Chapter 3

Product Design and the Environment

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Product design is a process of synthesis in which product attributes such as cost, performance, manufacturability, safety, and consumer appeal are considered together.[1] These principal design parameters are often constrained by regulatory requirements—for example, fuel efficiency targets, building codes, or tamper-proof packaging specifications. Thus, in virtually all cases, designers are forced to make tradeoffs among competing criteria.[2] At each stage of the design cycle, solutions are evaluated and reevaluated in light of a diverse ensemble of technical, economic, and social objectives. (For a discussion of how the design process works in the automotive industry, see appendix 3-A.)

The National Research Council has estimated that 70 percent or more of the costs of product development, manufacture, and use are determined during the initial design stages.[3] Design is therefore a critical determinant of a manufacturer's competitiveness. Because of the strategic importance of design, many corporations are adopting comprehensive programs for developing and introducing products.[4] With greater attention being given to the design process, new approaches to product development are emerging.

Companies are discovering that they cannot afford to have designers develop a concept in isolation and then toss it "over the wall" to production engineers. Instead, a "concurrent" design process is increasingly used, as depicted in Figure 3-1.[5] The product evolves continuously through a spiral of design, manufacturing, and marketing decisions. As a product progresses along the "design helix" toward commercialization, multidisciplinary product development teams take part in every major design iteration. This multifunctional approach safeguards product integrity and expedites product development from stage to stage. Implementation of concurrent design methods have allowed many firms to dramatically cut product cycle times, while delivering goods of superior performance and quality.[6]

The changing nature of design provides new opportunities for integrating environmental concerns into the product development process. The concurrent design methodology, with its multidimensional orientation, lends itself to the consideration of environmental impacts at every decision point. Similarly, total quality management (TQM) programs, which stress that quality must be "designed in," rather than tested for at the end of the production process, allow for a natural extension to

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[1] Historically, design has been divided into the fields of engineering design and industrial design. Engineering design primarily specifies a product's technical characteristics, while industrial design is principally concerned with the 'feel" of a product, such as styling and ease of use (ergonomics). Most products embody in varying degrees the inputs of these two disciplines. As used here, the term 'designers" refers to all decisionmakers who participate in the early stages of product development. This includes a wide variety of disciplines: industrial designers, engineering designers, manufacturing engineers, graphic and packaging designers, as well as managers and marketing professionals.

[2] For a general discussion of the design process, see Nam Suh, *The Principles of Design (New York, NY:* Oxford University Press, 1990).

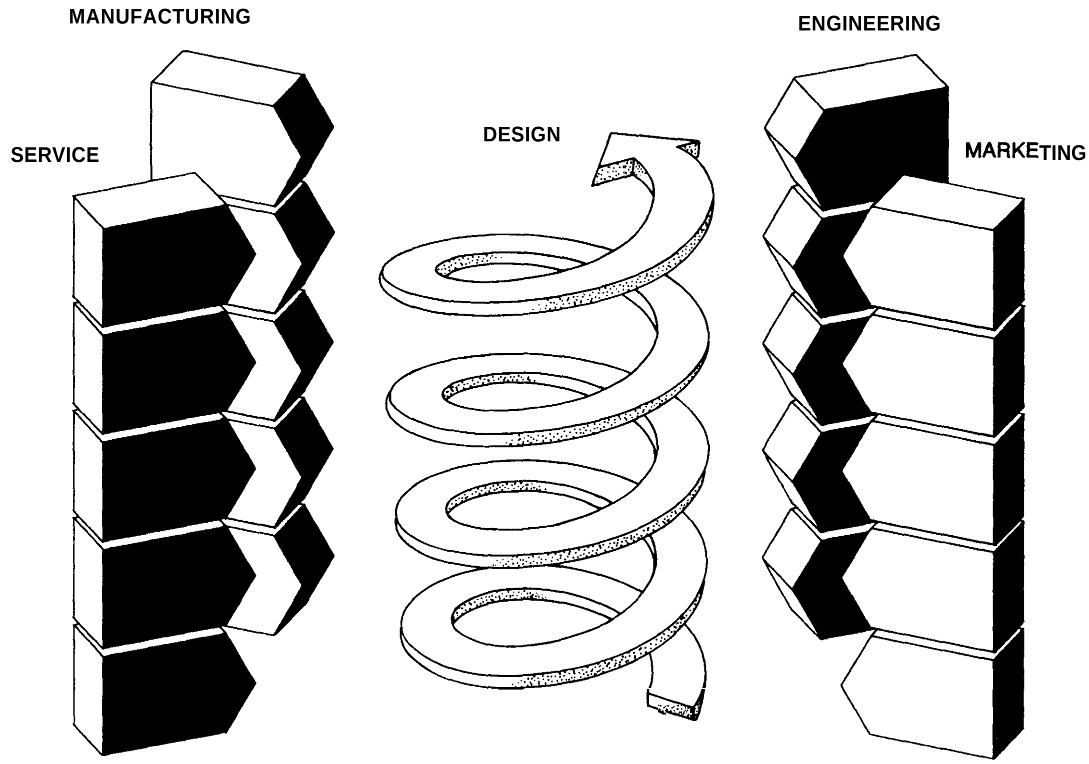
[3] National Research Council, *Improving Engineering Design: Designing for Competitive Advantage* (Washington, DC: National Academy Press, 1991), p. 1.

