

A Systems Engineering Methodology for Manufacturing Waste Minimization

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Reducing waste in our manufacturing environment has become a major area of focus across the corporation. We are developing methodologies to characterize and reduce the environmental impact of our manufacturing processes. As a starting point, we have conducted waste minimization audits, which typically consisted of two steps. The first step was to gather data on energy, material, product, and waste flow and their associated costs. The second step was to develop a thorough process characterization. To pursue these activities, we interviewed process and product engineers, reviewed paper and electronic central databases, and examined the real manufacturing operation. The results of these audits highlighted the expenditure of resources and helped identify options for waste minimization activities. When exploring options for waste reduction, determining their cost-effectiveness isn't always straightforward. Modeling can be a useful tool in this regard, because it can simulate alternative processes or systems and optimize new or current processes.

Why Minimize Waste?

Issues about the disposal of hazardous and nonhazardous waste are becoming increasingly important to all corporations throughout the world. Increased public awareness and concern over the associated environmental considerations have raised everyone's level of consciousness on waste disposal issues, and have brought these issues to the forefront of many agendas.

Government Regulations. Government policy concerning waste disposal is evolving through state and federal regulations that are becoming more numerous, stringent, and complex.

The *cradle to grave* tracking—i.e., the life-cycle documentation that must be maintained for hazardous waste today—may eventually be extended to all waste. A tax on waste is a real possibility. Regulatory noncompliance can lead to penalties, fines, and even imprisonment, as well as tarnish a corporation's public image.

AT&T's Environmental Goals. With the above concerns and changing government policy in mind, AT&T has imposed stringent

environmental goals on itself that exceed current regulatory requirements and establish a proactive leadership position for the corporation. These goals include:

- Phase-out of chlorofluorocarbon (CFC) emissions
- Elimination of toxic air emissions
- Decreases in the disposal quantities of manufacturing process waste
- Increased paper recycling
- Reduced paper consumption.

Panel 1 defines acronyms and terms used in this paper.

Costs and Benefits. When considering the costs associated with waste minimization, it is important to realize that one can minimize waste and save money doing it!

Waste represents purchased material that is not incorporated in manufactured products and sold. Each year, the purchase costs of the raw material used to manufacture our products can exceed hundreds of millions of dollars. If we can save just a few percent of these costs through more environmentally efficient processes and hardware, the cost savings can be substantial. (Such processes

Panel 1. Abbreviations, Acronyms, and Terms

C_a	— cost of dumping good processing chemical
C_b	— total cost of dumping good processing chemical and restoring the concentration level; $C_b = C_{b1} + C_{b2}$
C_{b1}	— cost of dumping good processing chemical when the concentration of processing chemical is below the nominal concentration level
C_{b2}	— cost of restoring the concentration of the processing chemical
[CC]	— concentration level of the concentrate used for replenishment
CFC	— chlorofluorocarbon
[NC]	— nominal concentration
[PC]	— concentration level of the sump processing chemical before adjustment
SP	— sodium persulfate
SV	— sump volume
UC	— unit cost of the processing chemical

and hardware use less raw material and generate less waste for the same level of production.) We are not saying that the current manufacturing process is inefficient or wasteful, but that it should be reexamined from the viewpoint of waste minimization.

When analyzing costs, one must consider the total cost of waste management, as well as the more conventional cost elements such as raw materials. For example, the cost of handling waste may sometimes be many times higher than the purchase cost of the material itself. Waste disposal, tracking, and permit costs are increasing while landfills are closing. What will these costs become when the landfills have been closed?

Another cost component to consider is the question of future liability for the "environmental sins" of the past. Such liabilities associated with waste disposal currently are unknown, but environmental remediation will be expensive. (*Remediation* is the process through which contaminants and contaminated material, such as soil or water, are removed or treated to clean up an area.)

Environmentally proactive, or *green*, corporations that move beyond compliance with environmental regulations to a leadership position are likely to enjoy a marketing advantage for their products and services.

