Environmental Issues in Collaborative Design

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> " … sustainable development ensures that future generations have access to the social capital—human, natural and physical capital—to create a life at least equal to that of this generation."

From the 1987 report of the World Commission on Environment and Development (the Brundtland Commission)

1. Motivation

Proper diet, regular exercise and relaxation techniques are proven to have a beneficial effect on leading a healthy life [Spears, 1999]. Another aspect to living a healthy life is living in a clean environment. When adverse conditions exist in the environment—in the form of air pollution, solid pollution and liquid pollution—the impact on the quality of life can be substantial [Naar 1990], [Pal 1998], [Wenzel 1997]. The greater the quantity of pollution, the greater the adverse effect on public health. And pollution quantities are staggering:

Air Pollutants: A principal measure of air pollution is the amount of carbon dioxide (CO2) in the air. Until about 1900, the global concentration level of CO2 hovered around 280 parts per million (ppm) for nearly a millennium. There has been a drastic increase in the chemicals being released into the atmosphere in the last century. This has been due in large part to increased use of coal, fossil fuels and natural gas—20 billion tons annually. This has pushed the global level of CO2 from 280 to 360 ppm, and much of this emission comes from the United States. Increased CO2 in the atmosphere leads to global warming (as is demonstrated by scientific studies) with detrimental effects to our fragile planet. Other gases, such as CFCs (chlorofluorocarbons) emitted by a variety of household products, also add to heat entrapment and ozone-depletion, with considerable health risks to the human race.

Solid Pollutants: In the U.S., the manufacturing, mining, and farming industry generates around 5 billion tons of solid waste, with homes and businesses contributing to another 230 million tons of garbage every year [Naar 1990]. The above waste contains hazardous chemicals, such as pesticides, nuclear waste, and toxic metals. Some of these cannot be reduced to harmless products in waste management units, such as incinerators. Unless disposed of properly, these eventually find their way into our water resources and air.

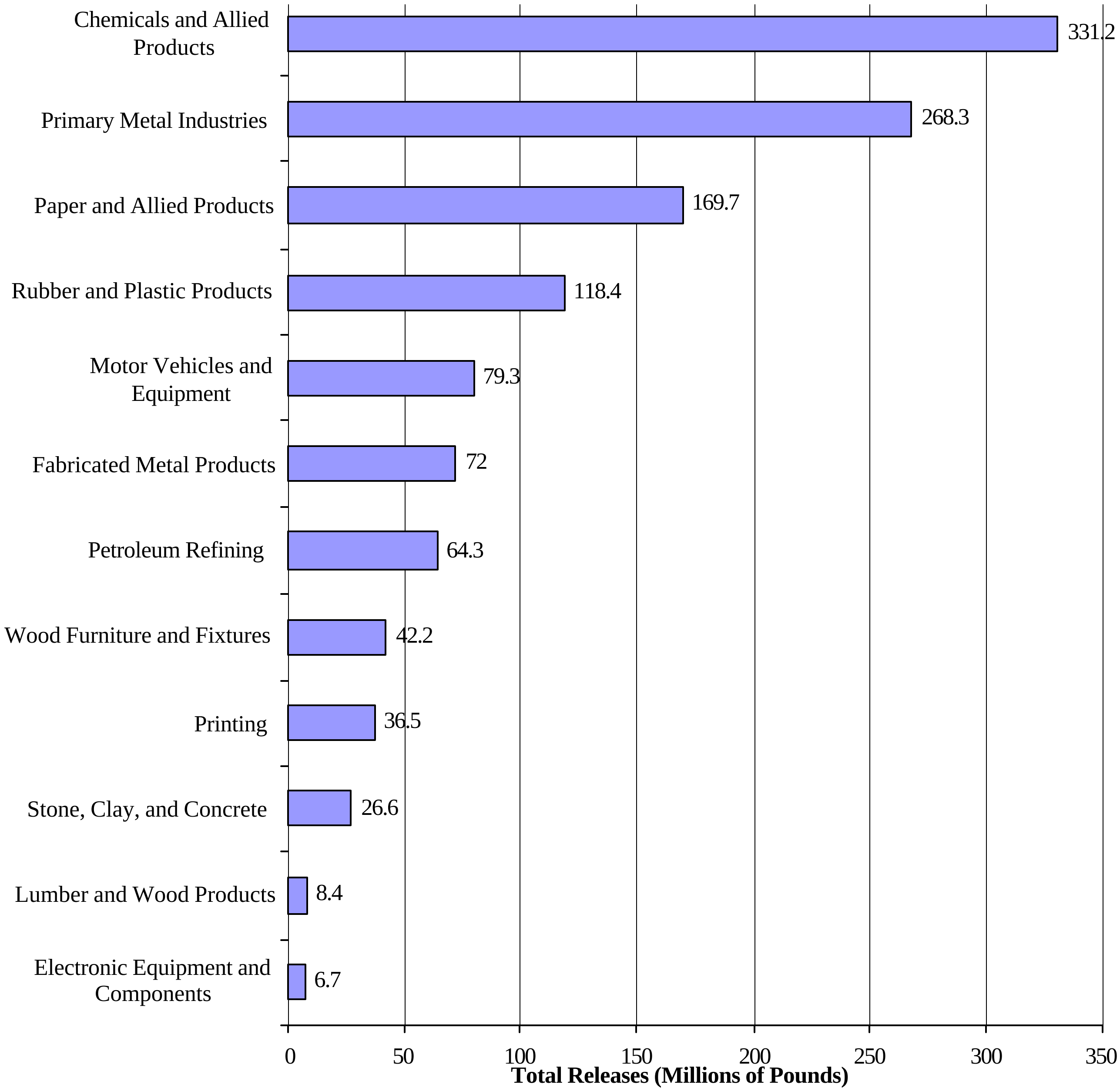
Liquid Pollutants: Liquid pollutants result as a by-product of many industrial processes, such as mining, manufacturing, and from a variety of other sources, including our homes. The U.S. produces about 700,000 tons of toxic waste every day. These include benzyl chloride (a by product from drug and perfume manufacture), chlorine, and hydrogen cyanide. Production of these is far above the quantity deemed dangerous to humans. Added to these toxic chemicals, we also spray 12 million tons of pesticide annually [Naar 1990].

There are a number of ways to reduce the amounts of pollution generated, many of which are interconnected. These include change in industry practice, economic incentives, technological development, shift in material use, change in consumer behavior and regulation. As shown in Figure 1, for example, end products (such as automobiles) produce the most toxic chemical waste among different categories of producers. One reason for this is the automobile, which, over the course of traveling 200,000-km, will consume about 21,000 kg of hydrocarbons and emit 59,000 kg of carbon dioxide [Sullivan 1998]. Clearly, one way to limit pollution is to design more fuel efficient vehicles. Another way is to develop alternative, less-polluting transportation systems.

Figure 1 also shows that the contribution from the manufacturing industry to toxic chemical releases is substantial. A large percentage of this comes from the chemicals and primary metal industries, which often provide the raw materials for consumer goods. In addition, of the 2.5 billion metric tons of materials consumed by the US in 1990, only 10 percent were recycled.