[4] For instance, Hewlett Packard, AT&T, and Ford have adopted such extensive product development strategies, sometimes known as "product realization" programs. Ibid.

[5] See, e.g., "Concurrent Engineering," *IEEE Spectrum,* July 1991, p. 22.

[6] Using concurrent planning techniques, Siemans Automotive has achieved extraordinary improvements in both productivity and quality. In 1975, Siemans produced 30,000 fuel injectors a month. In 1991, the company manufactured 30,000 fuel injectors a day with defect levels of 20 parts per million (.002 percent). Through the collaboration of designers and process engineers, the number of grinding steps was reduced six-fold. Over that same period, the direct human labor required for each fuel injector was reduced from 13 minutes to less than 2 minutes. Similarly, Motorola Inc., at one time required 30 days to build a pager. By implementing cross-functional design techniques and introducing significant levels of automation a single pager can now be manufactured in 30 minutes. PBS Series: "Quality or Else! Challenge and Change," Oct. 18, 1991.

Figure 3-l—The Design Helix



In a concurrent design process, each product discipline provides input into major design decisions. The interchange between disciplines reduces the time required for product commercialization.

SOURCE: GVO Design, Inc., Palo Alto, CA.

designing in the product's ''environmental quality."[7,8]

WHAT IS GREEN DESIGN?

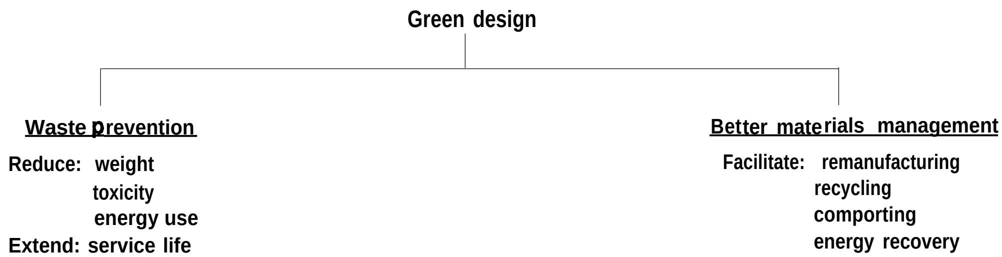
In general, products today are designed without regard for their overall impact on the environment. Nevertheless, many health and environmental laws passed by Congress do influence the environmental attributes of products. Some, such as the Clean Air Act, Clean Water Act, and Resource Conservation and Recovery Act, do so indirectly, by raising industry's costs of releasing wastes to the air, water, and land. Others, such as the Toxic Substances Control Act and the Federal Insecticide, Fungicide. and Rodenticide Act, control the use of hazardous chemicals and pesticides directly.

