present time, the American Institute of Architects is developing a program that aids design decision making, called the Environmental Resource Guide (ERG).[3] The major problem is the lack of both an overall scoring method, within a framework, and a decision tool that allows both factors to be evaluated for building construction.

There is no single system which can aid in construction material design decision making for the evaluation and comparison of alternatives in order to select products which minimize impact to the environment and have recycling potential. With the large volume of construction throughout the nation every year, it seems that there should be some effort at taking a long range, interdisciplinary point of view to consider the process involved in creating the products for the industry. This paper presents a framework for such a system, and manages impacts from the very beginning of resource utilization to, and including, recycling options for various building components.

B. ECONOMICS AND DESIGN PARAMETERS

The long range look at the utilization of resources and the minimization of energy over the facility's life cycle extends both the definition of the facility's life cycle (20-500 years for buildings) and certainly extends the implications for energy and ecological concerns. This long range view is, of course, permeated by the life cycle discount value of money. Most economic decisions are made on the basis of initial capital investment value, life cycle analysis (LCC), or returns on investment (ROI). It becomes apparent, however, that the linkage between economic investment and first choice savings of dollars may not be directly related to minimization of overall real cost to the society. The economic choices for both the initial investment and for the life cycle benefit may not be the correct approach without taking into consideration other variables which now become national priorities, such as energy and environment.

The attached diagram in Figure 1 will give an indication of the type of conceptual design evaluation cycle structure. If one were to examine this figure from the point of view of a series of "linked" representative computer data bases, then we could quickly see how a design engineer or architect could access the data base with the specification of the materials he was going to use in his constructed facility, and select the optimum path through both the raw material impacts and the recycling options to maximize the economic return on investment (ROI) for the actual productive life cycle of the building.

Furthermore, access to the environmental data base component of this nature would allow one to quickly see what kinds of tradeoffs need to be made between ecological impact, recycling options and waste and disposal options. Obviously impacts at the end of the building's life cycle should consider impact on landfill, recycling parameters and future health hazards to the groundwater at disposal sites.

The diagram in Fig. 1 represents a decision analysis framework for the selection of materials and the minimization of hazards to others. Previous work done in the area of formation of a methodology is limited in terms of its life cycle viewpoint. In a paper by Bridgestone, et al.,[4] there is a discussion of the relationship of scheduling tools to the design process, inclusive of the incorporation of CSI specification formats. However, this paper does not focus on the overall life of the facility, but does assume that design review is a primary point of decision making that affects the environment. In another related paper, Napier (1991)[5] proposes the use of an expert system for environmental review for building projects, but again does not extend the concept for the overall life cycle of the project.

The concept in Fig. 1 is a beginning for a framework of linked data bases required to make design selection judgments as done in other industries.[6] It also points out the encompassing interdisciplinary nature of the proposed research. It is obvious that the initial conceptual development will not remain static, but will continue for years in which the design tools developed for minimization of energy use, environmental impact, and health hazard danger, can be used over and over again as new knowledge can be input into the data base. The intent of this paper is to outline the schematic for the entire process.

C. DESIGN IMPLICATIONS

The design implications for this type of framework for a particularly large national industry become immediately apparent. One of the first uses might be a policy overview and review of ASTM and generic guide specifications for all types of construction work. The language in certain specifications can easily be changed and reissued to insure minimal environmental impact in the design process, but still provide a basis for ecological trade-offs (an example is presented in Fig. 9). Furthermore, the futureengineering design analysis attached to any set of drawings may require this type of design analysis to be submitted, as is being promoted in product design.[7]. It will insure consideration of all parameters in the design

NOTE: there is a wide variance in the length of each section of the chart from 1-500 years for each functional application

CONSTRUCTION MATERIALS LIFE CYCLE

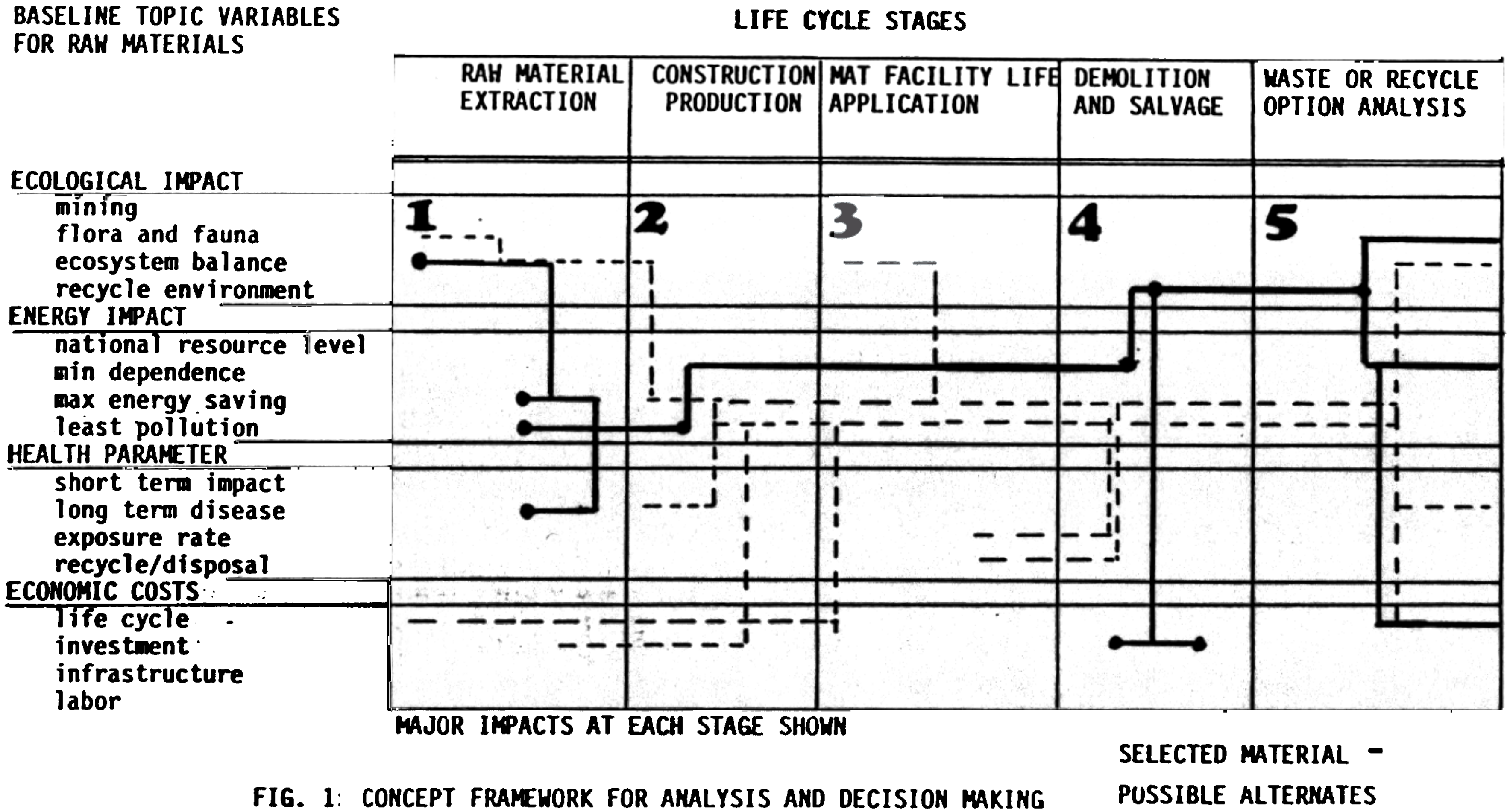


FIG. 1: CONCEPT FRAMEWORK FOR ANALYSIS AND DECISION MAKING FOR ALTERNATIVE CONSTRUCTION MATERIALS

OBJECTIVE: create a decision analysis system that allows design choices to minimize negative impacts over the entire product life cycle, operating in a user friendly PC environment.

process for a constructed facility which are now impacting various aspects of our national environment. One could quickly see that this type of product from a research effort would not only be interdisciplinary, but it certainly would be continuously applicable in various design and construction stages as it was upgraded over the years.