Fourtunately, there is a wealth of opportunities for design teams and manufacturers to create products that are less disruptive to the environment. To do this effectively, however, design teams need to have knowledge about environmental issues and access to environmental databases from the early conceptual design phase through manufacturing and ultimate disposition. This requires expertise that would likely come from different members of a collaborative design team. The purpose of this chapter is to explore several strategies for incorporating environmental impacts into the product life cycle and to see how collaborative techniques can be used to ultimately achieve pollution reduction in product design, manufacture and use.

This chapter is organized as follows. In the next section, we discuss factors that provide the impetus for environmentally conscious design and manufacturing. Then, we outline the various product development stages. We briefly discuss the design for recovery problem. This is followed by an architectural description of a collaborative design



framework. Finally, we discuss one component of this framework – access to various heterogeneous databases containing environmental information.

Figure 1: Annual Releases of Toxic Chemicals by the U.S. Manufacturing Industry (Source [Pal 1998])

2. Of Designing Greener Products

Green Engineering Design (or Green Design) is an approach to product and process design that reduces environmental impact without compromising a product's quality or its commercial viability. The aim is to identify, develop, and exploit new technologies that can bolster productivity while minimizing impact to the environment. Over the past decade, considerable research and effort has been put into understanding issues such as waste management and materials recovery, as they relate to products *after* they enter the waste stream [Sullivan 1998]. Attention is now being focused on the product design. The idea is to inject environmental considerations into the design process, where, the assessment of environmental impact is based on a life-cycle view of the product. This includes the product's manufacturing process, distribution, use, and final disposal. Hence, Green Design takes a *proactive* approach to environmental problems rather than a *reactive* approach, which tries to fix problems only after they occur. The notion of designing products for environmental concerns was introduced a decade ago [Navin Chandra 1990] and has since been adopted by many researchers and practitioners as part of the concurrent engineering process [Caspersen 1998, Hersch 1998]. This approaches requires that design teams perform their duties not only for specification, production and maintenance, but for disassembly, reuse, repair, materials recycling, remanufacturing and reassembly as well. This is a significant change from traditional design and manufacturing practices.

But why should designers and manufacturers change their processes and products to be green? In the US economy, a company must be profitable to be viable. If green design increases design and production cost, this may well undermine the ability to be profitable. One way to overcome this hurdle is to create products with environmental differentiation. For example, textile manufactures are willing to pay more for a certain type of dye that requires less salt for absorption into materials [Reinhardt 1999]. The reason for this that the dye ends up paying for itself by lowering processing costs that result from less salt consumed, reduced wastewater treatment and improved quality control. Two factors critical in the success of this product are finding customers willing to pay more and communicating the products environmental benefits to the textile industry.

An indirect economic reason for doing so is the rising cost of waste-disposal. In certain instances, it may be less costly to recycle than to pay for disposal [Chen 1994]. There are external factors as well that encourage green design. Environmental legislation often mandates specific processes to protect the environment. Another factor, curiously enough, is customer demand. As consumers become more environmentally conscious, their inclination for products made in an environmentally-conscious way increases. As a result, another factor is corporate image in the corresponding public perception. All these factors, primarily the economic ones, make it attractive for a company to invest in redesign, re-tooling and the establishment of recycling facilities. Specific cost-reducing concepts that encourage green design include the following:

1. Holism and Simplification. Taking an holistic view of a product, in terms of recycling and material compatibility can lead to simplification. For example, in one of our disassembly experiments [Navin Chandra 1994], we found a product to have dozens of different types of plastics. Using reverse engineering, however, we found only six different plastic specifications were needed. In retrospect, this product could have been designed with fewer types of materials. Such a simplification reduces the number of vendors used, material inventories, the different types of joining methods used and the number of assembly operations. These changes reduce cost *and* improve recyclability at the same time.

2. Remanufacture and Reuse. A product can be designed for ease of remanufacturing and reuse. Starting with materials recycling, which is the simplest form of recovery, other options include repairing the item, its disassembly to recover seprable materials, re-use of components, and remanufacture of parts. Automobile parts are classic examples of this process. Every time a part is reused, all the energy and emissions that were produced in its original manufacture and processing are partially salvaged.

3. Materials Mortgage. If a customer leases a new product every few years, and returns it to the manufacturer for recovery, then one can consider a long-term mortgage. For example, if we wanted to improve the vibration reliability of a computer, we could do this by introducing more gold on the connectors. Normally, this would undesirably increase the price of the computer. One the other hand, if we knew computers—hence the gold—would be returned, then the customer could mortgage the gold over a longer term. In this way, manufacturers can provide very high-quality products without sticker shock. With recycling, the large initial investment is spread out over several product life-times [Navin Chandra 92].

4. *Redefining markets.* By redefining its business model, a company can actually reduce overall costs by incorporating environmentally desirable activities [Reinhardt 1999]. For example, up until about 1980, Xerox had market dominance in copier equipment and was lax about cost savings and machine disposal (a nontrivial problem). When competition threatened this dominance in the 1980s, Xerox responded by retaining disposal rights to the equipment they sold. They set up an infrastructure to disassemble, remanufacture and incorporate new technology into existing machines; These were then resold at considerable profit. By 1995, Xerox estimates it was saving more that several hundred million dollars annually. More importantly, it redefined the market, forcing competitors such as Kodak, IBM, and Canon to follow suit.

The above strategies represent new ways in which products can be designed, marketed and recovered. Some other forward-looking organizations such as Dupont and Intel have already adopted some of these new strategies [Resetar 1999]. With the right kind of approach and design tools, it is possible to make environmentally compatible products that are also commercially profitable.

3. The Product Development Process

As shown in Figure 2, there are three fundamental phases in the life cycle of a product: 1) engineer; 2) use; and 3) dispose/recycle (see Figure 2). The engineering phase consists of several activities in design and manufacturing, which are described in detail by Barkmeyer [1995, 1996] and itemized below. The first four focus on design and the last four focus on manufacturing.