Government regulations typically influence the design process by imposing external constraints, for example, requirements that automobile manufacturers comply with Corporate Average Fuel Economy (CAFE) standards, and with auto emissions standards under the Clean Air Act. The Office of

[7] See, e.g.: Global Environmental Management Initiative, *Proceedings of the First Conference on Corporate Quality/Environmental Management*, Washington, DC, Jan. 9-10, 1991; Charles M. Overby, "QFD and Taguchi for the Entire Life Cycle," ASQC Quality Congress Transactions, Milwaukee, WI, 1991; and W. David Stephenson, "Environmentalism's Strategic Advantage," *Quality*, November 1991, p. 20.

[8] Contemporary designers have available an array of tools that can simultaneously improve product quality while reducing environmental impacts. The use of computer-aided design and manufacturing tools can result in more effective utilization of materials—for example, Levi Strauss is using computers to test out new fabrics, patterns, and designs before ever cutting apiece of cloth. The use of just-in-time delivery methods optimizes inventory flows, and the integration of suppliers into the product development process ensures low defect levels and greater compatibility of product subcomponents. Finally, statistical quality control methods that identify process defects can improve factory efficiency and promote pollution prevention.

Figure 3-2—The Dual Goals of Green Design



Green design consists of two complementary goals. Design for waste prevention avoids the generation of waste in the first place; design for better materials management facilitates the handling of products at the end of their service life.

SOURCE: Office of Technology Assessment, 1992.

Technology Assessment (OTA) uses the phrase "green design" to mean something qualitatively different: a design process in which environmental attributes are treated as *design objectives* or *design opportunities,* rather than as *constraints.* A key point is that green design incorporates environmental objectives with minimum loss to product performance, useful life, or functionality.

In OTA's formulation, green design involves two general goals: *waste prevention* and *better materials management* (Figure 3-2).[9] Waste prevention refers to activities by manufacturers and consumers that avoid the generation of waste in the first place.[10] Better materials management involves coordinating the design of products with remanufacturing operations or waste management methods so that after products have reached the end of their service life, their components or materials maybe recovered and reused in their highest value-added application.[11] These goals should be viewed as complementary: while designers may reduce the quantity of resources used and wastes generated, products and waste streams will still exist and have to be managed.

Design for Waste Prevention

The old dictum that "an ounce of prevention is worth a pound of cure" is finding new relevance as industries attempt to modify traditional design and manufacturing practices. Examples of design for waste prevention include reducing the use of toxic materials, increasing energy efficiency, using less material to perform the same function, or designing products so that they have a longer useful life.

When a designer specifies a smaller quantity of a material, that decision has a multiplier effect on both the industrial and post-consumer waste streams.[12] Waste discharges, emissions, and energy consumed at each stage of the materials life cycle will decrease in proportion to the amount of material used (see box 3-A). Similarly, increasing the lifetime of products can result in direct waste reduction. Over a given time interval, less waste is generated during materials extraction, product manufacturing, and disposal. Related energy costs associated with processing and transport are also reduced.[13]

Product life extension can be achieved through use of more durable materials or through modular

9 This formulation first appeared in U.S. Congress, Office of Technology Assessment, *Facing America's Trash: What Next for Municipal Solid Waste, OTA-O-424 (Washington DC:* U.S. Government Printing Office, October 1989).

10 See U.S. Congress, Office of Technology Assessment, *Serious Reduction of Hazardous Waste: For Pollution Prevention and Industrial Efficiency,* OTA-ITE-317 (Washington, DC: U.S. Government Printing Office, September 1986).

11 The dividing line between waste prevention and better materials management is not always sharp. For instance, remanufacturing helps to conserve resources, and to avoid the generation of wastes that would otherwise have occurred. But OTA believes the distinction is nevertheless important to make. Waste management technologies generate environmental risks in their own right; by designing for waste prevention, these risks can be avoided.