If the overall framework were developed so that it could be translated into an engineering usable instrument with decision analysis techniques attached, one could quickly see it would be a standard for many construction options within the country. It would certainly allow variation in C.S.I. decision choices, and would aid in both environmental impact statements from the point of view of the using public, to making policy tradeoffs and recommendations based on the review of longterm impacts for larger projects. The policy implications certainly represent a new type of view towards construction. Materials would be designed and selected in such a way that they either could be recycled or could be re-manufactured into further uses. This would minimize the national dependency upon raw materials and certainly would set the standards for other types of product design from automobiles to home appliances. The interdisciplinary nature of this research effort, and its conceptual framework, would affect and set the standard for new approaches to the process of engineering and architectural design.

II. CONCEPT DEVELOPMENT OF MODEL FRAMEWORK

A. STRUCTURE OF EVALUATION MODULE

As an example of the thought processes which might go into the design of a construction product, we can consider the steps of raw material acquisition, manufacturing, assembly, occupancy, and demolition and disposal. For the raw material acquisition we need to consider environmental impacts and ecological hazards associated with mining, refining, and extraction. These are specified in certain measurable units and in related federal standards and regulations. The knowledge of the environmental pollution caused by these "systems of acquisition" can be specified at the very initial stages in terms of product selection. Representative standards taken from industry practice will serve as a baseline. Improvements over this baseline over years could be entered into the data base. However, for the initial consideration of construction materials, i.e. concrete (cement) could be identified, and their ecological impact in terms of source, locale, and local environmental systems would be developed. Reference to legal constraints and government standards could easily be interfaced so that the selection of construction material caused minimal environmental damage.

Selection of a construction materials also could be based on minimum energy utilization for manufacture. This unit is more easily expressed since when one knows that energy occurs within a certain type of field range and in BTUs per mass unit manufactured, or in megajoules/kg.. A standard comparison weight, i.e. lbs. or kilograms, could be used for comparison and various tradeoffs could easily be done with a sophisticated data base. This data base would need to be structured in such a way as it related to the Construction Specifications Institute (CSI)[8] headings for construction materials. In this manner it could easily be tied into manufacturer's product catalogs and other listings relating to construction industry assemblies and components. The design engineer or architect would have the option of selecting the best choice which minimizes environmental ecological impact and minimizes energy use in fabrication.

Once the facility is constructed, we can begin to consider the occupancy stages of the life cycle of the building, i.e. when it is serving its functional purpose. This phase is interesting since most of the materials are inert at this time and have little impact on the environment. However, the construction project itself may use BTUs, or may generate excess BTUs, thereby affecting the environment nearby and at the power source. This phase is the longest portion of the life cycle, and has a major impact on overall energy consumption.

A serious look at how construction materials are disposed of at the end of a facility life cycle has not been well researched. Some construction materials are simply assumed to be part of general waste and are taken by the hauler to the local landfill. Other construction materials fall into either hazardous waste categories or possible fuels (i.e. wood studs). The overall nature of the construction waste problem has had little research and little effort pointing to developmental possibilities for recycling. Architectural salvage yards now exist for recycling historical components of buildings that possibly could be reused. However, construction waste still has major problems. In the construction of any building, the temporary scaffolding and the concrete form work are not designed in such a way to be recycled, and are thought of as disposable. Furthermore, construction material wrappings are not identified as being recyclable or biodegradable. For a typical million square foot building, there may be over a million pounds of construction waste generated for a landfill. While this occurs only once in the life cycle of a facility, it does have an impact on the volume of space taken up in the landfill. Therefore, there is a "gray area" which exists in relationship to new construction materials which could be investigated in order to determine possibilities for recycling certain elements of construction endeavor.

The issue of demolition is a separate one. When a building is demolished, it is assumed that the contractor simply piles the debris into waiting waste bins. Many construction projects could have partially salvageable materials such as plywood and 2x4's, but the labor involved in salvaging these materials is far greater than the cost of processing new trees. The problem will become more acute as one realizes the 30 to 50 year time cycle for creating new wood compared with the possibility of using adequately dried older wood. However, in the construction debris recycle area, there is a problem of legal liability. New construction materials are stamped for structural strength, durability, and wear. Therefore, meeting building code specifications becomes a means of reducing construction liability to a locally acceptable level. If certain construction materials are recycled, they probably will not meet new construction code requirements or CSI specification requirements. Therefore, the legal liability and structural certification associated with recycling construction waste becomes part of a "risk" evaluation and forecast problem for innovative products. Finally, the labor component of construction waste recycling becomes serious. The removal of nails from a simple 2x4 can be a tedious and labor intensive problem. The problem is not easily solved by simply redesigning the construction site or the actual process of demolition.

Referring to the chart in Figure 1, it is quite easy to follow the logic of the materials life cycle from one end to another in a construction scenario. What is more difficult is defining what the measurement values are one might wish to use in evaluating the overall efficiency of the model or the basis for making design decisions. In the case of many of the energy impact models which might be considered, one can use a standard definition of BTUs per pound of material, or BTU/sf/year for specific building types. This particular measuring device for an evaluation module for each section of the chart works because the measurement unit is the same, that is, a BTU per unit of mass. It furthermore works in the model because one can represent BTUs as an input to the final product or perhaps even an output. In some cases, the construction product will generate BTUs feeding back to the environment and have some degree of environmental impact. One can quickly see that the life cycle analysis will generally work in terms of BTUs per unit mass, even applied to the cost implications of waste disposal or recycling at the end of the life of the material.

The application of an evaluation module scenario to the measurement of environmental parameters, however, is not so clear. First of all, the word "environment" implies a wide range of parameters, some of which have not been clearly defined. Another sector of information which has not been fully developed is that of ecological balance. We talk of eco systems, but in rare cases are we able to define what a stable eco-system is, or what its relationship is to the surrounding environment. Most of the parameters which have been generated in the