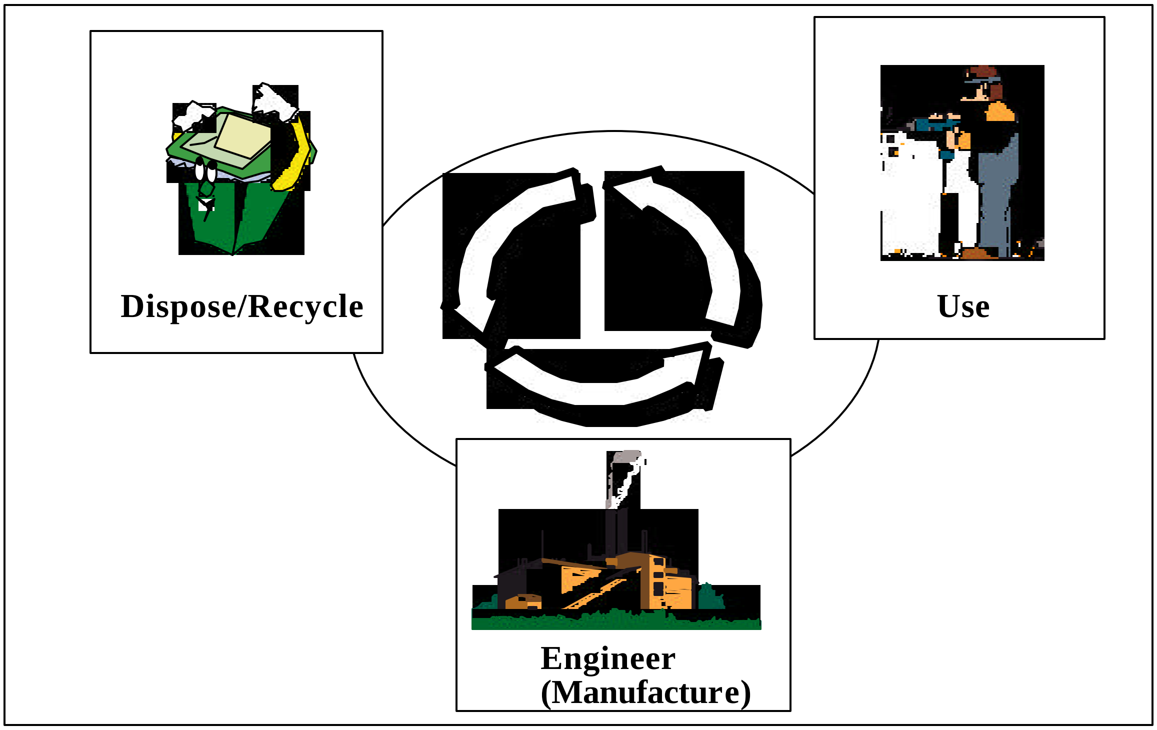


Figure 2: Fundamental Phases of a Product Life Cycle

1. **Plan products.** Depending on (potential) market needs and customer requirements, develop the idea for a product and characterize it in terms of function, target price range and relationship to existing products of the manufacturing firm. Other activities include: defining cost constraints, performance constraints, and other marketability factors; performing market analysis, cost-benefit analysis; and developing product development and marketing plans.

2. **Generate product specifications.** From the conceptual product specification, formulate an engineering specification for the product. This involves mapping the customer requirements into engineering requirements, and refining the engineering requirements in consideration of the relevant laws, regulations, product standards, and also of the existing patents in the same area. This process may involve determination of the relationship of the new product to the firm's library of existing product designs.

3. **Perform preliminary design.** Decompose the design problem into a set of component design problems and develop the specifications for each component problem. Define the integration of the components into product in a set of interface specifications and a preliminary layout model. This process is iterative, as the early phases of the component design will generate new considerations and changes. Primary results are the product layout drawing and annotations and the component design specifications. The preliminary design activity involves generation of various alternatives and evaluation of these alternatives against criteria.

4. **Produce detailed designs.** For each subsystem (or component) that is not off-the-shelf (or identical to an existing in-house design), and for the component integration, produce all specifications needed to completely describe the subsystem for manufacture. This includes drawings and geometry, materials, finish requirements, fit requirements and assembly drawings and tolerances.

5. **Engineer Manufacture of Product**. The process of making the product is defined. This includes determining the elementary stock materials and components to be acquired, the equipment, tooling and skills to be used and the details of that usage. Details include the exact sequence of setups and operations to be performed, and the complete instructions for each operation, whether by human or automated resources. For engineering purposes, every product is decomposed into a collection of component *Parts*, each of which is either a fabricated (piece) part or an assembly, including embedded parts that can be produced by rapid prototyping. Any Part, however, may be subjected to inspection and finishing processes. The final product is itself a Part — it may be a single fabricated part or a final assembly.

6. **Engineer Production System**. New or modified production facilities for the manufacture of a particular collection of Parts are designed. A "facility" may be a plant, a shop, a line, a manufacturing cell, or a group of manufacturing cells. This activity encompasses both design-from-the-walls of such a facility and reengineering of all or part of such a facility to improve the production of certain products. It includes identification of the parts, products and processes for which the production system is to be tailored, identification of the equipment to be installed or replaced, (re)design of the floor layout, and development of an implementation plan for the (re)designed production system.

7. **Produce Products.** The production facilities needed to produce the Parts according to the specifications in the process plans are developed and maintained. This involves defining the production schedules and controlling the flow of materials into and out of the production facility, scheduling, controlling and executing the production processes themselves, providing and maintaining the production equipment and the human resources involved, developing and tracking the tooling and materials.

8. **Manage Engineering Workflow.** This activity would involve the specification of engineering tasks, controls, reviews and approvals. The sequence of these engineering activities and the required resulting information objects, and their due dates, if appropriate are defined.

For complex design and manufacturing tasks, these activities typically involve thousands of personnel working in smaller, collaborative teams toward a particular subgoal. The next section expands some of the activities and details how those activities relate to the environment.

4. The Product Life Cycle and the Environment

The three basic stages of the product life cycle shown in Figure 2, can be elaborated as shown in Figure 3. Each aspect of this product life cycle—from mining the material, transporting material and goods, to disposing the product—has an impact on the environment. Identifying these impacts is important in developing green products. Our focus in this chapter is on assessing environmental impacts during the design stage. In particular, we explore pragmatic ways to deal with recovery issues (Section 6) and how to access heterogeneous databases that contain environmental data (Section 7).