12 For example, for every ton of copper extracted in open-pit mining, 550 tons of materials are moved and processed. Mining and processing wastes include substantial emissions of arsenic, sulphur dioxide, and other byproducts. These wastes could be drastically reduced if copper was used more efficiently. See Robert Ayres, "Toxic Heavy Metals: Materials Cycle Optimization" *Proceedings of the National Academy of Sciences, vol. 89, No, 3,* February 1992.

13 Walter Stahel, "Design as an Environmental Strategy," Paper presented at the Industrial Designers Society of America National Conference, Santa Barbara, CA, Aug. 8-11, 1990.

Box 3-A--Getting the Lead Out

The General Motors Delco Remy Battery Division has made significant strides in **reducing** hazardous constituents in both its products and processing operations. In 1974, a typical battery contained about 30 pounds of lead, whereas today a battery with much improved performance weighs only 19.5 pounds, This resulted in over 6 million pounds of lead waste prevention during 1990. In addition, the reformulation of alloy materials, changing from antimony-arsenic to calcium-tin, eliminated over 1 million pounds of antimony and arsenic waste in that same year.

Pollution prevention strategies have also involved an increased emphasis on in-process recycling. In one facility, 4.2 million pounds of lead, 730,000 gallons of sulfuric acid, and 250,000 pounds of polypropylene were reclaimed and reused. A new wastewater treatment process increases the percentage of lead in the resulting solids. This allows the lead to be more readily recycled. The solid precipitates are sent to a secondary lead smelter rather than a hazardous waste landfill.

SOURCE: GM **Delco Remy Division.**

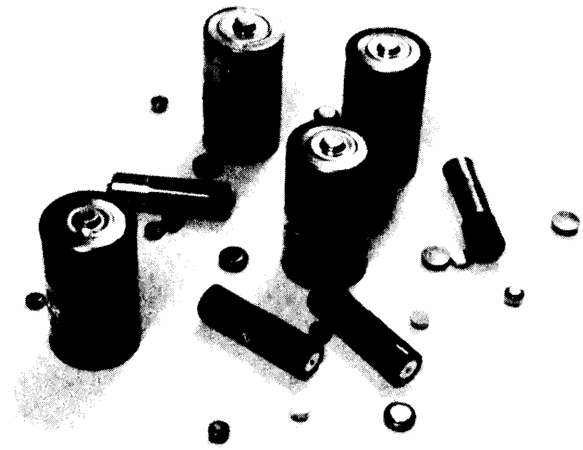


Photo credit: Office of Technology Assessment

Some products can be redesigned to reduce the use of toxic substances. Over the past 5 years, manufacturers have reduced the level of mercury in household batteries by more than 85 percent.

designs that facilitate repair or upgrading of product components (see box 3-B). Products that are designed in a modular fashion have components of definable functionality that can be easily replaced or upgraded without affecting other components. This permits both products and product subcomponents to be easily serviced or refurbished.[14] It also allows product performance to be maintained over a longer time period, thereby obviating the need for buying entire new systems.[15]

However, the actual useful life of a product is affected by a number of external factors including maintenance practices, conditions of use, and the rate of technical or stylistic obsolescence.[16] While a number of industries have improved the durability of their products in recent years, a large percentage of materials that are extracted and processed through the economic system are still transformed into waste almost immediately.[17]

The belief that companies cynically pursue strategies of planned obsolescence in order to maximize profits is overstated.[18] Companies do shape consumer demand through their marketing strategies, but they also respond to customer demand for convenience and ease of product use. Since many consumers exhibit a greater sensitivity to a product's initial cost rather than its lifetime costs, this can inhibit the design of more durable, but expensive products. This sensitivity to cost is particularly evident in the area of energy-efficient home appliances and equipment-for example, air condition-

14 Designing products so that they can be serviced is not mutually exclusive with designing for reliability. But due to proficient manufacturing methods and high labor costs, many complex products are designed to be extremely reliable over a given time period and then disposed (e.g., consumer electronics goods).