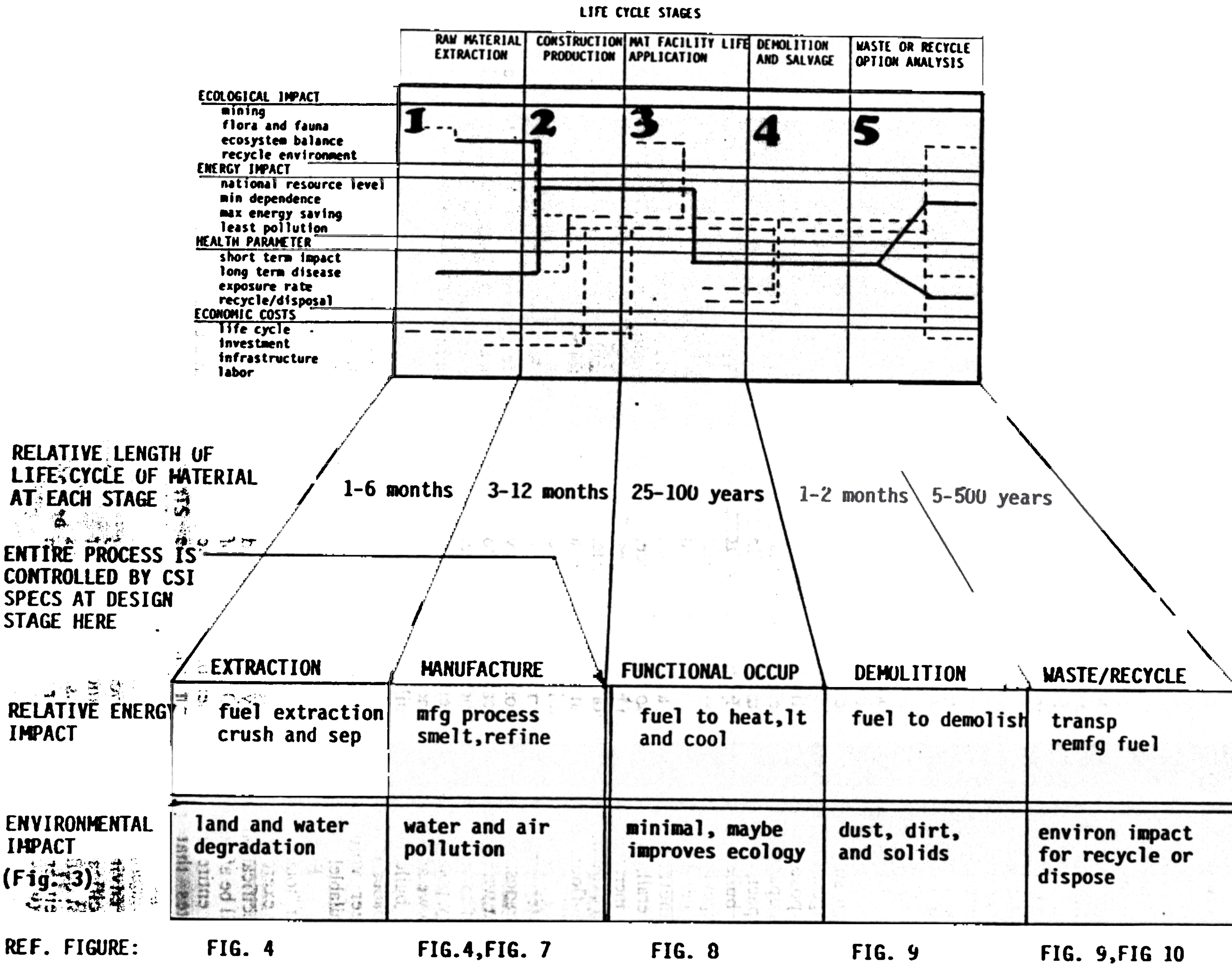


FIG. 3: EXPANDED VIEW OF CONCEPT FRAMEWORK, SHOWING RELATIVE LIFE CYCLE IMPACTS

last twenty years are based upon compliance models, i.e. the specification of some level of particulate matter per "X" number of units, (for instance, carbon monoxide per million parts of air.) Although these models provide legal parameters, they do not necessarily define the correct balance for an eco system which would be self-sustaining and renewing. Therefore, there is a difficulty in using a module with a single valued parameter to define the nature of environmental impact.

An inspection of the chart in Fig. 2 with the graphs gives some useful insights when we note the relative "life" of each product stage, and the impact on resources at each stage. If we look at the life cycle for each stage, then we quickly note that the longest is generally during occupancy and disposal for the facility. However, occupancy has the lowest environmental impact, and yet uses the most energy per lb of building mass, merely because of its longevity. Substantial environmental impact however, occurs in extraction and manufacturing stages, and in disposal. Overall, disposal is hard to categorize since, for inert materials, we can have large masses, and extreme longevity. For hazardous waste, i.e. flourescent tube coatings, we have a unique problem of dissolution in ground water etc., which only may take a few decades. Furthermore, most of the masonry that we are disposing of can be expected to last as long as man has been civilized, i.e. clay pottery and stone axes do not degrade. Do we anticipate that in another 50 years, all the buildings we have built in the last two decades will be sent to a landfill? What a sheer volume of space must be made available!

Further inspection of Fig. 2 reveals that "total control" of the entire life cycle can be exercised in the design selection and specification phase, i.e. any material selected will be affecting the 25-500 year life cycle of the entire architectural assembly. When one notes that all building materials are categorized into 16 sections by the CSI, the designer hopes that major decisions affecting the environment can be incorporated using specifications, yet the standard format for most building specifications gives no hint as to either energy used per pound mass in manufacture, or in environmental impacts. Material performance standards are expressed in terms of ASTM reference, or in MILSPEC citations. Therefore, there is no reference data available for decision making at the most critical control point in the entire life cycle process, in order to minimize parameters of energy or environmental impact.

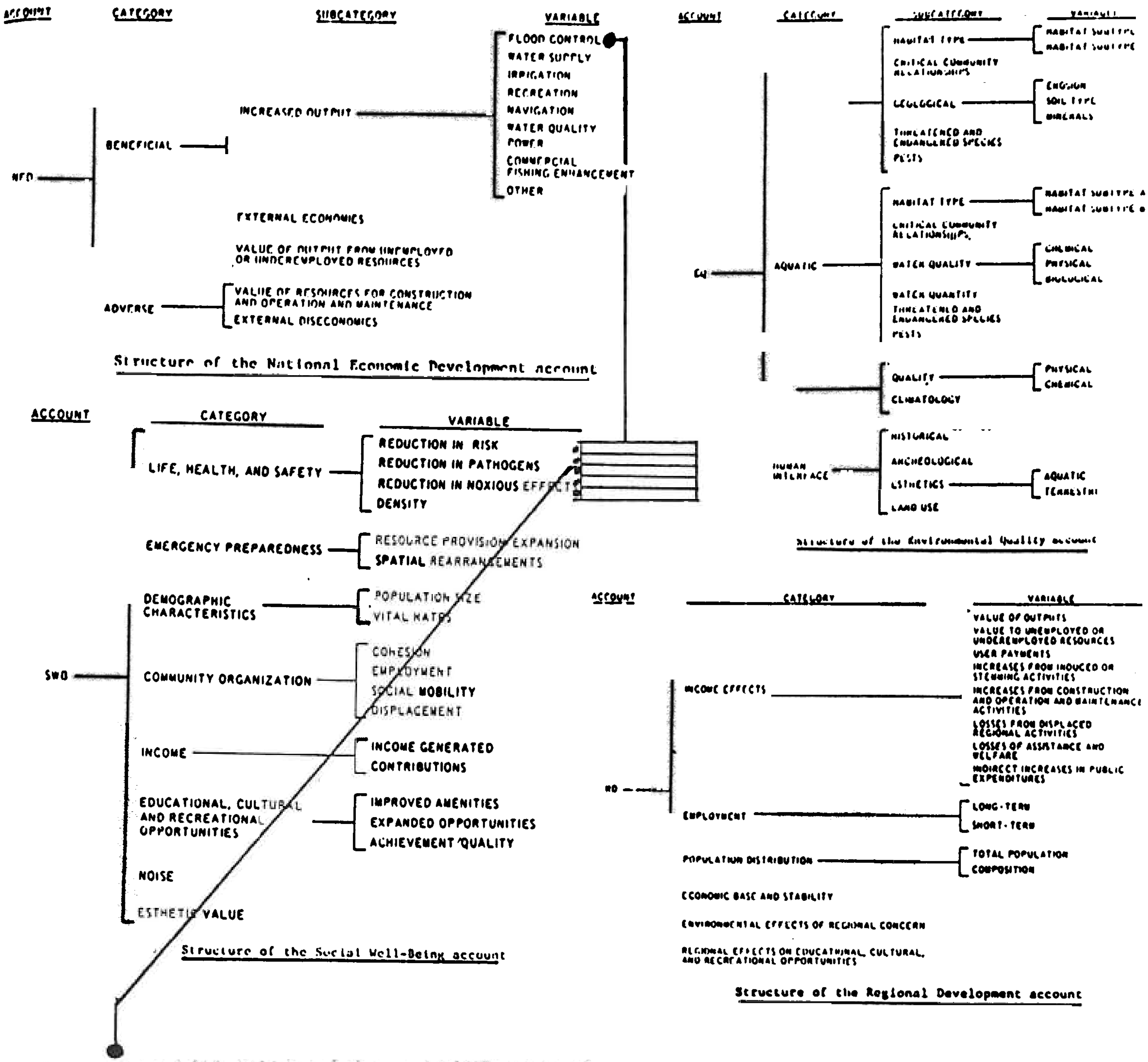
The question then becomes one of defining a structure and accounting for those parameters that can be used during the design process and embedded in the specification text. As noted in the previous NBS research paper on RIFs, there is a partial accounting in the dollar cost for various products, but both parts of the manufacturing and the disposal process are paid for in this manner. At the risk of making a too detailed structure, we must develop an accounting procedure.