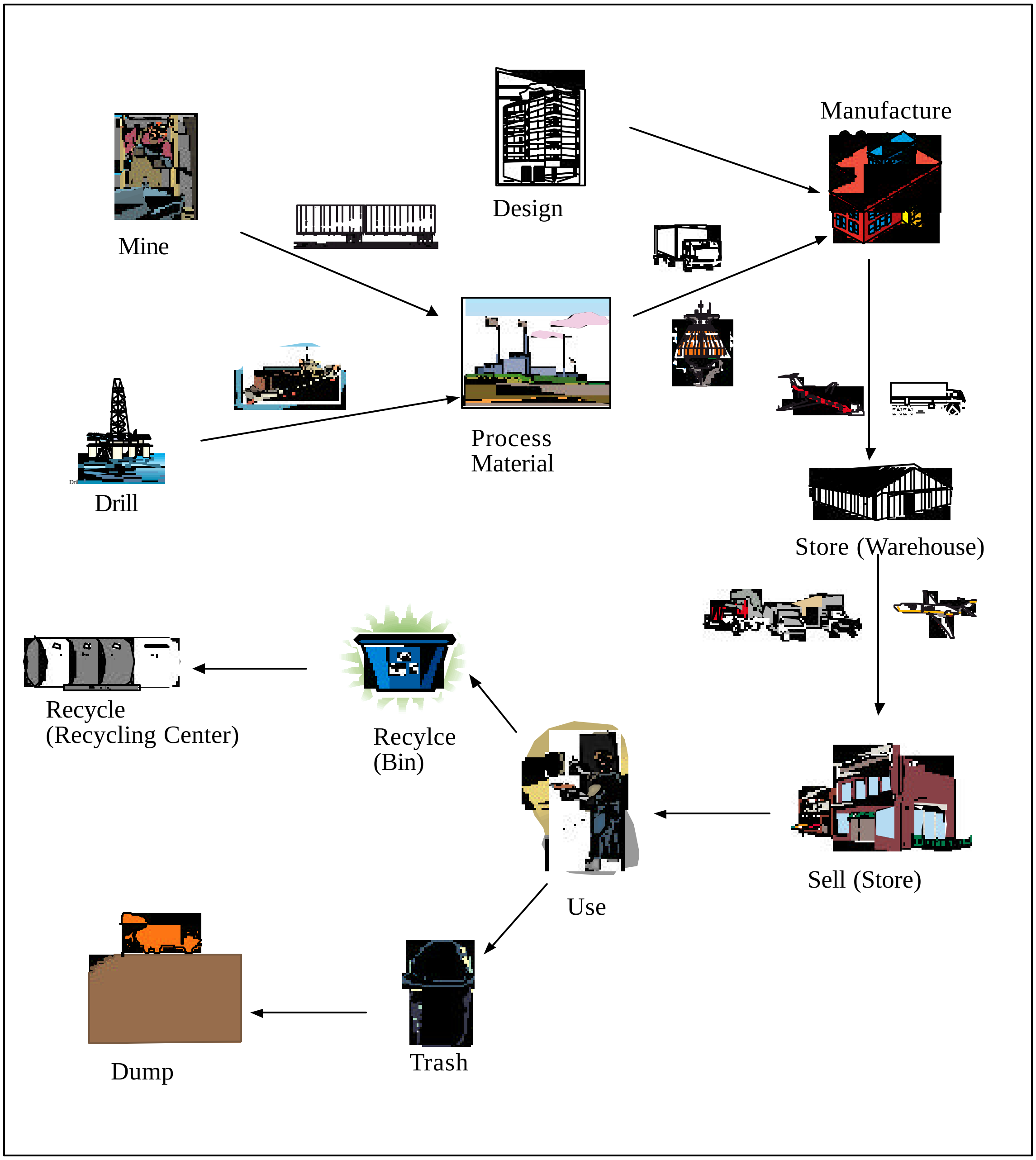


Figure 3: Product Life Cycle: From Mining to Reuse

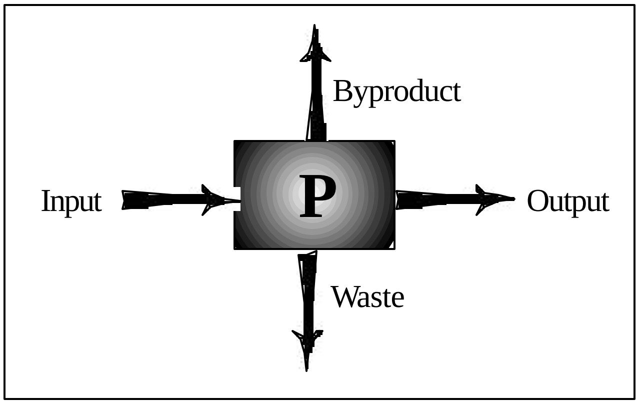


Figure 4: Process Input/Output Diagram for Products

Figure 4 depicts an input/output diagram identifying the basic activities that impact the environment. By minimizing waste, designers and manufacturers achieve one green goal; even better, would be to have waste products be fed back into input.

Consider, for example, the automobile. A life cycle inventory (LCI) study conducted by the United States Automotive Materials Partnership Life Cycle Assessment Special Topics Group (USAMP/LCA) identified over 30 materials utilized in a generic vehicle, which was based on the "generic" 1995 Intrepid/Lumina/Taurus cars [Sullivan 1998]. A few of these materials are shown in Figure 5 and a comprehensive list is provided in Table 1. The USAMP/LCA study identified reuse and materials recycling for five major stages of the product life cycle: raw materials acquisition and processing; parts and sub-assembly manufacturing; vehicle assembly; use; and disposal. An example of one process input/output diagram (for steel manufacture) is shown in Figure 7. By having many of these type diagrams for alternative materials, design teams can assess the environmental impact of each material and make it part of their design decisions, not unlike the way cost, performance and safety considerations are normally considered.

Another example–PVC manufacture—is shown in Figure 7. Note that the process input diagram includes numerical estimates per unit of the product produced, e.g., kilowatts of energy and gms of vinylchloride. The figure also shows the toxic vinylchloride as a waste product. Most manufacturers claim that it is fed back into the input, to minimize potential environmental impacts. It will be useful to generate such flows for all activities, from cradle to grave.

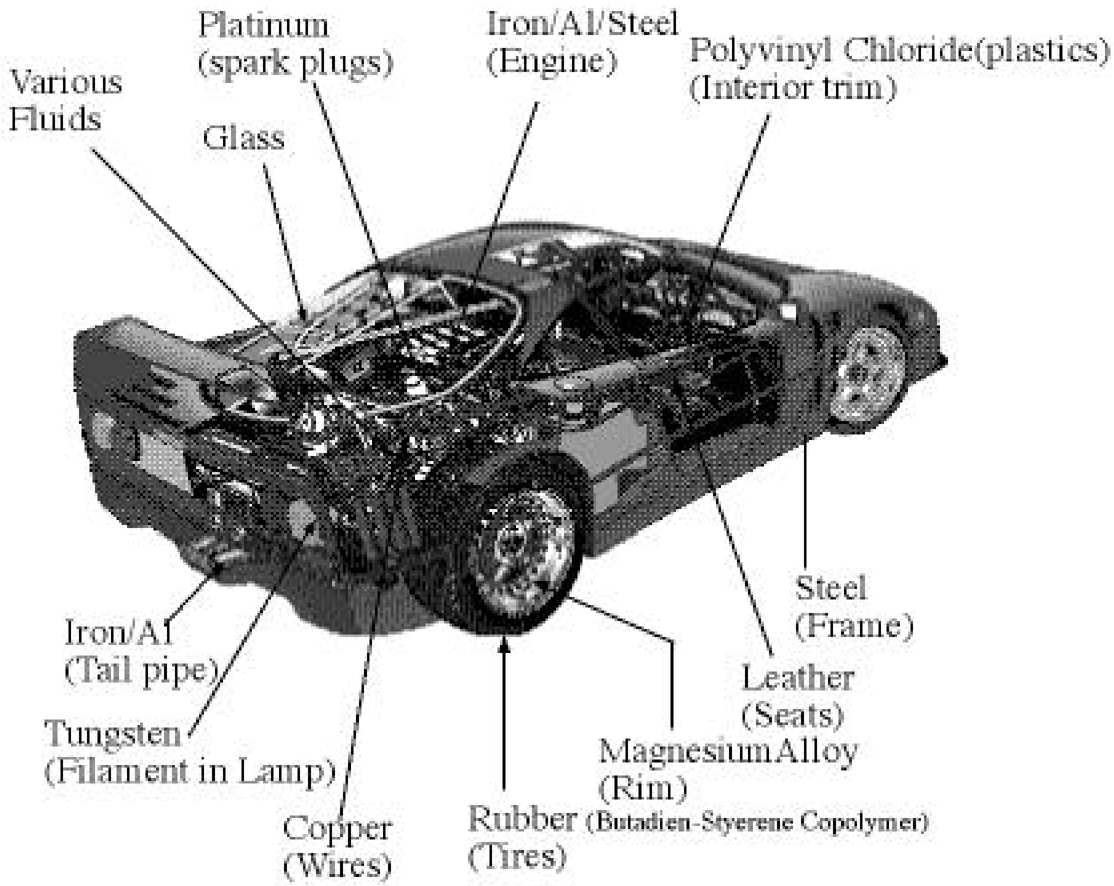


Figure 5: Some Typical Material Components used in a Car

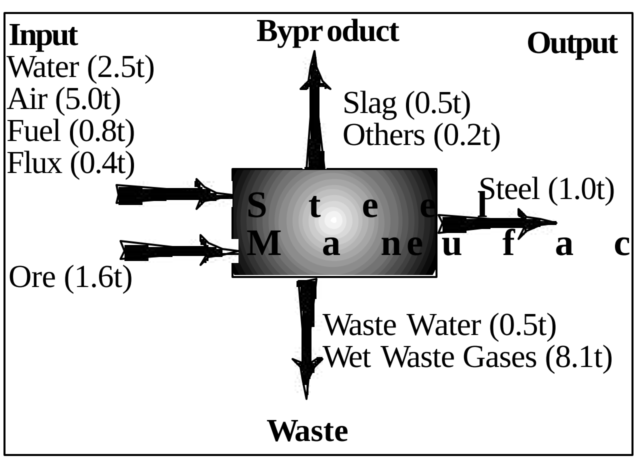


Figure 6: Input/Output Diagram for Steel Manufacture (t—metric ton)