15 For example, "modular upgradability" is quickly becoming a de facto standard in the personal computer industry. Fast growth companies such as Dell Computer Corp. and AST Research Inc. have based their success on designing modular machines. The designs permit customers to take advantage of the latest advances in microprocessor and memory technologies without buying anew computer. See *Wall Street Journal*, Sept. 10, 1991, p. B1, and *Electronic Engineering Times,* Oct. 28, 1991, p. 1.

16 For example, steel-belted tires have twice the durability of tires that were made 20 years ago. If maintained properly, modern radial tires can last 60,000 to 80,000 miles. In practice, however, consumer misuse and neglect results in the tires wearing out much sooner. See 'The Bumpy Road to Tire Recycling in America, " *Garbage, May/June* 1991, p. 37.

17 Robert Ayers, *Technology and Environment* (Washington, DC: National Academy of Engineering, 1990)> Po 26.

18 T. Teitenberg, *Environmental and Natural Resource Economics* (Glenview, IL: Scott, Foresman and Co., 1988), p.191.

Box 3-B—Modular Design in the Housing Industry

An example of modular design is the Integrated Building and Construction Companies (IBACoS) project—a consortium of companies led by GE Plastics that have joined together to explore design concepts for homes of the future. In a demonstration house built in Pittsfield, Massachusetts, several key design ideas have been implemented.

One principal concept is the notion of designing a home as a collection of "disentangled" systems—systems that can be developed, produced, and installed independently of one another. Heating, lighting, power, and plumbing systems are designed to permit adaptability and flexibility to accommodate changing lifestyles. This flexible design strategy allows various elements of these systems to be upgraded with the latest technologies. Thus, the energy efficiency of a home could be continually improved, and critical components can be accessed without requiring destruction of walls or floor/ceiling structures. For example, kitchens or bathrooms could be enlarged, modified, or moved to different parts of the home. Also, as new information services become available to households, fiber-optic cable could be brought into a home without displacing existing wiring or fixtures.

Photo credit: GE Plastics

General Electric Plastics has constructed a 2,900 square-foot home that is designed to provide a "living laboratory" for the development of advanced building systems and components. The home is made from recycled engineering thermoplastics and a variety of traditional construction materials.

The main thrust of the IBACoS strategy is to develop a set of core systems—a kit of parts designed and coordinated by computer, manufactured by member companies, and capable of being used in a wide variety of ways in both new and old buildings. This approach envisions significant cooperation among many different players. Consortium participants will include architects, builders, materials suppliers, and an array of manufacturers with expertise in pre-built structural components, energy and electrical systems, and kitchen and bath systems. Streamlined delivery and storage of "core systems" will provide quick response capability to meet customer needs. The IBACoS network will thus be able to provide a diverse set of product offerings while fostering resource efficiency and environmental quality.

Houses represent one of the largest potential markets for secondary materials. In the IBACoS scheme, materials efficiency would be encouraged by using recycled plastics, high strength composite woods made from wood scrap, and reconstituted gypsum. For instance, plastic roof shingles have been produced from discarded computer equipment. In addition, by using prefabricated structural components and subsystems, the generation of on-site waste and scrap could be reduced.

SOURCE: Michael Dickens, Director-IBACoS Program.

ers, refrigerators, and light bulbs. Consumers usually do not invest in energy efficiency unless it offers a fairly short payback--typically less than 2 years for home appliances.[19]

Design for Better Materials Management

By and large, resources flow through our society in one direction only. Designers rarely think about how their products will be managed as wastes after their useful life is over. And waste management providers tend to accept the composition of waste streams as a given. If product design and waste management were coupled more closely, this could reduce the cost of materials to industry and address environmental problems at the same time. This will require coordinated research on both principles of design and improved waste management processes.

19 See U.S. Congress, Office of Technology Assessment *Building Energy Efficiency*, OTA-E-518 (Washington, DC: U.S. Government Printing Office, May 1992).