The solution to part of this problem is to use an evaluation model developed in the early 70's by Dee[9] for water resource impact analysis. This model provides a basis for scoring inputs and weighting to various parameters for an environmental resource analysis. A description of the model is shown in Figure 3 and further analysis can be found in the original paper. The application of this particular resource model to this paper is that it forms a separate environmental module with defined measurement parameters which can be applied to each stage of the material life cycle. Therefore we have a common means of evaluating environmental impacts at each stage using this structure, and it can combine with the energy process module.

Since it is necessary to present a means of accounting for each stage of production, we need a structure for a "module" that will determine the data format. In Fig. 3 we can see tabulation of BTU and environmental impacts. Note the energy format is such that the material can use BTUs or can simply reduce their use, i.e. in heating. The unit of BTU/mass unit are obvious, but the transfer rate is more difficult to determine.

The second component of the framework in Fig. 3 comes from Corps of Engineers research. The environmental impact tabulation consists of structure, measures, levels, and laws. The structure

FIG. 3 ENVIRONMENTAL IMPACT DATA STRUCTURE (Dee,et al) with COMPLIANCE REGULATIONS AND VALUE PARAMETERS ASSIGNED FOR MODULE.



ENVIRONMENTAL PARAMETERS AND VALUE ASSIGNMENTS

MANDATED LEVEL	BASELINE LEVEL	LEGAL REFER	VALUE	ECONOMIC IMPACT
stated in ppm or other req level	starting level before impact	EPA,DOD,etc. state or Fed source doc.	target	material impact on locale, does it create or destroy jobs,etc.

determines how data will be arranged. The measures are the units commonly used for calculating the level of a toxin. The level is the acceptable value of toxic units per volume that can be accepted with reasonable risk. The law is the regulatory authority that has set the "risk" level. These structures are a way of keeping the accounting straight. The accounting parameters are well defined in a paper by Solomon, et. al., done for the U.S. Army Corps of Engineers (1977).[10]

Given the foregoing discussion, the following description of various sections of the structure of the overall construction materials life cycle framework can be developed. In each of the sections attached there will be a discussion of references and data sources with suggestions for measurement units and evaluation modules at each stage. The intent here is to expand on the concept basis for construction materials life cycle and to demonstrate data sources as a means of linking the decision making capability throughout the entire cycle.

B. Description of Stages in Figure 1

1. Resource Recovery: In the process of raw material extraction from the ground, we find that there are a wide range of parameters which can be used as evaluation units. For the extraction operation itself, we can define energy usage in terms of kwh/ton, or megajoules/kg. of material extracted as presented in Fig. 4[11]. We also can indicate the level of resources needed to provide raw material for manufacturing processes. By using the environmental impact model presented in Fig. 3, we can evaluate the environmental degradation for the mining or resource recovery operation.

In this case there are two problems. The first is that the relationship between the environmental resource and the resources available, i.e. non-renewable, undiscovered resource levels become a factor that is difficult to evaluate. Furthermore the impact on various renewable resources becomes a problem. For instance, in the case of solar energy, it is easily apparent that the resource is renewed every day and it is reasonable to expect this will not have a major impact. However, in the terms of timber from forests, the recovery rate for the individual resource life cycle can extend to fifty to sixty years for certain trees. Therefore the question of using the environmental model for determining the impact on the environment becomes involved with another "layer of ecological life cycles." The burden on the environment becomes more subjective in this evaluation mode.

An evaluation of the values of resource recovery at this point in time becomes quite difficult since the individual tradeoffs at this level can be balanced by certain other parameters. As previously mentioned, individual eco systems balance points are not generally known and, in fact, there is some question as to the cost of restoration of resources in a recovered environment, i.e. strip mining. Although these costs are buried within the actual material costs, in some cases the general society carries them through a tax revenue base. The difficulty here is assigning a value to the pound of material for that particular cost basis.

2. Manufacturing Cost Basis: The transition from the raw material to the manufactured product is the next step. This particular transition in building products can vary a great deal. The simple point of view of looking at BTUs per pound of material does not necessarily cover the entire social and environmental cost of creating a manufactured product. For instance, in the case of concrete block, the BTUs per pound of material would be quite minimal and a large mass generated. More sophisticated production of electronic HVAC control systems, i.e. electronics for buildings may have a lower environmental impact but extremely high costs in terms of BTU/pound of material.

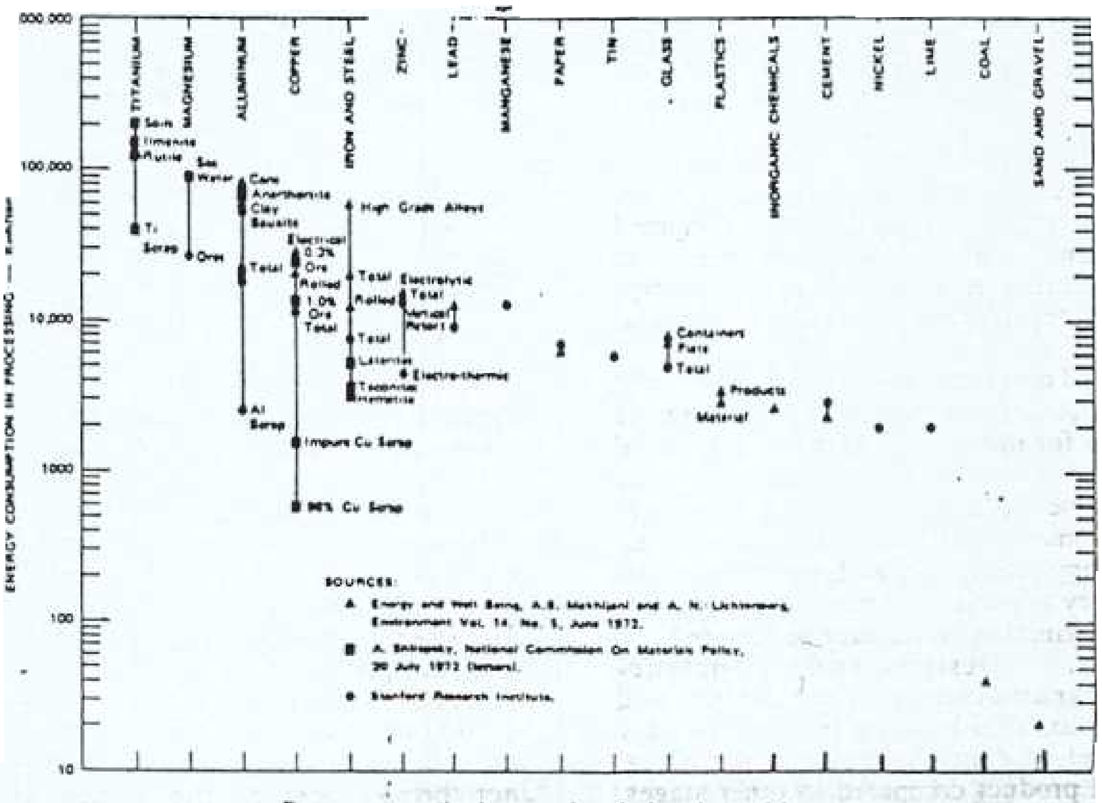
Although one product may lose in terms of overall costs in a particular section of the construction materials life cycle, it may have dramatic paybacks in another section. In the case of an HVAC control system, the lower energy use which is created in the facility life cycle dramatically offsets he actual cost of production. The construction industry however uses 85% of the energy demand in manufacturing for paper, chemicals, petroleum, refining, and stone-

Typical Energy Contents of Materials and Manufactured Product

	Energy megajoules/kg*	*Cost of energy/* Value of product*
Metals		
Steel (various forms)	25-50	0.3
Aluminum (various forms)	60-270	0.4
Copper	25-30	0.05
Magnesium	80-100	0.1
Other Products		
Glass (bottles)	30-50	0.3
Plastic	10	0.04
Paper	25	0.3
Inorganic chemicals (average value)	12	0.2
Cement	9	0.5
Lumber	4	0.1

* These are typical values. The actual value depends on the purity, form, manufacturing process and other variables.