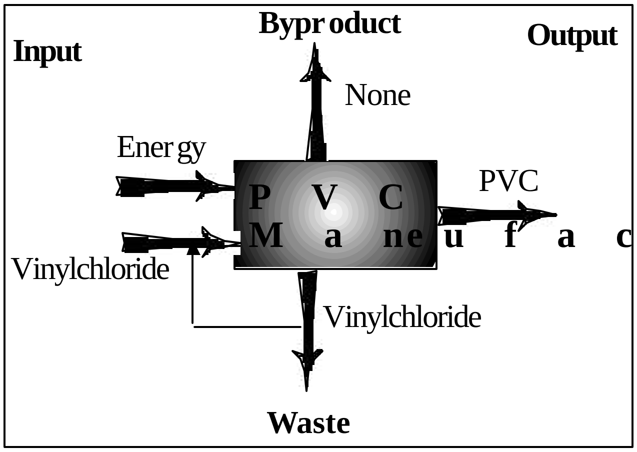


Figure 7: Input/Output Diagram for PVC Manufacture (note that the above should also include various numerical quantities per unit of the product)

Plastics		
Material	Mass (kg)	Mass (%)
ABS-PC (acrylonitrile butadiene styrene-polycarbonate blend)	2.8	0.18%
Acetal	4.7	0.31%
Acrylic Resin	2.5	0.16%
Acrylonitrile Butadiene Styrene (ABS)	9.7	0.64%
Acrylonitrile Styrene Acrylate (ASA)	0.18	0.012%
Epoxy Resin	0.77	0.050%
PA 6-PC (polyamide-polycarbonate blend)	0.45	0.030%
Phenolic Resin	1.1	0.072%
Polyamide (PA 6)	1.7	0.11%
Polyamide (PA 66)	10	0.67%
Polybutylene Terephthalate (PBT)	0.37	0.024%
Polycarbonate (PC)	3.8	0.25%
Polyester Resin	11	0.75%
Polyethylene (PE)	6.2	0.40%
Polyethylene Terephthalate (PET)	2.2	0.14%
Polypropylene (PP)	25	1.6%
Polypropylene (PP, foam)	1.7	0.11%
Polystyrene (PS)	0.0067	0.00044%
Polyurethane (PUR)	35	2.3%
Polyvinyl Chloride (PVC)	20	1.3%
PP-EPDM (polypropylene-ethylene propylene diene monomer blend)	0.10	0.0067%
PPO-PC (polyphenylene oxide-polycarbonate blend)	0.025	0.0017%
PPO-PS (polyphenylene oxide-polystyrene blend)	2.2	0.14%
Thermoplastic Elastomeric Olefin (TEO)	0.31	0.020%
Total Plastics:	143	9.3%

Metals (Non-Ferrous)		
Material	Mass (kg)	Mass (%)
Aluminum Oxide	0.27	0.018%
Aluminum (cast)	71	4.663%
Aluminum (extruded)	22	1.438%
Aluminum (rolled)	3.3	0.2%
Brass	8.5	0.55%
Chromium (Cr)	0.91	0.060%
Copper (Cu)	18	1.1%
Lead (Pb)	13	0.85%
Platinum (Pt)	0.0015	0.00010%
Rhodium (Rh)	2.9E-04	0.000019%
Silver (Ag)	0.0034	0.00022%
Tin (Sn)	0.067	0.0044%
Tungsten (W)	0.011	0.00073%
Zinc (Zn)	0.32	0.021%
Total Metals (Non-Ferrous):	138	9.0%

Metals (Ferrous)		
Material	Mass (kg)	Mass (%)
Ferrite (Fe)	1.5	0.10%
Cast Iron (Fe)	132	8.59%
Pig Iron (Fe)	23	1.48%
Steel (cold rolled)	114	7.46%
Steel (EAF)	214	13.94%
Steel (galvanized)	357	23.29%
Steel (hot rolled)	126	8.23%
Steel (stainless)	19	1.23%
Total Metals (Ferrous):	985	64%

Fluids		
Material	Mass (kg)	Mass (%)
Automatic Transmission Fluid	6.7	0.44%
Engine Oil (SAE 10w-30)	3.5	0.23%
Ethylene Glycol	4.3	0.28%
Glycol-Ether	1.1	0.069%
Refrigerant (R 134a)	0.91	0.059%
Unleaded Gasoline	48	3.1%
Water	9.0	0.59%
Windshield Cleaning Additives	0.48	0.031%
Total Fluids:	74	4.8%

Other Materials		
Material	Mass (kg)	Mass (%)
Ethylene Propylene Diene Monomer (EPDM)	10	0.68%
Adhesive	0.17	0.011%
Asbestos	0.4	0.026%
Bromine (Br)	0.23	0.015%
Carpeting	11	0.73%
Ceramic	0.25	0.016%
Charcoal	0.22	0.014%
Corderite	1.2	0.081%
Desiccant	0.023	0.0015%
Fiberglass	3.8	0.25%
Glass	42	2.8%
Graphite	0.092	0.0060%
Paper	0.20	0.013%
Recycled Textile Fibers	12	0.78%
Rubber (except tire)	23	1.5%
Rubber (extruded)	37	2.4%
Sulfuric Acid (H2SO4)	2.2	0.14%
Tire	45	3.0%
Wood	2.3	0.15%
Total Other Materials:	192	13%
Total Weight of Generic Vehicle:	**1532**	**100%**

Table 1: Materials used in a Generic Vehicle (from [Sullivan 1998].

5. Issues in Design for Recovery

In the process of recovery, the optimal solutions represent a tradeoff between cost, time and environmental distress. One cannot expect that the best strategy for dealing with a discarded item is going to always involve 100% recycling. For example, it sometimes takes far more energy—and hence pollution—to recycle a product than it takes to make it in the first place. In such cases, landfilling may well be the most environmentally benign option, as well as the less expensive one

In the process of recovering a product, some parts may be reused while others may be recycled and the rest may be incinerated or landfilled. Such a process might represent a balance that has to be struck between the amount of emissions, cost of recovery, energy usage and the environmental impacts of landfilling. The engineering team must find a balance such that, to the extent possible, one objective should always be to design so that the landfilled volume is reduced. For example, in an automobile dashboard there are many plastic parts that are worth recycling, but often the cost of isolating the parts is more than the value of its materials. Consequently, these parts end up in shredder fluff. Through clever redesign, it is possible to make recycling more attractive by making recyclable components more accessible. Finding the balance point for a product and redesigning it in order to move the balance point in a favorable direction is the aim of the green design process. We call this the Recovery Problem:

> **The Recovery Problem:** For a given design (or product) find a recovery plan that balances the amount of effort (e.g., energy) that is put into recovery and the amount of effort that is saved by reusing parts and materials. In this way, recovery is a leveraged process.