Environmental Research

With the above concerns and issues in mind, the Environmental Research Group at AT&T Bell Laboratories' Engineering Research Center (ERC) in Princeton, New Jersey, is working with other organizations within AT&T. We are trying to reduce or eliminate any adverse impact that AT&T's manufacturing operations may have on the environment. In particular, we are trying to

minimize waste in these operations.

As an operating strategy, a *Waste Management Hierarchy* has been established at the ERC to drive our environmental research activity to help meet corporate environmental goals. The elements of the Waste Management Hierarchy, ranked according to their desirability as operating strategies, are:

- Pollution prevention (most desirable option)
- Source reduction, i.e., reducing the generation of waste at the source
- Recycling
- Waste treatment
- Waste disposal (least desirable option).

The primary focus of the Environmental Research Group at the ERC is on the upper echelon, or more desirable elements, of the Waste Management Hierarchy.

Ways to Achieve Waste Minimization

To minimize waste, we must examine all our manufacturing processes and products, using a *systems engineering* approach that considers material flow and energy consumption from the production of raw materials to the reuse of materials through recycling. Based on this analysis, we will develop integrated solutions to achieve waste minimization and mitigate any adverse environmental effects of our manufacturing operations.

The above systems approach to manufacturing waste reduction is a multifaceted problem that requires a broad range of skills and disciplines. Included are all engineering disciplines, mathematics, statistics, cost accounting, and operations research. To meet the challenges of waste minimization, these skills and disciplines must be blended with process and product design and engineering, as well as with manufacturing experience.

Some of the steps required to achieve waste minimization are:

- Track inventory.
- Change processes and equipment through improved process science.
- Recycle and reuse materials.

Elements of these steps must incorporate *Design for the Environment* into all aspects of product design including packaging, fabrication, and eventual disposal—ideally through recycling and reuse.

Another element is *Design for Recycling*, which stresses ease of disassembly and the recovery of materials for reuse. We must consider the end of a product's life to

be a new beginning. It is essential that we strive for pollution prevention and source reduction in product and process design, as opposed to waste treatment and waste disposal downstream. By being environmentally proactive *today*, rather than reactive *tomorrow*, we can eliminate the potential need for environmental remediation in the future.

Additional elements of an effective waste minimization program include:

- Support and encouragement from top management
- Establishment of waste minimization committees at manufacturing locations to identify opportunities and to implement and track the waste reduction strategies
- Development of a thorough understanding of waste generation through process audits
- Periodic assessments of the waste minimization effort and tracking of metrics as a way to measure progress
- Development of a cost-allocation system for tracking the true costs of disposal and waste processing
- Transfer of the waste minimization technology and methodology within and between manufacturing locations.

Methodology Development at the Richmond Works

In applying the above approaches and techniques to achieve waste minimization, our initial focus was on the manufacture of printed-wiring boards at AT&T's Richmond Works in Virginia. We used this factory as a test vehicle and laboratory for the development of an integrated, multidisciplinary, systems engineering methodology to achieve waste minimization. Later, we would extend this methodology to other factories. In this way, we could sow the seeds of research in the manufacturing environment, while developing a deeper understanding of the real needs of our customers.

Our principal waste minimization partners at Richmond have been the Environmental Safety and Health Organization and various members of the engineering staff. At the Richmond Works, several chemical-intensive manufacturing operations and the treatment facility for waste water have been audited for chemical consumption and waste generation.

The remainder of this paper focuses on the development of a generic methodology for waste minimization. To illustrate this methodology, we give spe-

cific examples of process audits and modeling activities to achieve waste minimization at the Richmond Works.

Waste Minimization Audits

The first step in a waste minimization program is to collect information related to material consumption and waste generation. A *waste minimization audit* is a review of all processes and waste streams at a particular facility. The objectives of the audit include the generation of a detailed picture of the facility's current operations to help identify options for waste minimization. By examining the results of the audit, we can identify the options available to the facility to minimize its waste.