Source: Technology of Efficient Energy Utilization, Report of a NATO Science Committee Conference, Les Arcs, France, October 8-12, 1973, Scientific Affairs Division, North Atlantic Treaty Organization, Brussels, Belgium. Conference report has been reprinted (with NATO's permission) by Pergamon Press, Oxford, UK, and available from that publisher.



Energy consumption in processing of selected materials.

Source: Stanford Research Institute, *Support of Energy Program Planning*, sponsored by the Advanced Research Projects Agency, Menlo Park, Calif, September 1972, as shown in *Energy Facts*, prepared by the Science Policy Research Division, Congressional Research Service, Library of Congress, for the Subcommittee on Energy of the Committee on Science and Astronautics, U.S. House of Representatives, Nov. 1973.

FIG. 4: ENERGY CONTENT OF VARIOUS MATERIALS USED IN CONSTRUCTION: FROM EXTRACTION TO AND INCLUDING MANUFACTURE (public sources)

clay-glass processing. (SERI, 1981)[7] Therefore a reduction in overall energy used in materials production for construction could have a dramatic national impact.

There is a further problem in the manufacturing arena. This is defining the actual manufacturing costs or BTUs per pound of materials. The transition cost from resource material, i.e. raw materials into a manufactured item, i.e. cement material for concrete block is moderately well defined. However, the transition manufacturing cost and environmental impact from the cement into the concrete block represents another transition to the final product. In this case BTUs per pound might be a reasonable value for energy expenditures, but we again run into problems with the environmental impact model. For some manufactured items the pollution caused by the manufacturing process itself may be quite great and certain compliance levels allowed by individual policy bodies may have false manufacturing parameters.

Furthermore, the manufactured items may be partially subsidized and thereby not represent true costs. The diagram in Figure 4 gives an idea of the assignment of manufacturing data for various construction items. It represents the manufacturing costs in terms of energy per mass unit. An associated development of the environmental impact assessment module, however, is required for manufacturing costs associated with environmental degradation. This data must come from industry and government and in some ways represents manufacturing technology interfacing with compliance and regulatory agencies. Perhaps an "efficiency of transformation" value may be required.

3. Design and Construction Parameters: The design and construction of a building represents a very low level of energy input into the actual finished product compared to other stages. However, during the design process, the material choices and their locations are defined by the plans and specifications. Most specification documents, i.e. MASTERSPEC, represent a standard format for building construction items following the Construction Specifications Institute guidelines or other guidelines such as the American Institute of Architects (AIA). This sixteen section format allows specifications for materials to be generated for bidding purposes for the construction of the building. The quality references within the specification generally refer to the material quality and inherent characteristics, again further defined by ASTM or MILSPEC criteria (see Fig. 5). Both of these levels of material characteristic description represent "performance parameters" which are linked all the way back to resource recovery for refining and into the future for the durability during life cycle stages of the building's construction. This linkage is merely defined by the descriptive parameters but is not carefully documented in terms of energy usage or environmental resource impacts. This linkage, "forward chaining," through the building life cycle into its disposal or recycling options needs further explication also. When the designer selects the material the ease of disposal or the energy input into recycling options is not defined in the initial decision making matrix.

In the design process and in the selection of materials for a proposed facility, it would be useful to be able to make tradeoffs based on energy consumption besides the normal architectural function logic. In a study by Stein and Associates, and documented in a book by the same author,[12] a comparison of various "embodied" construction energy alternates is presented similar to Fig. 6. In this case, the "extraction to assembly" energy is presented in a comparative bar chart type graph, and one can see the energy to assemble (direct energy) and the embodied energy in the manufacture of the item. In the examples discussed, the designer can make alternative choices in terms of BTU/sf for construction "embodied" energy, i.e. 625,000 to 2,000,000 BTU/sf based on different assemblies of materials. Stein however does not bring together the issues of the environment in this process. We note that environmental impacts would have occurred in the extraction of the material and in the manufacture of the construction product.

Certain environmental analyses, represented by environmental impact statements are made as a facility is constructed on site, usually pertaining to

1. GENERAL REQUIREMENTS
2. SITEWORK
3. CONCRETE
4. MASONRY
5. METALS
6. WOOD AND PLASTIC
7. THERMAL AND MOISTURE
8. DOORS AND WINDOWS
9. FINISHES
10. SPECIALTIES
11. EQUIPMENT
12. FURNISHING
13. SPECIAL CONST
14. CONVEYING
15. MECHANICAL
16. ELECTRICAL

FIG. 5: STANDARD DIVISIONS OF CSI SPECIFICATIONS

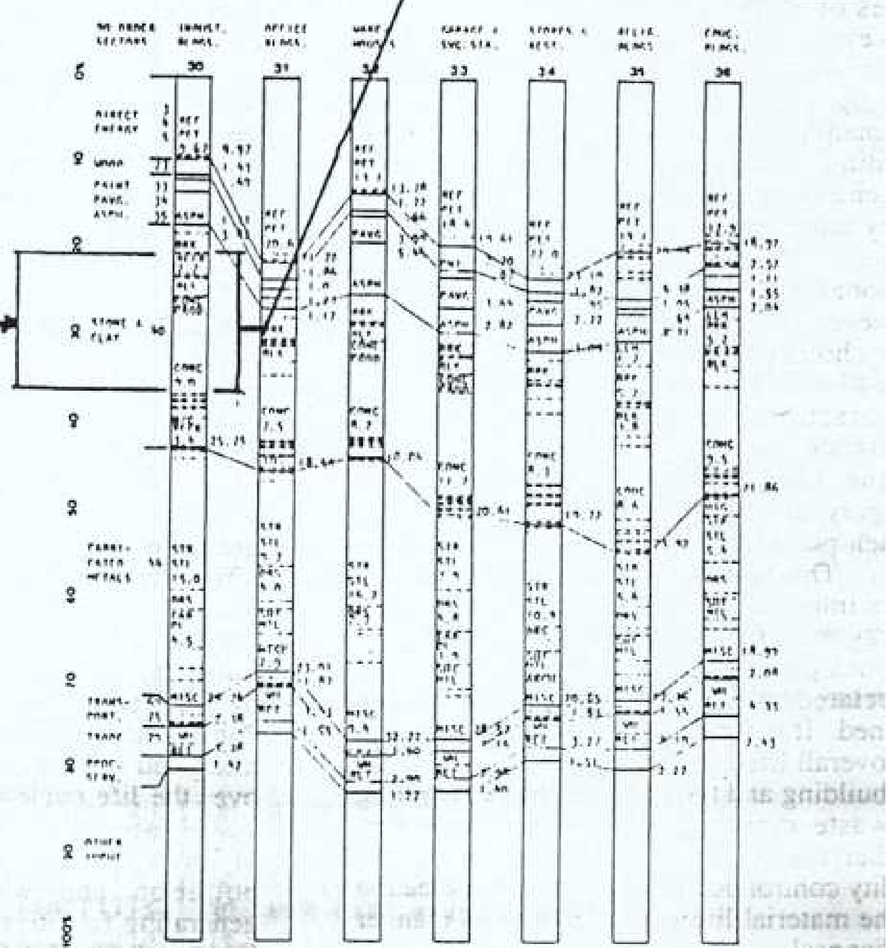
PART I: GENERAL
- DESCRIPTION OF WORK
- SUBMITTALS

PART II: PRODUCTS
- MATERIALS
- FABRICATION
- STANDARDS
- REFERENCES

PART III: EXECUTION
- INSTALLATION
- WORKMANSHIP
- QUALITY CONTROL

FIG.9 shows suggested format to be added to specs at this point for energy/envir impact

FIG. 6: TYPICAL SECTIONS OF AN INDIVIDUAL SPECIFICATION



RELATIONSHIP BETWEEN BTU's IN CONSTRUCTION MATERIAL (Stein,1977 AND CSI SPECIFICATION FORMAT FOR LINK TO ENVIRONMENT runoff, wetlands, or site drainage, but not usually incorporating effects on the local ecosystems. This is partially because the effects are small, and with landscape architecture, we really design a new ecosystem when we build. The real question become one of whether or not the new design is an ecological improvement or degradation. Generally, we do not have a means of scoring our success. Furthermore, once we change the environment, do we consider that the new ecological baseline? For the moment we can still use our format chart for evaluation, but there are some real questions involved when one views it from a life cycle perspective.

