# Life-Cycle Assessment of Technological Processes

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**ABSTRACT** : "Pollution prevention" is an important and appropriate part of effort to minimize the environmental impacts of industrial processes, but it is only a part. Even more important is to assess the environmental characteristics of processes across all stages of their lives. This paper presents a formalism for evaluating the environmental implications of processes at each life stage(a procedure termed "life-cycle assessment").

## Process Environment Assessment

Assessing the environmental impacts of process begins with the construction of flow diagram like those of Fig. 1. The usual aim in pollution prevention is to minimize the flow of process chemicals out of the process by such step as monitoring concentrations more closely, avoiding leaks, and minimizing dragout(i.e., unintended loss of chemical onto products). Following minimization, one tries to optimize the chemical output flows in the direction of reuse by the residue generator or someone else. Even better is to renew the process residues, say by filtration, addition or concentration, and recycle them back into the process chemical stream. The degree to which these efforts are successful is measured by the amount of remaining residues that must be discarded. Energy use is assessed similarly. First, the amount of energy used is minimized. Second the amount lost as heat or in form is reduced as far as possible.

Once one goes beyond the stage of process operation to consider other life stages, assessing the environmental implications of a process is much less prescribed. How should an environmental analysis of the entire life cycle of a process be performed?

## Process Life Cycle Stages

Five life cycle stages can be identified for industrial processes. Process life stages have three epochs (Fig. 2): resource provisioning and process implementation occur simultaneously, primary process operation and complementary process operation occur simultaneously as well, and recycling and disposal is the end-of-life stage. The characteristic of the life stages are described below.

### Resource Provisioning

An initial stage in the life cycle of any process id the provisioning of the materials used to produce the consumable resources used throughout the life of the product being assessed. One consideration is the source of the materials. In many cases, the materials will be extracted from their natural reservoir. Recycled materials are nearly always preferable to virgin materials where they meet process requirements, however, because they (1) avoid the environmental disruption that virgin material extraction involves, (2) generally require less energy in recycling than would be required for virgin material extraction, and (3) avoid landfilling or other disposal of the material being recycled. In addition, the recycling of materials often produces less solid, liquid, or gaseous residues than do virgin materials extractions. The second consideration is the methods used to prepare the materials for use in

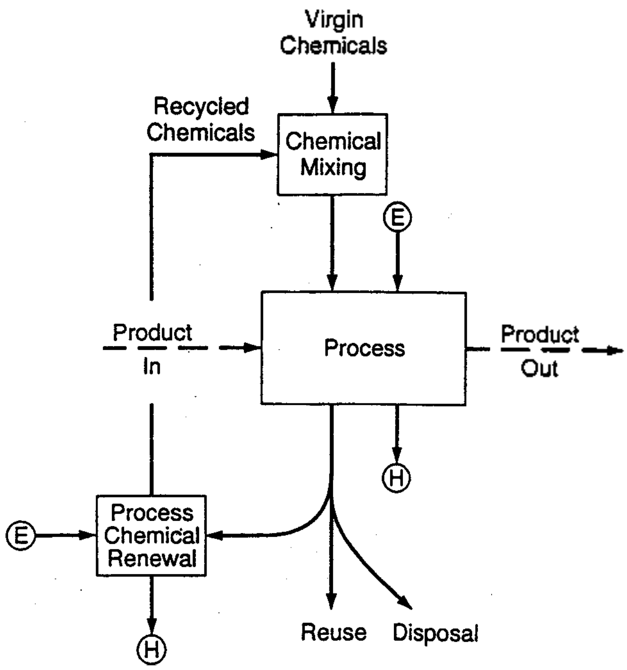


Figure 1. Representation of flows of materials and for an industrial process(solid lines) and the product being manufactured by that process(dashed lines). A circled E indicates energy input, a circled H indicates heat output. Process materials enter from the top and waste products leave from the bottom.