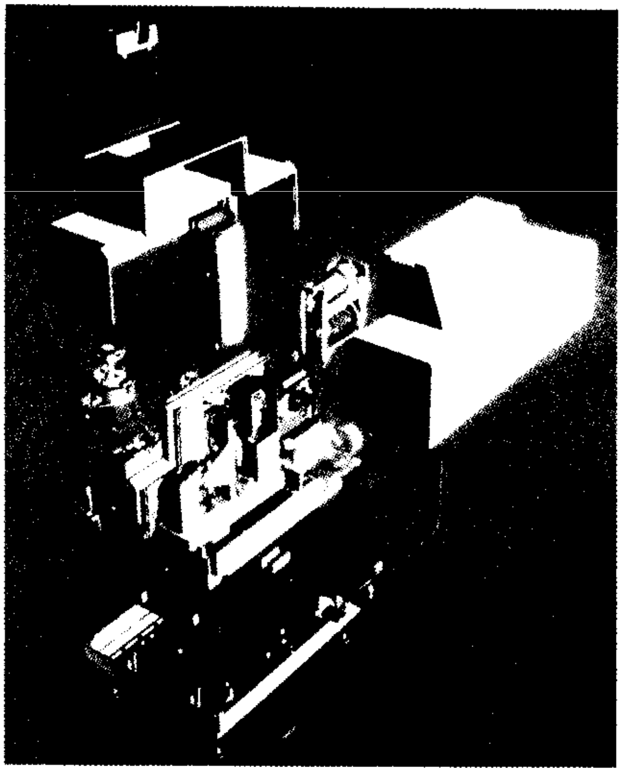


Photo credit: NCR Canada Ltd.

The NCR 7731 Personal Image Processor features the latest in optical imaging technology and incorporates a number of green design concepts. The product features modular components that can be readily disassembled, parts consolidation, and the use of recycled materials. The modular design allows the device to be configured to meet specific customer needs, and so avoids unnecessary hardware and reduces waste.

Examples of design for better materials management include making products that can be remanufactured, recycled, composted, or safely incinerated with energy recovery. Broadly speaking, these management options are listed in order of preference, both from a business perspective and an environmental perspective. One model of plastics management, for instance, envisions a life cycle in which virgin plastic components are reused as long as possible, then the materials are repeatedly recycled through lower and lower value-added applications until the plastic is finally incinerated to recover the chemical energy.[20]

Table 3-l—Principles of Design for Disassembly

Minimize material variety
Use compatible materials
Consolidate parts
Reduce number of assembly operations
Simplify and standardize component fits and interfaces
identify separation points between parts
Use water-soluble adhesives when possible
Mark materials to enhance separation

SOURCE: General Electric Plastics, Pittsfield, MA.

Design for Remanufacturing and Recycling

Giving consideration to how product components or materials can be reclaimed will likely cause companies to alter conventional design and manufacturing strategies.[21] Although not widely practiced, design for remanufacturing can be attractive from both an environmental and a business point of view (see box 3-C). Similarly, recycling offers a number of potential benefits. Recycling can reduce virgin material extraction rates, wastes generated from raw material separation and processing, and energy use associated with manufacturing. It can also divert residual materials from the municipal waste stream, relieving pressure on overburdened landfills.

Products that can be rapidly disassembled into their component parts lend themselves both to remanufacturing and recycling (see table 3-l). Design for disassembly can go a long way toward establishing both closed-loop production-reclamation systems where components and materials are reused in the same products, and open-loop systems where materials are recycled several times for use in different products. A number of durable products including automobiles, refrigerators, and cooking appliances are beginning to embody aspects of this design approach.[22] However, durable products present special problems because it is difficult for designers to anticipate how waste management

[20] This model of materials management has been proposed by GE Plastics, Pittsfield, MA.