The American Institute of Architects Environmental Resource Guide, (ERG) proposes to provide a basis for product evaluation that can be used at the design stage. The intention is that the ERG would aid in product selection life and technical issues of durability, cost, and maintenance. However, one other element is missing from the toolkit of the architect and engineering designer. That is the "value specification" for the manufactured object stated in terms of building volume. For instance, a certain percentage of the building mass may have many alternatives such as exterior cladding. This could be granite, masonry, or wood and reasonable choices could be specified. However, in terms of power distribution, our only choices might be copper or aluminum wire, which use great amounts of manufacturing energy, but have almost negligible building volume. Note that most of the hazardous materials fall in this category, and have intense toxicity compared to their percentage of building mass.

This particular stage of construction is more important for resource utilization and energy minimization than any other. It is at this design stage that material quality and associated energy input for resources are defined. It is further at this point in time that the overall life cycle costs are designated for the building and the opportunity for recycling or waste disposal is defined. However, neither the AIA specifications nor ASTM quality control documents give any indication of the material life expectancy or its manner of disposal.

Two studies which represent possible approaches to this can be referenced. The first is the Resource Impact Factors Study by the National Bureau of Standards in which the economic basis for tradeoffs between resources is developed. Although this study provides a methodology, it does not define the individual material specifications for each construction material type. (See ref. 2) A study by the Army Construction Engineering Research Laboratory dealing with material life cycle categorization in a format related to the CSI specifications grouping provides a better base for life cycle projections based on actual field usage.[12] In the example in Fig. 7, one can see the relationship between various proportions of materials used in facility categories and the discounted present value of dollars invested over the life cycle of facility occupancy and maintenance operations.

Although both of these approaches provide economics-based overall material choices for the architect or designer, they still do not have parameters within them that would allow for the use of our environmental impact module presented earlier. Therefore, material choices in design and construction scenarios are made without an understanding of their impacts on the environment or on energy usage nationally and there is no linkage to the future life cycle of the building. The data is not available nor is it formatted in a way in which it can be fed into the decision making matrix of the designer.

4. **Occupancy and Facility Use:** Once the facility is constructed, the issue of operations and maintenance becomes a factor. Since all buildings use energy generated elsewhere, the issue of energy efficiency (and conservation) really becomes one of environmental performance and impact. If one can lower energy use in any building, then environmental impacts are minimized. The payback for even conservative actions in this arena is huge as mitigated environmental damage pays back over the life cycle of the facility. One can quickly see that BTU/sf could be an indicator of environmental performance, since air pollution and water contamination at generating facilities would also be involved. One method of stating operational building

RESOURCE SUMMARY REPORT

INSTALLATION: Funding Reporting System Demo FACILITY ID: P08931

REPORT NAME: RSMY1038.XDB

0611100 PLASTER

	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Occurrences	12.0	14.0	12.0	10.0	12.0	10.0	12.0	12.0	10.0	12.0
Hours										
Labor	138.68	172.14	138.68	105.22	138.68	105.22	138.68	138.68	105.22	138.68
Equipment	138.68	172.14	138.68	105.22	138.68	105.22	138.68	138.68	105.22	138.68
Costs										
Labor	2286.	2833.	2286.	1739.	2286.	1739.	2286.	2286.	1739.	2286.
Materials	525.	628.	525.	422.	525.	422.	525.	525.	422.	525.
Equipment	444.	551.	444.	337.	444.	337.	444.	444.	337.	444.
Totals	3255.	4012.	3255.	2498.	3255.	2498.	3255.	3255.	2498.	3255.

Total dollars for all years 31040.

0611102 REPAIR

	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Occurrences	1.0	2.0	1.0	.0	1.0	.0	1.0	1.0	.0	1.0
Hours										
Labor	24.54	49.08	24.54	.00	24.54	.00	24.54	24.54	.00	24.54
Equipment	24.54	49.08	24.54	.00	24.54	.00	24.54	24.54	.00	24.54
Costs										
Labor	401.	802.	401.	0.	401.	0.	401.	401.	0.	401.
Materials	99.	199.	99.	0.	99.	0.	99.	99.	0.	99.
Equipment	79.	157.	79.	0.	79.	0.	79.	79.	0.	79.
Totals	579.	1158.	579.	0.	579.	0.	579.	579.	0.	579.

Total dollars for all years 4632.

FIG. 7: MATERIALS AND ASSEMBLIES LIFE CYCLE DATA BASE FOR BUILDINGS: developed by US Army CERL, give LCC predictions of costs based on real world field investigations and serves as a baseline for the data base required for suggested environmental framework.

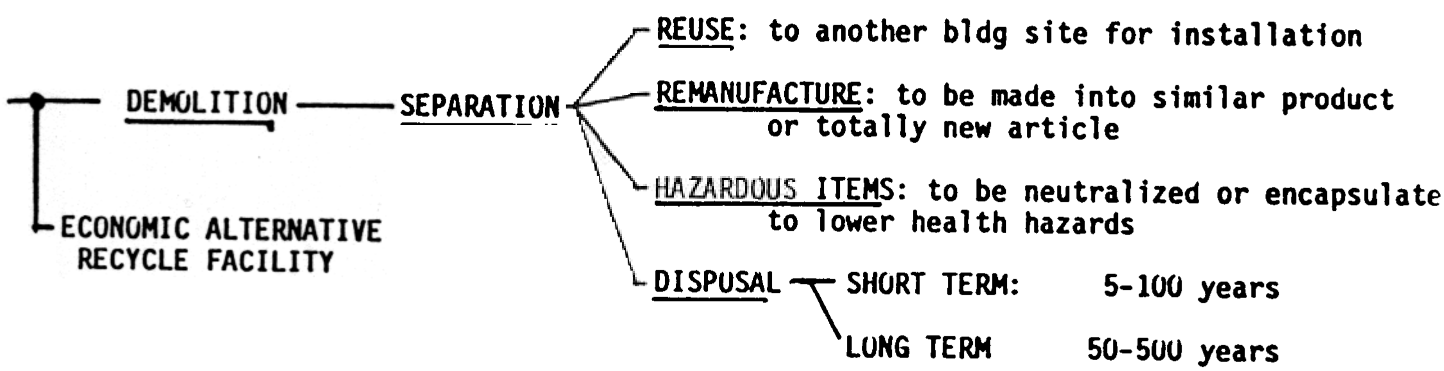


FIG. 8: SUGGESTED CONSTRUCTION MATERIALS RECYCLING ANALYSIS FORMAT, this model would need a waste materials degradation life cycle analysis to predict materials life in landfills. No such data exists now for construction materials.

performance developed for designers during the energy crisis was Building Energy Performance Standards (BEPS). The measures used were BTU/sf/yr and DOE created targets for each facility type. It is interesting to note that there was never any link between Stein's early work on embodied energy in building materials and BEPS, seemingly a natural linkage to be developed. Even using the LCC materials factors developed by CERL does not focus enough on environment, since the energy numbers are mixed in with operations and maintenance costs for the occupancy life cycle.