When conducting waste minimization audits, we consider the following questions:

- *Major Consumables*
 - What raw materials are used in the manufacturing facility?
 - What in-process materials are used?
 - Where are these materials used?
 - What are the consumption rates of these materials, and how is consumption monitored?
 - Where are the storage sites for these materials both on and off the shop floor, and what are their storage capacities (i.e., volume, weight, and area)?
 - Do these materials have special handling requirements? If so, what are they?
 - What are all the costs associated with the use of each of these materials?
- *Major Waste Streams*
 - What waste materials, by-products, and trash are generated in the manufacturing facility?
 - Where are these wastes generated?
 - What is the generation rate of these wastes and how is this generation monitored?
 - Where are the storage sites for these wastes, and what are their storage capacities (i.e., volume, weight, and area)?
 - Are there special handling requirements for these wastes? If so, what are they?
 - What are all the costs associated with the disposal of these wastes, including costs of future liability?

Information to answer these questions can come from many sources, including facility design information, hazardous waste manifests, permits and permit applications, production information, safety data sheets for materials, production schedules, and accounting reports.

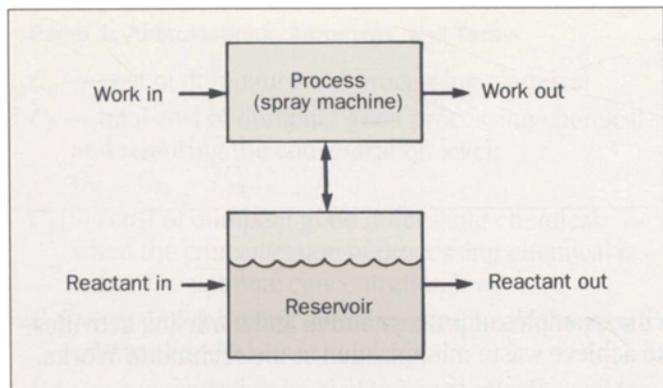


Figure 1. Process with chemical feed and bleed. A reactant dissolved in a solvent is directed onto work pieces and reacts chemically with the surface it wets. Fresh process fluid is fed into the reservoir to replenish the reactant. Fluid must be bled from the reservoir to keep the volume constant and the concentration of reaction products below specified limits.

Also useful are product and waste flow diagrams and material balances. Ultimately, the auditing process should identify waste minimization options that can be the subject of formal feasibility studies.

Value of Modeling to Minimize Waste

We have used both cost and process modeling to analyze waste generation at the Richmond Works. Process modeling and simulation are useful tools for designing and optimizing processes to minimize the consumption of reactants and to meet other process constraints. Process modeling permits the effective design of process control systems.

Benefits of Modeling. Deterministic or probabilistic models can be used to study how real systems respond to changing conditions. The type of model that can be created depends on the modeler's level of knowledge about a particular system, the degree of complexity of the system, and the skill of the modeler.

Waste minimization programs benefit from modeling in many ways. For example, models help us:

- Predict the effect of a change in environment, operating procedure, or physical system.
- Sell a new procedure or system to management.
- Train personnel to operate a new system.
- Optimize a system's use of expensive consumables.
- Develop an estimate of capacity or throughput.
- Provide a basis for the design of effective process control systems.

In the sections that follow, we discuss several modeling efforts that we have undertaken to realize these benefits.

Chemical Concentration Control. Our first example is a process model created to show how the concentrations of chemicals can be controlled.

Figure 1 illustrates a class of chemical processes in which a reactant that is dissolved in a solvent, such as water, is directed onto work pieces and reacts chemically with all or part of the surface that it wets. Sometimes, the reaction product remains attached to the surface; more often, it separates and dissolves in the process fluid. Examples of such processes are microetching of copper or developing a photoresist.

In these processes, fresh process fluid must be fed in to replenish the reactant. We must also bleed fluid from the reservoir to maintain a constant volume and keep the concentration of the reaction products below specified limits.