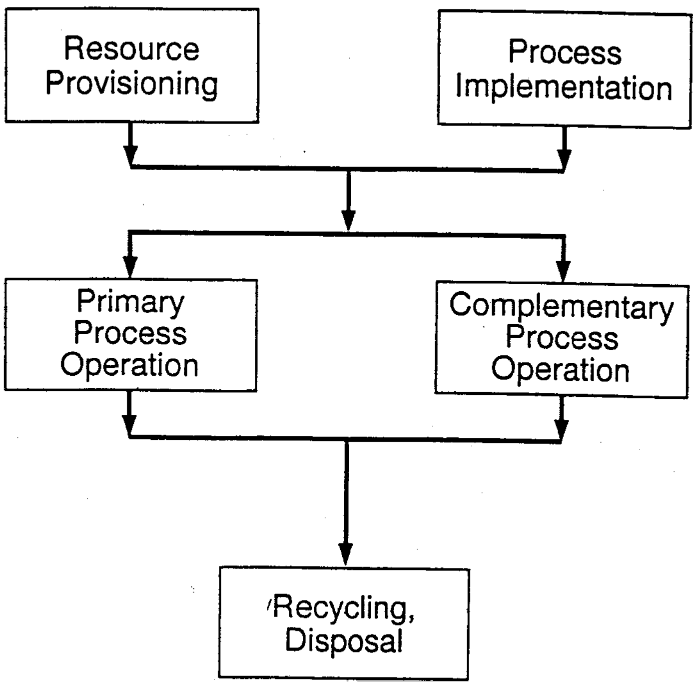


Figure 2. The life-cycle stages of a process

the process. Regardless of the source of a metal sheet to be formed into a component, for example, the forming and cleaning of the sheet and the packaging of the component should be done in an environmentally responsible manner. Supplier operations are thus a topic for evaluation as the process is being developed and, later, as it is being used.

#### Process Implementation

The other initial life stage is process implementation, which treat the environmental impacts that result from the activities necessary to implement the process. These principally involve the manufacture and installation of the process equipment and other resource that are required. As a consequence, this topic has a strong commonality with the considerations used in evaluating a product.

#### Primary Process Operation

A process should be designed to be environmentally responsible while it is in operation. Such a process would ideally limit or eliminate the use of toxic materials, minimize the amount of energy required, avoid or minimize the generation of solid, liquid, or gaseous residues, and ensure that any residues that are produced can be used elsewhere in the economy. Effort should be directed toward designing processes whose secondary products are salable to others or usable in other processes within the same facility. In particular, the generation of residues whose toxicity renders their recycling or disposal difficult should be avoided. Since successful processes can become widespread throughout a manufacturing sector, they should be designed to be environmentally responsible under a variety of conditions.

#### Complementary Process Operation

Most manufacturing processes form symbiotic relationships in which each assumes and depends upon the existence of others. Thus a comprehensive process evaluation needs to consider not only the environmental attributes of the process itself, but also those of the complementary processes that precede and follow. In the manufacture of an integrated microcircuit, deposition of materials in followed by etching, then by cleaning, and so on. Similarly, a welding process generally required a preceding metal cleaning step, which traditionally required the use of ozone-depleting chlorofluorocarbons. A soldering process generally required a post-cleaning to remove the corrosive solder flux. This step also traditionally required the use of chlorofluorocarbons. Changes in any element of this system - flux, solder, or solvent - usually required changes to the others as well if the process is to continue to perform satisfactorily. The responsible process designer will consider to what extent his process imposes environmentally difficult requirements for complementary processes, both their implementation and their operation.

#### Recycling, Disposal

All process equipment will eventually become obsolete, and equipment must therefore be designed to optimize disassembly and reuse, either of modules (the preferable option) or materials. In this sense, process equipment is subject to the same considerations and recommended activities that apply to any product - use of quick-disconnect hardware, identification marking of plastics, and so on. Many of these design decision are made by the corporation actually manufacturing the process equipment, but the process designer can control or frustrate many environmentally responsible equipment recycling actions by his or her choice of features or constraints on the original process design.