A recovery analysis can be used to determine the pragmatic recovery process for a given product or design. In recycling a photocopier, for example, one rather complicated component is the control panel, with its many small plastic parts. It takes more energy to recover these materials than it will take to make them from original sources. It is hence important to understand that the pragmatic aspect of recovery might call for some environmentally undesirable actions as part of the recovery process, actions such as landfilling or incineration. The aim is to detect break-even points and points of maximum payoff, where payoff can be measured in terms of any accumulative such as emissions, energy, money or disposal volume.

There are many aspects of recovery that are considered during disassembly. Each step in disassembly involves a decision on what action to take next. At each decision point, the following issues need to be considered for each subassembly:

1. *Dismantle Further?* At some stage in the disassembly process one reaches a point at which the cost of further disassembly might be more than the value of parts that will be disassembled.
2. *Send to Shredder?* If a subassembly of compatible materials is reached, it might make more sense to send it to a shredder than to disassemble it further. If a

subassembly has a small number of parts that are of incompatible materials, the subassembly could still be shredded without further disassembly. This, of course, requires knowledge about acceptable levels of impurities.

3. *Sell?* A subassembly can be worth more than the sum of parts. In an automobile alternator, for example, the rotor can be sold for refurbishment as an assembly: the actual value of the materials in the rotor is substantially lower than the rotor itself.
4. *Remanufacture?* While remanufacturing operations, such as cleaning, plasma spraying and machining, have environmental impacts, they are often less then the original materials processing and manufacturing processes that are used to make the part from scratch.
5. *Hazardous materials in subassembly?* If a subassembly contains some hazardous materials, it is imperative to perform the disassembly until the hazardous material is reached. Whether further disassembly should proceed depends on the expense of sending the leftover subassemblies to a hazardous landfill.

These ideas have been captured in an automated disassembly and recovery analysis tool called ReStar [Navin Chandra 1994]. At every stage, the system evaluates whether it would be better to continue dismantling or whether the parts should be reused, sold or sent to a shredder for material recycling. This process is recursively applied to each subassembly that is generated through the disassembly process.

Having established that environmental issues in design and manufacture are necessary to consider, we focus in the remaining two sections on how design teams can collaborate to achieve greener goals.

6. A Framework for Collaborative Design

Recent trends in computing environments and engineering methodologies indicate that the future engineering infrastructure will be distributed and collaborative, where designers, process planners, manufacturers, clients, and other related domain personnel communicate and coordinate using a global web-like network [Nidamarthi 2000]. The designers may be using heterogeneous systems, data structures, or information models, whose form and content will probably not be the same across all disciplines. Hence, appropriate standard exchange mechanisms are needed for realizing the full potential of sharing information models. The various applications are coordinated by a work flow management system, which acts as a project manager. They are connected to one another by a Design Net, which provides the infrastructure for high bandwidth communications. These applications retrieve relevant design data and knowledge from distributed design repositories and the evolving design (or designs) is stored in a database. This database provides various snapshots of the evolving design, with design artifacts and associated design rationale stored at various levels of abstraction. Finally, design applications communicate with other manufacturing applications and databases through various nets, such as production, process planning, and user networks (see Figure 8).

The information exchange between various applications do not occur at only one level. We envision the interoperability problems between heterogeneous engineering applications to occur at several levels. These levels are described below.

- *Physical:* This level is concerned with the physical transmission medium, such as Ethernet, and fiber optics.
- *Object:* At this level, the engineering objects are transported using appropriate object transfer modes, such as CORBA (Common Object Request Broker Architecture), EJB (Enterprise Java Beans) or COM (Microsoft's Common Object Model).
- *Content:* This level deals with the communication of engineering artifacts, and should include feature, constraint, geometry, material, process, etc. Information at this level can be expressed in an appropriate modeling language, such as STEP's EXPRESS (http://www.nist.gov/sc4), KIF (http://logic.stanford.edu/kif/kif.html), or XML (http://www.w3.org/XML/).
- *Knowledge/Design Rationale:* This level deals with design rationale and design history issues, which provide additional information (including inference networks, plans, goals, justifications, etc.) about the engineering objects at the Content level.
- *Communication:* This level provides additional detail to the Content and Knowledge/Design Rationale levels. Such details include the specification of engineering ontologies used, sender, recipient, etc., as defined by the KQML standard (http://www.cs.umbc.edu/kqml/).
- *Negotiation:* Any multi-agent activity will involve negotiation activity. The protocols needed to conduct such negotiations will be defined at this level.

The Design Net provides the infrastructure for supporting the above communication levels. Next, we discuss issues involved in accessing heterogeneous environmental databases during various design stages. We focus on the content level protocol.