Most of the studies for facility life cycle analysis are done based upon a specified occupancy time. Although facilities can last for hundreds of years, it is the decision of most agencies to do the ROI studies over the life cycle of twenty-five years. This is reasonable since functional use and many parameters change in that time duration. However, the linkage to the functional use of the building and its materials design parameters is not necessarily made in relationship to environmental impacts during the building occupancy. Furthermore, if we review the environmental module which we are using at each stage of the material life cycle, we will note that we have little information which gives us an indication that the environment might actually be better because of the constructed facility.

This implies an assumption that all construction is degradation, but this may not be true. With further knowledge of eco system development of various habitation parameters, one may make an environment better than it was in the beginning. For instance, reclamation of desert areas for food production is a good example of environmental management which destroys the original environment but improves habitability of the area and could, in fact, improve human habitation. The question becomes one of the design of a new environment and the value it would place on the empty Sahara desert.

Finally, at some point in time a building will become non-productive or non-functional. Before disposal actions should be taken for an overall building one might even consider economic recycling the entire building to another functional use. This is the logic in involving a twenty-five year life cycle in which the basic shell of the facility with its associated mechanical systems may in fact be rennovated to extend the life cycle for another time period. Because of the cost of disposal actions of building components, it is apparent that this may be better than considering either recycling and disposal of building components.

5. **Disposal Actions:** Given the need to demolish a building for whatever purpose, there is a great deal of construction material which must be disposed of. Until recently, landfills would accept this material without any question, and piles of brick, concrete block, plumbing supplies, etc. were disposed of with impunity. However, the rising cost of disposal actions for almost anything has created a need to review the sheer volume of material in any building compared to the available space in landfills. One quickly perceives that building disposal by volume and mass creates serious landfill problems, i.e. a ten story building with the sheer mass of concrete and brick, becomes a major landfill volume user. As landfills become more aware of the cost of the volume of this material, the building disposal costs may become greater than their possible recycling and reuse.

Furthermore, the distruction of a particular building can be treated in two ways. It can either be demolished entirely with explosives, or it can be stripped of valuable material and hazardous waste before destruction. At the present time, it is usually the owner which makes the "least cost" choice for the disposal of the facility. However, it becomes apparent that further investigation of disposal and separation of materials could provide better benefits to recycling building components, and eventually may be required legally.

The disposal of certain components within the buildings becomes a serious problem in terms of hazardous waste. Asbestos fibers certainly are one area which is most concern at the moment.[13] Other disposal problems might be plastics, electrical wiring, and insulation fibers for buildings constructed within the last twenty years. Although this problem will not be viewed for another forth to fifty years in the social context, it is certain that the costs for safe disposal of the items must be borne by the society at that point in time. It is also apparent if one knew the costs of asbestos disposal with its health hazards at the time of building specification development, no one would have used asbestos for a building material and the question of long term health effects would not have come up.

For years, the question of construction debris, both from assembly and demolition, has not been well addressed, under the assumption of unlimited space in landfills. In the early seventies, a CERL study[14] looked at the problem in some depth, with some final recommendations to the sponsor, but little has been done since. The content of this study needs to be expanded to 1) track the paths and lives of various materials, 2) provide a volume analysis that relates to economic costs, and 3) provide an economic trade-off model that links reasonable choices to disposal and recycling with economic incentives for building reuse.

Therefore, the question of a disposal of building components and materials becomes a very delicate one in which the amount of energy input into the construction of the facility may in fact equal the energy required to demolish and dispose of the building. The impacts at this point in time also require evaluation; environmental impacts in terms of health, environmental degradation and the life cycle of the hazardous waste dump itself. In conclusion, one must look at the overall life cycle of the public areas around a dump and determine their value for the separation of the material to the society. In many ways the constructive reuse of a building may be a best option when all of these costs are defined.

6. Recycling Building Components: Building construction components range widely in the nature of their materials and in the ability of industry to recycle certain components. At the present time, we are recycling construction materials that were created twenty-five years ago and very little is able to be recycled economically. Old boilers are sold for scrap steel and represent a good recycling option when reprocessed with virgin material. Alternately flourescent lightbulbs are simply sent to the landfill and their broken glass component with the flourescent powder represents a hazardous cost which no one is accounting for at the present time. The cost of recycling salvagable architectural components for real dollars is an industry which is already developed, but the future sheer volume of concrete block which must go into landfills may represent a hidden cost which society is not taking into account at the present time.

Recycling of used building components is very difficult. Since the building lasts for 25-100 years, most of the components have outlived their functionally useful lives, i.e. boilers, control systems, mechanical equipment. The only parts that have a chance at recycling are the heavy mass and volume items like masonry and concrete and steel. In most cases, the labor involved in material separation is extensive and cost prohibitive. However, the sheer volume of mass in a landfill should make us consider other ways of recycling components. Can masonry and concrete be reground up to become part of the aggregate for new buildings, just as top layer asphalt is recycled in road repaving? Can retrieved steel effectively be recycled from a structure, as the sheer mass of metal represents an untapped resource? Finally, can one incorporate designs that promote recycling 50 years in the future? For all of the concern in landfill space restrictions, no one seems to notice that building materials do not biodegrade.

An extreme example of recycling costs which have affected a certain industry are the disposal or irradiated materials from nuclear power plants. Certain of these materials must reside in a protected landfill for a period of time equivalent to their radiation decay life cycle. The cost of protecting these materials and preventing health hazards is extreme and represents a recycling cost which the entire society and utility industry pay for. It is a cost that must be amortized by society over the 10-40,000 years, an extreme life cycle.

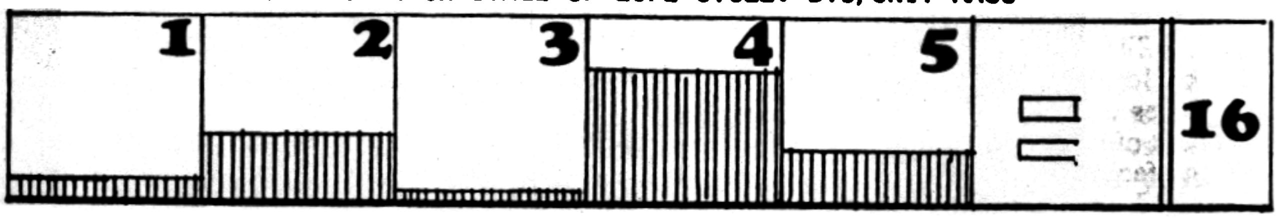
A means of evaluating the recycling component of the building construction scenario is shown in Figure 8.

FIG. 9: CONCEPTUAL PRINTOUT FOR DATA SHEET ON CONSTRUCTION MATERIAL WITH INFORMATION FOR EVALUATION FOR SELECTION

The intent is that the following information would aid the designer in making ecologically appropriate choices at the early design stages, if provided in the mfg.s catalogues or in a central data base. This data could then be included in appropriate sections of the CSI specifications to inform the contractor on product sources, assembly rationale, and disposal actions. The designer can immediately see the comparative effect of his selection on energy use and environmental impact throughout the system. The computer would automatically select "alternates", but the final judgement would still the the designer's.