To construct mathematical models of these *feed-and-bleed* processes, we can write and solve differential equations of the general form:

$$[\text{Rate of Accumulation}] = [\text{Rate In}] - [\text{Rate Out}] - [\text{Rate of Consumption}] \quad (1)$$

which shows the conservation of mass. Solving such equations yields expressions for concentrations of the reactant and the reaction product versus time for specified production rates, reservoir volumes, operating temperatures, and other relevant parameters.

We have written programs to simulate feed-and-bleed processes. To select jobs for processing, we use a random number generator. Each job consists of a specified number of parts from which a specific fraction of exposed material must be completely or partially removed.

For example, suppose we want to remove 1.3 μm (micrometers) of copper from portions of a printed-circuit panel's surfaces that are not protected by a solder mask. (A *panel* can consist of several separate printed-wiring boards; typically, two to four boards.) The fraction, f , of exposed copper ranges from 0.10 to 0.25, and the lot sizes range from 7 to 60 pieces. Throughput is 180 panels per hour with 0.56 m^2 (square meters) of total surface per panel.

Panels pass through *modules* (i.e., processes) in tandem on a belt. There is a module for cleaning and a module for rinsing before the etching module. To etch the copper, we will use sodium persulfate (SP) that is maintained at the process temperature and at a persulfate ion concentration of 145 g/L (grams per liter), while contained in a 416L (liter) reservoir or *sump*. We expect that each panel will drag in 0.10L of rinse water per

square meter of panel surface from the preceding module and drag out process fluid at the same rate. To replenish the SP, we will add concentrate (i.e., 290 g/L persulfate ion) at 110 percent of the rate needed to hold the persulfate ion concentration in the sump at a set point of 145 g/L.

Suppose we start with a concentration of 159 g/L persulfate ion in the sump. What will the concentration of SP and copper be over time? Will the specified feed rate be enough to maintain the cupric ion concentration below a maximum allowable level of 15 g/L? What fraction of the SP will actually be used to etch the copper?

Part of the answer appears in Figure 2, where we plot the concentrations of persulfate ion and cupric ion over time for the first 300 minutes of operation. Note that the persulfate ion concentration drops to the set point concentration after 168 minutes, at which time the feed starts. The feed is off from time equals 236 to 241 min (minutes) while 15 panels ($f = 0.25$) are running, and from time equals 289 to 300 min while 35 panels ($f = 0.15$) are running.

The cupric ion concentration will eventually reach a steady state at 6.8 g/L, which is acceptable. Only 13 percent of the SP will be used to etch copper. The rest will be dragged out on the panels or exit in the stream that is bled to maintain constant volume in the sump.

If the feed-and-bleed rate were reduced to 0.20 L/min (liters per minute), then the cupric ion concentration at steady state would be 15 g/L, which is the maximum allowable level. This rate would permit use of 23 percent of the SP that is fed. However, the SP would have to be fed in as the pure solid and be dissolved without clogging the spray nozzles.

Costs of Concentration Control. Our second example is a probabilistic model developed to determine the costs of controlling the chemical concentration of a process fluid.

Many manufacturing processes use a fluid contained in a reservoir, as illustrated in Figure 1. The process fluid could be a solvent in solution; an aqueous cleaner; or a solution of a reactant, such as SP. It often is feasible to operate in a batch mode, where the solvent or solution is replenished or replaced periodically. Product quality is maintained through effective use of control charts and replenishment strategies.

Two major requirements must be addressed:

- The concentration of reservoir reactants and products

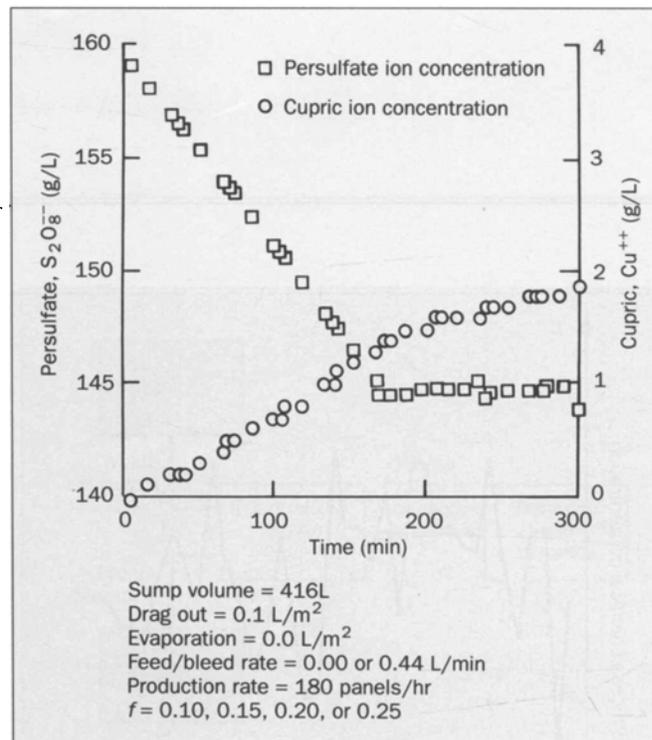


Figure 2. Models can show the benefits of concentration control. Here, we see the ion concentrations of persulfate ($S_2O_8^{2-}$) and cupric (Cu^{2+}) for the first 300 minutes of operation. After 168 minutes, the persulfate ion concentration drops to the set point concentration and the feed starts.

must be monitored to know when to bleed and when to replenish.

- The width of the operating band must be carefully set to ensure product quality yet conserve costly reactant. A case history will illustrate how these requirements apply. Figure 3a shows processing chemical concentrations over a two-week period. The data points are established for each shift through analyses of the concentrations. Each shift, the operator adjusts the concentrations according to these data.

By using the statistics (i.e., average and standard deviation) in Figure 3a, we can generate simulated concentration data for a full year. Suppose the processing chemical concentration is adjusted once per shift, 15 shifts per week for 1 year. First, we can generate several thousand, uniformly distributed, random deviations between 0.0 and 1.0. We assume that the real concentration data is normally distributed. Therefore, we generate normally distributed deviations by using the nominal average and standard deviation of the real concentration data. These data represent annualized concentration data from which we can estimate the annualized cost.

If the concentration is high, fluid is dumped from the sump and the sump is backfilled with water to lower the concentration to the nominal level. If the concentration is low, fluid again is dumped but the sump is