[21] See Michael E. Henstock, "The Conflict Between First Cost and Recyclability in the Design of Manufactured Goods," *Resources Policy*, September 1978, pp. 160-165; "Design for Recycling, ''Institute of Scrap Recycling Industries *Phoenix Quarterly*, vol. 21, No. 1, winter 1989; and Rick Noller, "Environmentally Responsible Product Design,'' paper presented at the National Academy of Engineering Workshop on Engineering Our Way Out of the Dump, Woods Hole, MA, July 1-3, 1991.

[22] "Built to Last-Until It's Time To Take It Apart,'' *Business Week*, Sept. 17, 1990, pp. 102-106.

Box 3-C—Remanufacturing

When durable goods such as kitchen appliances or machine tools wear out, they are usually discarded But there exists another option that may offer considerable economic and environmental benefits: remanufacturing. Remanufacturing involves the restoration of old products by refurbishing usable parts and introducing new components where necessary. It simultaneously results in product life-extension (a form of waste prevention) and promotes reuse of subcomponents and materials. Thus, in the case of remanufacturing, waste prevention and materials management strategies can be mutually reinforcing.

Because of the economic advantages that can accrue from remanufacturing, a variety of different industries are embracing the concept For example, Xerox Corp. restores and remanufactures many used parts from its copiers, including electric motors, power supplies, photo-receptors, and aluminum drums. Xerox is now recycling about 1 million parts a year in this way, resulting in savings around $200 million. The parts are used as both replacement components and in new equipment. To facilitate the refurbishing and recycling of various components and product subsystems, Xerox is standardizing its designs so that a larger number of parts can be used in a variety of different products. The company has setup its remanufacturing lines in parallel with its new production lines to achieve the same levels of high quality. It has also involved its suppliers more directly in the design process, so that opportunities to use recycled components and materials, especially plastics, will not be overlooked.

The use of replacement parts for automobiles and trucks is one of the most prevalent applications of product remanufacturing. For instance, Arrow Automotive Industries, a company that remanufactures automotive components such as starter motors, clutches, and carburetors, has annual sales of approximately $100 million. However, the largest single remanufacture in the United States is the Department of Defense. Military equipment and systems ranging from aircraft and radar to rifles are remanufactured on a regular basis to extend the life of expensive technological hardware.

Apart from the economic benefits that can accrue to a manufacturer, the reuse of high value-added components takes advantage of the original manufacturing investment in energy and materials. This yields greater environmental benefits than simply recycling the constituent materials of the components. In most cases, the energy embodied in a new product is many times that needed to remanufacture the same product.

SOURCES: Jack Azar, Xerox Corporation, personal communication, Aug. 15, 1991; Robert T Lund, "R manufacturing," TechnologyReview, February/March 1984, pp. 19-29.

practices might change by the time the product enters the waste stream.[23]

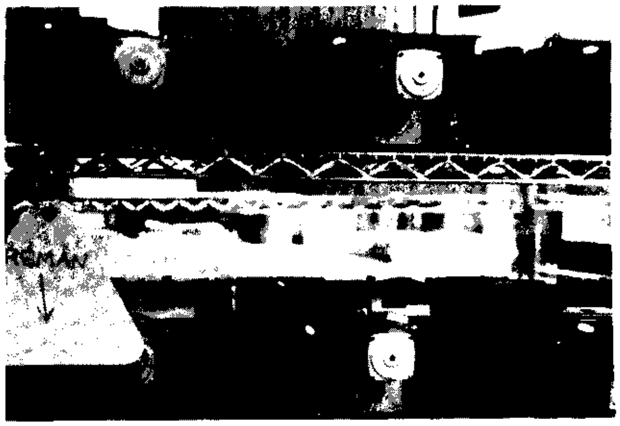
Just as important as designing for materials recovery is designing for the *use* of recovered materials. Developing design configurations that facilitate the disassembly and separation of product components is not enough. Companies must actually incorporate recycled materials and components into their products to bring about true environmental benefits. While the primary barriers to recycling are economic,[24] the limited availability of high-quality recovered materials can also complicate efforts to introduce recycled materials into new designs.[25] Contamin ation and indiscriminate mixing of materials during collection and separation can undermine recycling efforts, and chemicals added in the original manufacturing process may be difficult to remove, or may degrade the properties of reprocessed materials.[26] Even if materials are free of