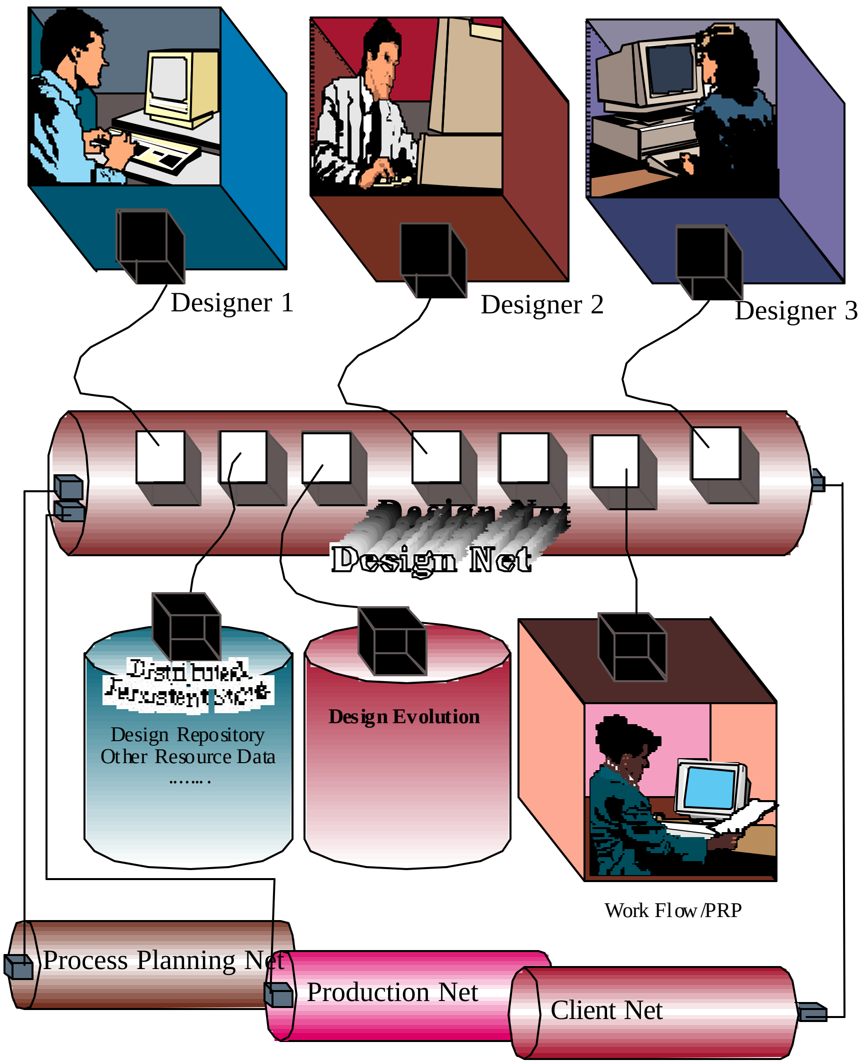


Figure 8: One Framework for Distributed Design

8. Environmental Database Access

During the course of product design and manufacturing, engineering teams typically access several large databases, such as Numerica and Sigma-Aldrich's Hazardous and Regulatory Data Library. These databases typically contain physical and chemical characteristics, environmental impact data of chemicals, equipment information, and regulatory standards and guidelines (such as those addressing hazardous waste transport). However, engineers encounter several problems accessing appropriate information. A few of these problems are enumerated below.

1. The data reside on heterogeneous databases, with different formats which require knowledge about multiple query languages, i.e., we have several independent databases, where each database has its own schema, is expressed in its own data

model (relational, object-oriented, etc.), and is accessible through its own query language;

2. Query mechanisms provided with the databases are not in a format which is natural to the engineer;

3. An answer to a query may be spread across different databases, which may require generating multiple queries and their integration;

4. The engineer has to navigate through several pages before s/he gets the information required; and

5. The database developers may have used a wrong data model, which results in inefficient retrieval strategies.

Here, we describe an architecture for an intelligent interface for integration of heterogeneous chemical and environmental databases and application programs. The architecture provides a virtual integrated database management system with a high-level data manipulation language (DML) for the engineering teams. The main issues that need to be addressed for integrating the heterogeneous databases are the following:

1. Resolving the incompatibilities between the different databases; these could include conflicting schema names and data types.

2. Resolving any inconsistencies between the databases; these could be inconsistencies in copies of the same information stored in different databases.

3. Transforming the query expressed in the high-level DML posed by the designer into a number of sub-queries that need to be posed to various databases in their respective DML's. The resulting responses to the sub-queries are to be collected and an appropriate answer is to be filtered from them.

These concepts have been incorporated in a commercial software tool called Enchilada™, an information integration technology [TimeØ 2000], that is used to automatically access heterogeneous databases and web databases in real time and to integrate the results into an uniform data schema. The data can then be exported in XML, RDF, or some other formats into a design application. Figure 9 depicts a schematic of Enchilada's function. The recipes serve as the basis of information integration that underlies our collaborative design framework and the user contexts place the heterogeneous information in a form that is most usable to the user.

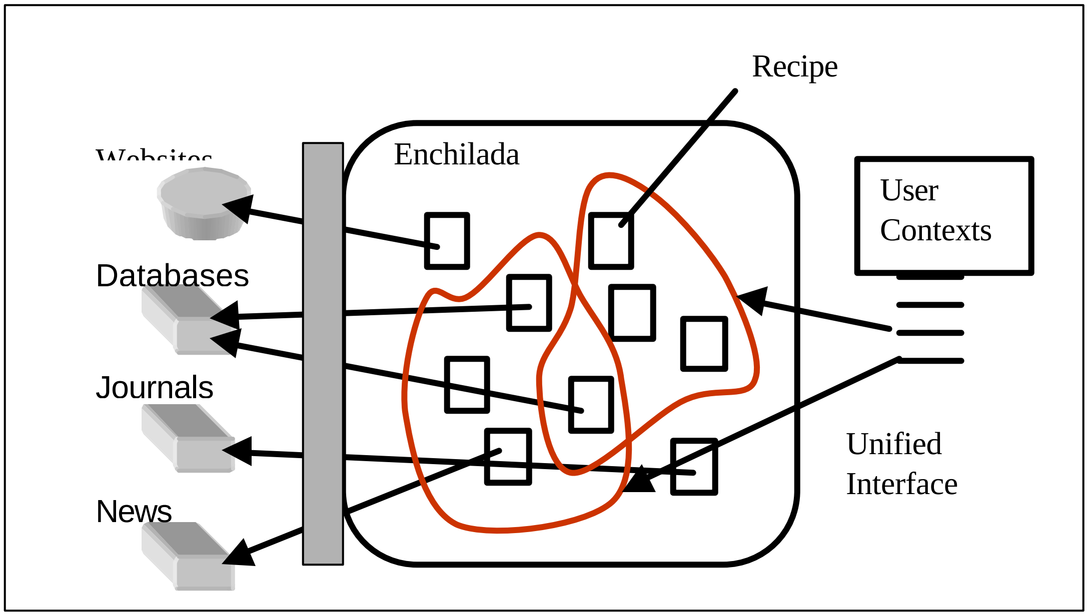


Figure 9. Enchilada accesses multiple databases via recipes 'wrappers' that operate as independent information agents. The agents collaboratively collect, normalize and re-purpose the data into a user's context via an unified interface.

8. 1 Environmental Data Manager (ENVDM)

Within the collaborative design framework, we include an *environmental data manager* (ENVDM), which provides an intelligent interface between various databases and applications programs, as shown in Figure 10. Other data managers, such as Numerica and Dipper, can also be attached to the Design Net as the need arises. In this example, we assume pharmaceutical design because its associated manufacturing process uses and produces chemical solvents. These have a profound impact on the environment. The interactions in this framework are as follows.

1. Any new design application that plugs into the design net has to provide interfaces to various Design Net services, which would involve appropriate CORBA's IDL (interface definition language) entities. In the current framework, each application should also map its domain terms into the terminology of ENVDM (as described below).

2. By deploying intelligent agents on the net, ENVDM constantly monitors the environmental (and other associated) databases accessible on the Design Net.

3. ENVDM's agents gather various metadata, such as local schemas of each database.

4. The metadata is processed by ENVDM, as described below.

5. When a designer queries the ENVDM, it accesses the appropriate databases and returns the needed information to the design team.

The Environmental Data Manager (ENVDM) consists of the following modules.

1. *Global data schema or an ontology*, where an ontology is a collection of class objects with certain relationships between these objects.

2. *Syntactic query translator*, which transforms the queries expressed on the objects in ENVDM.

3. *Query decomposer and access path selector*, which translates a query over the internal model into a plan for processing the query. The plan consists of: 1) a set of queries each of which is posed on exactly one database; 2) a set of move operations to ship the results of these queries to each of the databases in an appropriate format; and 3) a set of queries locally executed to integrate the results of the above queries.

4. *Ontology builder*, which generates the ontologies (this can be automated or user defined).

5. *Persistent store*, which stores the ontologies in a database. This was EXODUS—an object-oriented database management system developed at University of Wisconsin-Madison—in the initial prototype.

6. *Knowledge-based inference engine*, which is utilized by various modules. COSMOS, developed at MIT, was used in the initial prototype.

7. *Query composer*, which takes the results of a set of queries and presents in an appropriate format to the designer.