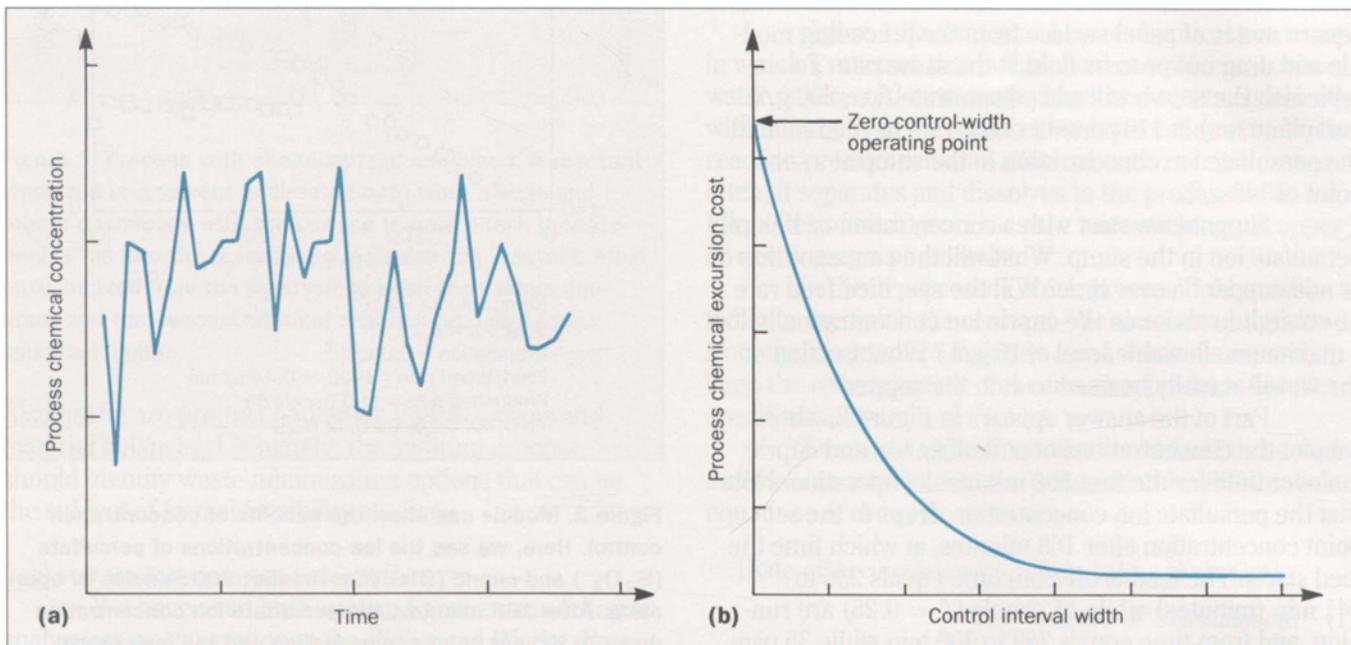


Figure 3. Models can help evaluate the cost of control options. (a) Sample chemical concentrations from a constant volume sump over a two-week period. Each shift, the concentration is adjusted based on these data points. The average and standard deviation of the data can be used to generate simulated concentration data for a full year. (b) Annualized cost of operating with a control interval of variable width. The solution is corrected whenever the actual concentration of processing chemical deviates from the nominal concentration, an expensive option.

backfilled with an SP concentrate. In either case, this concentration control policy can waste *good* chemical that could be captured and retained for backfilling purposes. Thus, it is important to monitor concentrations to know when to add fresh reactant or bleed the reservoir fluid.

By using data from a control chart, we could estimate the worst case annualized cost of this policy. Equation (2) gives the cost C_a of dumping the good processing chemical.

$$C_a = ([PC] - [NC]) \times SV \times UC \quad (2)$$

Here, $[PC]$ is the concentration level of the sump processing chemical before adjustment, $[NC]$ is the nominal concentration, SV is the sump volume, and UC is the unit

cost of the processing chemical.

The costs calculated by equation (2) assume that the active ingredient can be fully used. For example, we can extend the life of cleaning solutions by using ultrafiltration to separate contaminants. Or, we can use solvent recovery processes to reclaim organic solvents. On the other hand, solutions that contain oxidizers such as SP must be discarded when the concentration of dissolved metals has reached an upper limit. Consistent with that limitation, we can achieve maximum conservation of an oxidizer by replenishing the sump with pure solids rather than a concentrated solution.

Where the concentration of processing chemical is below the nominal concentration level, the cost C_{b1} of dumping the good chemical is given by equation (3).

$$C_{b1} = \frac{SV \times [PC] \times ([NC] - [PC]) \times UC}{[CC] - [PC]} \quad (3)$$

where $[CC]$ is the concentration level of the concentrate used for replenishment. The cost C_{b2} of adding the make-up concentration of the processing chemical is given by equation (4).

$$C_{b2} = \frac{SV \times [CC] \times ([NC] - [PC]) \times UC}{[CC] - [PC]} \quad (4)$$

The total cost C_b for this case is then given by equation (5).

$$C_b = C_{b1} + C_{b2} \quad (5)$$

Let us turn now to the second requirement (i.e., set the width of the operating band to maintain product quality and conserve reactant). What is the effect of not setting the proper width for the control chart limits? As a worst case, use the example we just gave and assume that the width of the control interval is zero. That is, whenever the actual concentration of processing chemical deviates from the nominal concentration, we correct the solution.

The annualized costs of this procedure can be calculated as before. Having done this, we find that operating with a control interval of zero width can be an expensive option, as suggested in Figure 3b. The main point here is that it pays to set the width of the control chart limits carefully to ensure product quality while conserving costly reactant.

A Model for Waste Treatment Cost. Our third example is an activity-based model to determine the cost of waste treatment.