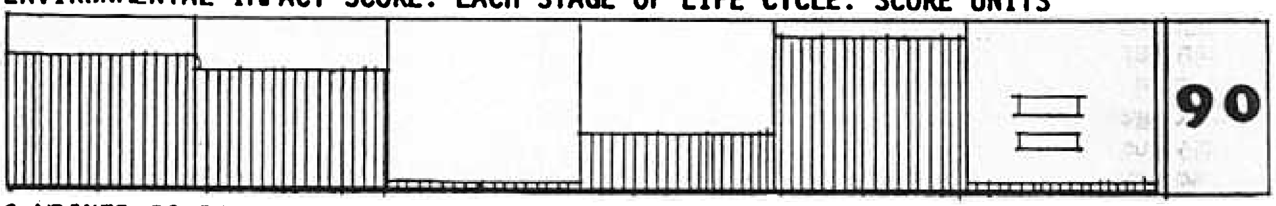
MATERIALS SELECTION DATA SHEET

ENERGY CONSUMPTION: FOR EACH STAGE OF LIFE CYCLE: BTU/UNIT MASS



LIFE CYCLE DATA:FUNCTIONAL USE

ENVIRONMENTAL IMPACT SCORE: EACH STAGE OF LIFE CYCLE: SCORE UNITS



COMBINED SCORE FOR BOTH PARAMETERS

PROBLEMS: HEALTH IMPACT
HAZARDOUS WASTE
RECYCLE POTENTIAL

DESIGN MITIGATION ACTIONS:

ALTERNATE MATERIALS SUBSTITUTION

BASELINE:	THIS MATERIAL	ALTERNATE:

STANDARD SCORES EMBODIED ENERGY BTU/sf/yr LANDFILL LIFE VOL./UNIT

C. DEVELOPMENT OF LINKS

The connections between the various sections of the materials life cycle for buildings are not at all clear. One certainly can trace ecological and health impacts through various stages but by looking at energy inputs and outputs to the overall life cycle one becomes much more skeptical that the parameters involved are clearly defined. For instance, how many BTUs does one put into resource recovery in order to make sure that a minimal amount of energy will be used and the material will fit a profitable recycling budget at the salvage stage of the building. The linkages between environmental modules used at each stage are also not clear. What is the social cost and benefit for material extraction of a non-renewable resource such as oil compared to the disposal cost of plastics used in buildings? In particular since they do not degrade, this becomes an extreme balancing act in which inadequate data is available.

D. DEVELOPMENT OF UNITS

All throughout this discussion we have been using BTUs/unit mass to represent energy input and extractions. We have no comparable numerical unit for environment. In many cases we use the environmental compliance laws as our baseline for evaluation, but we must recognize that these are connected to process technologies and material resource locations under which we have no control. The development of these units and the inner-relationship between them in modeling the overall tradeoffs is what is required.

The question of scoring environmental damage is more difficult since many parameters and non-equivalent measures are used, such as ppm and ecosystem balances, for which there are no set values. In the early system (Ref. 10) developed by the Corps of Engineers, a categorization for environmental impacts is presented with a structure for analysis and a set of curves for indicators of the performance of various parameters. It is this type of study that will serve as the basis for developing the impact assessment for building components throughout the life cycle. The categories of terrestrial, aquatic, air, and human interface are representative of environmental quality measures. The distribution of parameter measures into a scoring model supports the logic of the lifecycles for building materials.

E. DECISION ANALYSIS

Over this entire discussion of construction materials life cycles for buildings we have been looking to an ability to make certain tradeoffs between alternative materials using data bases dealing with energy and with environmental impact. In most instances these tradeoffs are not necessarily clear. They are somewhat akin to value engineering in the construction industry. In a paper by Kibert, Roudebush, and Waller[15] one is presented with a discussion of making alternative value engineering tradeoffs from the basis of energy inputs based on the solar energy equivalence work by Odum.[16]

Although this work is excellent for the point of view of decision analysis, a larger scope and schema for evaluating BTU inputs and environmental degradation would be useful for the designer's point of view. Furthermore, as one begins to understand the costs in energy and environment for each decision node for materials specification, it would be apparent that certain policies for manufacturing industries and subsidy re-evaluations would be required. The actual cost burden for the creation of certain materials perhaps would have to be shifted from the tax base to the industry itself. Looking at materials from a decision analysis point of view, one can see that the architect and builder are definitely involved in ecological management and environmental impacts. More than any other individual group, they are in the main decision node for the overall evaluations. This node is represented by the grouping of materials specifications in the bidding process for building construction. The performance specifications for workmanship and materials also effect the overall BTU inputs.

Based on the foregoing discussion, we can surmise that there is a least cost and least impact path through the product matrix in Fig. 1. Certain measures are available to provide an empirical basis for design decision making. The probable best location for some of these results would be in the 16 divisions for material specifications for CSI formats, and some means of scoring would be helpful, particularly in the environmental impact area. The AIA Environmental Resource Guide, now in the process of development, is a step in the right direction, but perhaps could go farther in presentation and in feedback to industry. In our society, capitalistic economics is where changes are managed in the manufacturing area by cost analysis, and now, by environmental degradation. With the proper data from a LCC system such as has been described, the impact analysis could result in national policy changes.

Some of the links for data base development requiring further research are the following:

Extraction resource data that would be fair in terms of competitive dollars, and <u>at the same time include tax dollars paid to either subsidize</u> the industry, or restore damaged lands.

2 Manufacturing resource data that would include <u>efficiency data for transformation energy</u>, and also compare products in terms of environmental damage at manufacturing sites.

3 Resultant data standardized in the CSI format and in various product catalogues to <u>allow comparative tradeoffs between design choices</u>.

4 Lifecycle data for <u>efficiency of use during the building occupancy phase</u> whereby comparisons could be made, i.e. how much is fiberglass insulation worth in terms of its energy saving adjusted for its manufacture energy requirement.

5 <u>Disposal analysis that would provide an accounting method for both mass and volume, and a tradeoff</u> for economic reuse. Recycling whole buildings maybe a better capital investment than paying for landfill space.

And of course, running through all of these considerations is the lack of an environmental scoring model, even though all of the parameters may be available, they are not in the right format for design decision making that affects the entire life cycle of all materials in construction.

III. TECHNOLOGY TRANSFER

Based on the foregoing one can quickly see that the development of multiple data bases which would allow the management of material selections to minimize energy use and environmental impacts is feasible but very, very complicated. The development of this data base and decision analysis tool, however, could be inter-linked with AIA and MasterSpec Specification Guides and certainly documented with ASTM standards. A possible format for this is shown in Figure 9. By inspection one quickly can see that decision analysis would be quite possible in this arena and reference to overall cost impacts would not only take into account initial costs, but would track the entire life cycle cost over the material life cycle from resource extraction to disposal and recovery. Policy makers using this data base would be able to see construction industry parameters displayed in terms of their true social and economic costs and certainly their real environmental impacts nationwide.

This paper suggests a framework for categorizing a life cycle construction product chain, but some focus is needed on the technology transfer issue to make the alternatives work. One method of information dissemination is data on a CD-ROM disk, accessible in CSI sections. An overlay software program could then be developed that would "take-off" (as in estimating) the overall energy and environment score for product selections. The resulting print-out might be like a small value engineering baseline analysis whereby environmentally sound alternatives could be dispassionately evaluated and compared. The designer would still make specific choices based on function and aesthetics, but new criteria would allow a better overall balance. Each material choice also represents employment and industrial growth, and these parameters could be embedded in the data.

IV. SUMMARY

The basic problem is that there has not been a long-term, ecological, comprehensive look at the possibilities for material usage, recycling, or legal liabilities associated with the construction industry. Furthermore the design professions have not looked at construction waste as a "design problem" in itself, with the selection of materials designed to mitigate their impact on upon the environment. This problem needs further investigation in order determine the scope, volume and cost of setting up a design analysis approach for recycling and analyzing construction waste. It is clear that this problem exists from product inception to product demolition.

When a new construction product is created, the materials used in it should be designed in such a way that they not only weather well for the life of the physical facility, but also they provide an environmentally safe means of disposal at the end of their service life. Obviously this becomes a design, construction and disposable sequence of actions which must be orchestrated together to mitigate the impact on the environment.

It is suggested that the concept framework exists for an environmental impact minimization guide for construction processes and demolition waste could be developed based upon this methodology. This would allow an overall minimization of the impact on the environment by the design process calculated from a life cycle point of view. The application of a "green engineering" decision system could enlarge the way in which the construction industry develops guide specifications, and environmentally expand the nature of its contracting "boiler plate" for AE services.

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