8. *Integration schema module*, which keeps track of all metadata obtained from various databases and mapping between these database entities and the ENVDM ontology. For example, consider two databases each containing some physical properties of organic chemicals. One database might store the heat of fusion (at melting point) of Benzene as 30.1 cal/g whereas the other might record the same information as 2.370 kcal/mol. To integrate these two databases, we need information about mapping these two scales. Such information is stored in an Integration Database, whose schema is based on an object-oriented data model. The Integration Database might also contain information necessary for reconciling any inconsistencies between copies of the same data stored in different databases.

9. *Intelligent agents*, which roam the net and gather meta information about various databases. The meta information would include database type (relational, object-oriented, network), data/class dictionaries, access pathways and privileges, and other

relevant information needed to retrieve data. It is assumed here that databases have interfaces to the Internet. Huhns and Singh [Huhns and Singh 1998] categorize agents (including many of the modules described in our work) into: User, Broker, Ontology, Mediation, and Resource Agents. Agents communicate using KQML, which is a knowledge-based query manipulation language developed with DARPA sponsorship. At the content level, we believe that XML is the appropriate language for communicating domain data.

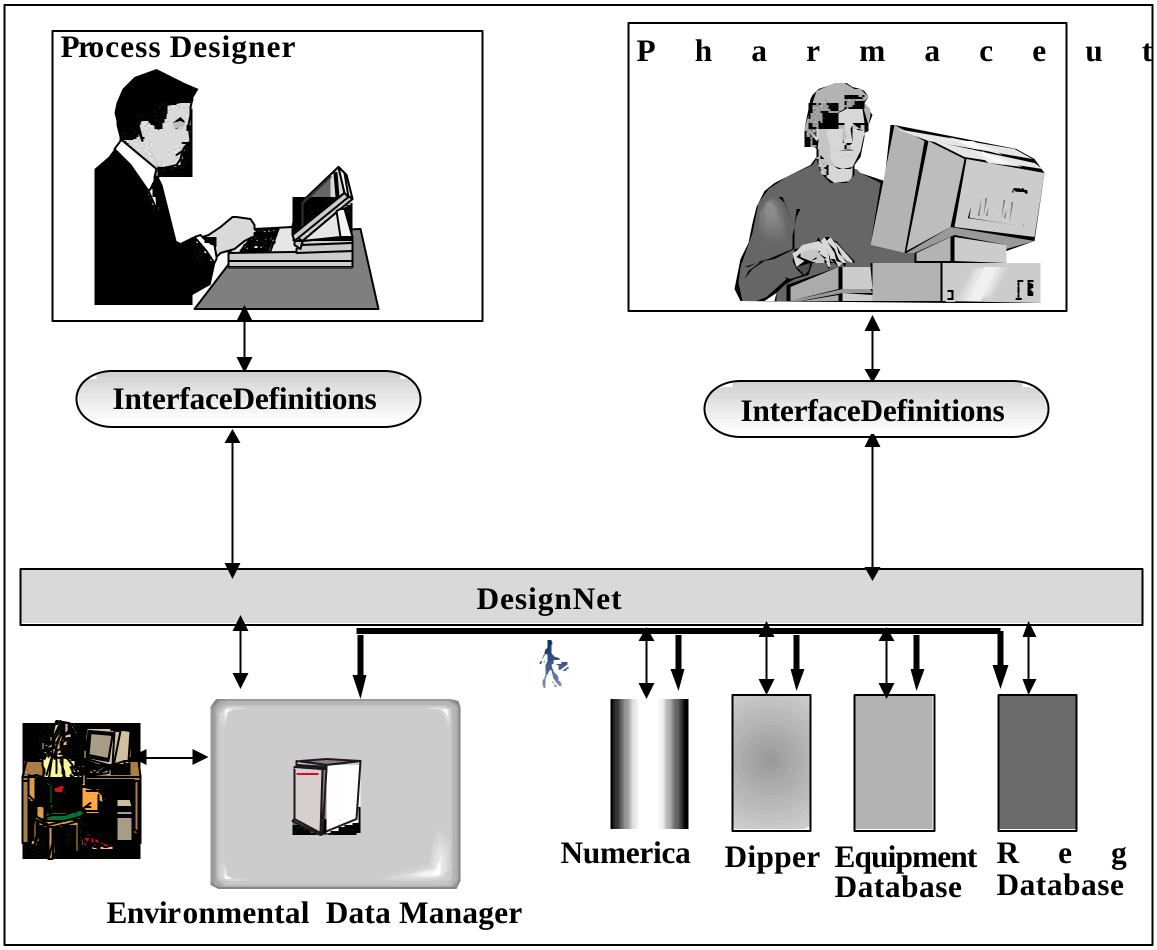


Figure 10: Schematic View of the Intelligent Database Interface

8.2 Example

The following example provides a flavor of querying on heterogeneous chemical and environmental databases. For simplicity, the transformations here are evident. However, in actual practice these transformations involve considerable processing.

We assume one database to be in a relational format, which has the following relation:

Substance		
Slot	*Type*	*Constraint*

Boiling Point	number	> 0
CAS-Registry	number	integer
Chemical Formula	string	
Density	number	> 0
Molecular-Weight	number	> 0
Phase	enum	One-of solid, liquid, gas
Toxicity	number	> 0

The CAS-Registry (Chemical Abstract Service Registry), which stands for chemical abstracts service, allows a unique identifier for materials with multiple names. Benzene, for example, is also known as benzol, benzolene and carbon oil, Let the other database be in an object-based format, with the following objects:

EnvironmentalData
common-name:
half-life:
(pointer to half-life)
fate-rate-constant:
(pointer to Fate-Rate-Constant)

Half-life
air:
surface-water:
ground-water:
soil:

Fate-Rate-Constant
volatization:
photolysis:
oxidation:
hydrolysis:
biodegradation:
bioconcentration:

Integration Schema to link the synonyms of a chemical with its unique CAS-registry number:

The above integration schema is attached to ENVDM.

CAS

CAS-registry Number	Synonyms
71432	Benzole, benzene, cyclohexatriene, …
100414	Ethylbenzene, phenylethane, …

Assume that the following query is posed to ENVDM.

Find the half-life of phenylethane in surface water.

The processing of this query involves the following two stage process:

1) Generate the query: *Find the CAS-registry number of phenylethane.* The response would be: *100414.*

2) Using the above response generate the query: *Find half-life frame for CAS-number 100414 and find value of the surface-water slot*. The response would be: *5 hours.*

With such a framework, environmental factors can be brought to bear on any design or manufacturing consideration and help play a pivotal in the decision-making of design and manufacturing teams.

9. Summary

To create environmentally conscious products, product designers should consider environmental impacts of design when decision making during the product development process. Green Engineering Design is an approach to product and process design that achieves environmental consciousness without compromising a product's quality or its commercial viability. It takes a proactive approach to environmental problems rather than a reactive approach. The factors motivating Green Design were explored in this chapter.

The future engineering infrastructure will be distributed and collaborative, where designers, process planners, manufacturers, clients, and other related domain personnel communicate and coordinate using a global web-like network. We also presented an architecture for realizing effective collaborative green design, where designers access to heterogeneous environmental-related databases. This access can be achieved through an object-oriented data management framework, which utilizes ontologies for semantic resolution.

Disclaimer

The bulk of the work reported here by the first author was conducted during his tenure at MIT. Commercial equipment and software, many of which are either registered or trademarked, are identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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