In recent years, the burgeoning costs of managing the hazardous waste from materials processing in the United States' electronics industry have posed a formidable competitive challenge. Too often, products have been designed and manufactured with little regard to the associated costs for managing hazardous waste. Unfortunately, manufacturers frequently don't understand the relationship between particular materials processes and the incurred cost of managing the resulting hazardous waste.

Traditional accounting practices often make it impossible to allocate these costs fairly to individual products, which makes it difficult to target processes for waste minimization. These practices either subsume costs in overhead or allocate costs based on product volume. In the former case, uniform waste costs are allocated to all products regardless of the costs that individual products really incur. In the latter case, waste costs are allocated fairly only when the costs are proportional to volume. Yet, many costs not related to the volume of waste contribute significantly to the cost of the product.

In both cases, manufacturing performance suffers by inaccurately allocating waste costs and, hence, product costs. One sees the effects of this inaccuracy not only in the misallocation of important processing

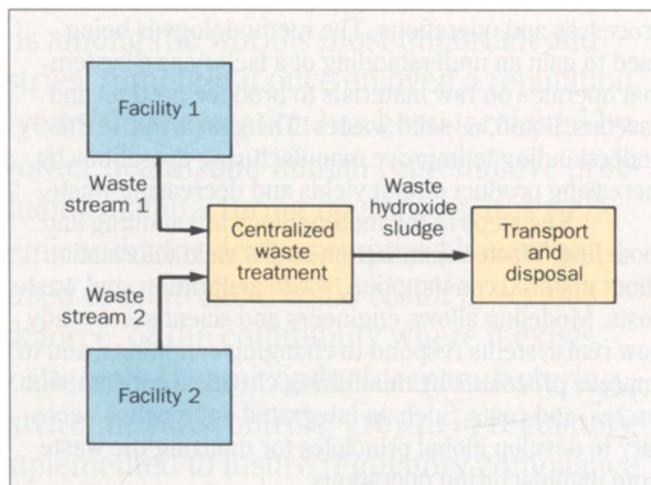


Figure 4. Facilities model for cost allocation. The two facilities generate and send hazardous, liquid wastes to a centralized, waste treatment facility. Costs of treating, transporting, and disposing of waste are charged to each facility.

resources, but even in product designs that respond to inaccurate cost information.

To demonstrate the effect of improper cost allocation, we decided to model the costs associated with the wastes generated by two different facilities within the same factory. Figure 4 depicts the structure of the model. The two facilities generate and send hazardous, liquid wastes to a centralized, waste treatment facility. The costs of the waste treatment and for transporting and disposing of the waste are charged to each facility. In the model, the charges are calculated with a traditional cost-allocation system (e.g., allocated according to relative rinse water flow) and compared to the true costs.

A major benefit of such a model is that it can show the true costs associated with different manufacturing activities. Application of this model has already shown that the true and flow-allocated costs can differ by several hundred percent. In addition, the model provides information at appropriate points in the design and manufacturing cycles for the product and process, so that the costs associated with hazardous waste materials can be properly allocated.

Summary

We are establishing a methodology for characterizing the environmental impact of manufacturing

processes and operations. The methodology is being used to gain an understanding of a factory as a system that operates on raw materials to produce product and gaseous, liquid, or solid wastes. The goal is to use this understanding to improve manufacturing operations by increasing product output yields and decreasing waste.

Key steps in the methodology are auditing and modeling. Waste minimization audits yield information about material consumption, waste generation, and waste costs. Modeling allows engineers and scientists to study how real systems respond to changing conditions, and to improve processes by minimizing chemical consumption, wastes, and costs. Such an integrated approach is necessary to develop global principles for minimizing the waste from manufacturing operations.

We began our methodology development at the Richmond Works, where we are using the printed-wiring-board factory as our laboratory. Board manufacture is chemical intensive. What we learn here can be applied to other factory operations that rely on chemical processes. We hope to extend the principles of waste minimization that we develop for process factories to assembly factories in the future.

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