## The Rating Matrix

Industrial processes can be evaluated by streamlined life-cycle assessment matrix techniques[1]. The approach needs to encompass all stages of product life-cycles and all relevant environmental concerns, and be simple enough to permit relatively quick and inexpensive assessments to be made. An assessment system used successfully within Lucent Technologies and elsewhere feature a 5×5 matrix, one dimension of which is life cycle stage and the other of which is environmental concern(Fig. 3).

In arriving at an individual matrix element assessment, or in offering advice to designers seeking to improve the rating a particular matrix element, the assessor can refer for guidance to underlying checklists and protocols[2,3].

quantitative as possible, provided quantitation can be done quickly, but much can be done with qualitative data and th e analyst should not get bogged down in attempting to precisely quantify everything.

Once the data are assembled, a checklist is used in making matrix element assessments.

As before, the goal is to effect improvements, not to get mired in the quicksand of attempting to

| Life stage | Environmental Stress | | | | |
|---|---|---|---|---|---|
| | Material Selection | Energy Use | Solid Residues | Liquid Residues | Gaseous Residues |
| Resource Provisioning | | | | | |
| Process Implementation | | | | | |
| Primary Process Operation | | | | | |
| Complementary Process Operation | | | | | |
| Recycle, Disposal | | | | | |

Figure 3. The Environmentally-Responsible Process Matrix

Thus, the assessor studies the product design, manufacture, packaging, in-use environment, and likely disposal scenario and assigns to each element of the matrix an integer rating from 0 (highest impact, a very negative evaluation) to 4 (lowest impact an exemplary evaluation). appropriate checklist, and other information. The is purposely qualitative and utilitarian.

## The Approach to Process Analysis

Process analysis begins with data gathering. The focus is in three areas: the process itself, the equipment used in the process (including its manufacture, packaging, shipping and installation, if appropriate) and any complementary processes in involved (including their manufacture, packaging, shipping, and installation, if appropriate). The information should be as

do a perfect job of matrix element evaluation. A list of prioritized recommendations should then generated.

### The Process Itself

The analysis of a process begins with the study the actual operation that the process performs. Almost certainly, the process required energy. Where is the energy source. and can less energy or a more benign source of energy be used? Often the process required chemicals(an example is etching of metal). If so, what are the chemicals used, and are they toxic to humans, other biological species, or ecosystems? Are the chemicals from virgin source or from recycling streams?

Data are also required on output streams. What are the chemical by-products of the process, if any? (Note that by-product production can occur without an input chemical stream, since the by-product may be derived from the incoming component, as in turning from lathe operation.) If energy is consumed, it is very likely that heat is given off. Is the utility of the heat captured in any way and reused, say to heat nearby offices? If heat is not reused, is the process well insulated so that little heat is lost?

The mechanical and geographical arrangements of the processes can also be a useful item to review. Is the process located in proximity to other processes, or to flows of incoming or outgoing components, so as to minimize transport requirements? If a substantial by-product stream is generated, is there a nearby process that can receive and use it ( either within the corporation or in another nearby corporation)?

The information derived from answering these questions permits the analyst to complete rows one and three of the process matrix.

### The Process Equipment

Process equipment should be analyzed as through one were analyzing a product. (It is, of course, the product of the equipment manufacture, and the purchaser of the equipment acquires the equipment's environmental attributes, good and bad.) Working with the equipment manufacturer, one should study the materials used to manufacture the equipment, the methods by which the equipment was assembled, equipment modularity, the ease with which the equipment can be disassembled, and the degree to which the materials from which it is made are identified. Most process equipment is made from steel. Depending on the process, especially outside the generally painted on exterior surfaces. Some process equipment, especially outside the heavy machinery industries, includes or is made entirely of plastic. Computer control and the associated electronics components are common. Surface coatings, if used, should ideally be designed for ready removal and recovery, and the welding and bonding of dissimilar materials should be avoided.

If the process is being installed, or soon will be, examine the techniques and materials used for packaging, shipping, and installing the equipment.

Energy use is an important attribute of a product made to be used in a manufacturing process. Any component that draws electrical current should be designed for partial or complete shutdown when not in active use. Motors should generally be the variable-speed, load-controlled type.

The information derived from answering these questions permits the analyst to complete rows two five of the process matrix. If the process is not already in place, but rather is being designed or will soon be installed, the analyst will have a particularly complete picture of the row information.

### Complementary Process

Most processes precede and/or follow other processes. Examine whether the process that you are assessing requires that a preceding or subsequent process be of a particular type or use a particular chemical. If the complementary processes are thus defined, are such processes themselves environmentally responsible? If not, can they be modified to improve their characteristics?

If any of several complementary processes can be used, have the designers chosen ones that are environmentally responsible? If not, can alternatives be suggested?

The information derived from answering these questions permits the analyst to complete row four of the process matrix.

## Guideline for Process Assessments

Comprehensive life-cycle assessments of industrial processes are rare in the technical literature, pertly because relatively few have thus far been performed, partly because the information often is proprietary. One example that can be studied, however, is callahan's LCA analysis of the tradeoffs between vapor degreasing and aqueous cleaning[4]. in which he finds that the added energy required by aqueous cleaning is at least partially offset by the produce the hydrochloro fluorocarbon (HCFC) molecule used for vapor degreasing, and by the global environmental impacts of HCFCs.

In a more general sense, it is useful to present a brief discussion of some of the items one should look for at each process life stage, as given below. These lists have been constructed in part from information contained in other relevant publications[5-9].

**Resource Provisioning**

Process chemicals may be procured either from virgin materials sources or from interval or external recycling streams. The latter are much preferred.

Environmentally-responsible corporations should ideal only with environmentally-responsible supplier. Environmental performance surveys of suppliers are no more intrusive than are the supplier surveys commonly done to assess dependability of product delivery and financial stability; all should be carried out routinely.

Much of the industrial waste disposed of by corporation consists of packaging and other residues that are externally purchased, not internally generated. Supplier negotiations are required to tailor and minimize incoming material that will not leave the process as a part of salable product.

**Process implementation**

It is appropriate to determine what fraction of material in process hardware (pumps, tanks, conveyer belt, etc.) was made from recycled materials streams, and to negotiate with suppliers to increase that fraction.

Process designs should minimize the volume of residues that are produced, particularly if the residues require special handling.

Designs should minimize the use of energy by the process equipment. Attention to energy budgeting in clean rooms and the specification of energy-efficient motors are examples of the approaches that can be taken.

Hardware for recycling the chemical that are used should be designed into every new industrial process.

**Primary Process Operation**

The use of hazardous chemicals should be minimized. If possible, hazardous chemicals should be generated on-site rather than being transported.

Toxic heavy metals in processes should be monitored closely, as they have the potential to be detrimental to the products being made and to require detailed remedial treatment if discarded.

Process chemicals that are suitable for use within the facility that generates them should be efficiently collected and transferred to others who can use them.

**Complementary Process Operation**

The use of energy in complementary processes such as cleaning or polishing should be carefully examined and limited as much possible.

Water use, especially use of energy-intensive deionized water, should be strongly minimized.

The use of HCFC gases, which have detrimental impacts on Earth's ozone layer, should be minimized or (even better) avoided.

**Recycling, Disposal**

Process equipment should be designed so that it si relatively easy and profitable to recycle components and materials upon obsolescence.

Process equipment should be designed so that toxic residues that could complicate the recycling of the equipment are not retained or are easily removed.

Process equipment should be designed so that modules can be replaced rather than requiring the replacement of the entire equipment package.

## Conclusions

Industrial processes play major roles in defining the environmental impacts attributable to a manufacturing operation. Those impacts occur not only while the process is in operation, but while the process itself is being constructed and installed and when the process is obsolete and the equipment reclaimed or discarded. It is imperitive that process designers and process users incorporated this broader approach into their thinking in oder to minimize the environmental interactions throughout the process life cycle, not just during the manufacturing stage.

In order to structure a consideration of the myriad aspects of industrial process environmental interactions, a formalism and matrix assessment techniques has been developed and described. Examples of environmental concerns relevant to processes used in industry were then presented. This approach will aid the process designer and manufacturing engineer in conducting operations in a manner that serve the corporation as well as the environment.

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