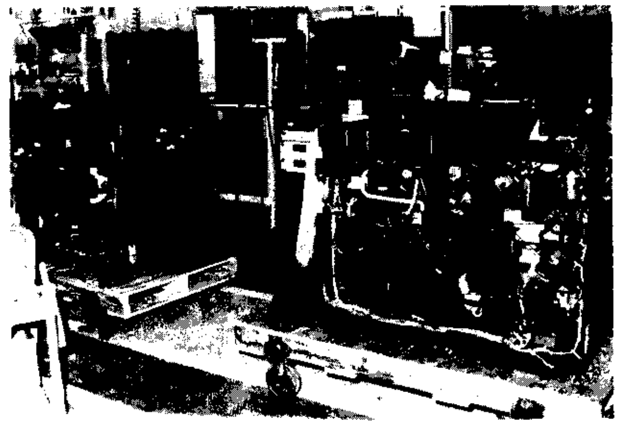
23 For example, even if designers radically altered the design of automobiles and household appliances to&y, current models would continue to enter the waste stream well into the next decade. Other products, such as household chemicals and batteries, can linger in basements and garages for years until eventual disposal. Thus, such time lags can complicate the efforts of designers to incorporate environmental objectives into their designs.

24 William L. Kovacs, "Dark Clouds Carry Silver Linings: Recyclable Materials Are the Basis for a Competitive Industrial Policy," *Resource Recovery,* August 1989, pp. 5-6.

25 The problems associated with the collection and processing of recycled materials are discussed extensively in the OTA report, Facing *America's Trash,* op. cit., footnote 9, pp. 135-190.

26 As an illustration, glass cullet itself is 100 percent recyclable, but it is difficult to make glass entirely from cullet because cullet lacks "fining" agents that are needed to reduce bubbles in the glass. (See Testimony of the Glass Packaging Institute before the Subcommittee on Environmental Protection of the Senate Committee on Environment and Public Works, June 6, 1991; Also see OTA, *Facing America's Trash,* op. cit., p. 151). In the case of aluminum, the presence of mixed alloys in discarded aluminum goods complicates the secondary production process. Unless the alloy mix is controlled precisely, the recovered aluminum will fail to meet product specifications. (See R.E. Sanders and A.B. Trageser, "Recycling of Lightweight Aluminum Containers: Present and Future Perspectives," Proceedings of the Second International Symposium-Recycling of Metals and Engineered Materials, held by the Minerals, Metals & Materials Society, October 1990).





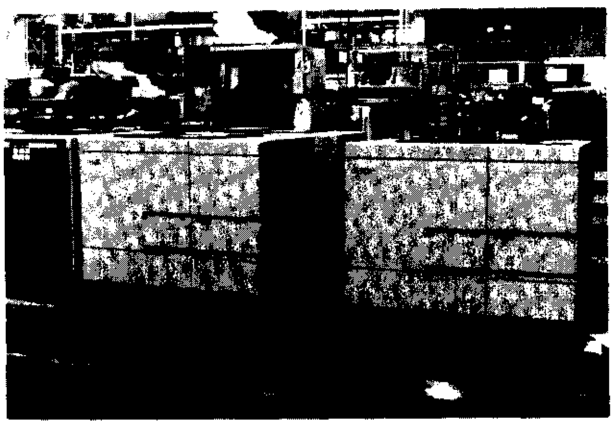


Photo credit: Xerox Corp.

Xerox reuses and remanufactures many of the sophisticated components from Its copiers. Remanufactured machines and new machines are assembled on the same production line to the same quality standards. Top left: "Remanufactured" and "new build" assemblies on the same cart adjacent to the production line. Above: In the middle of the production line the two machines appear similar—"remanufactured" on the left and "new build" on the right. Bottom left: At the end of the production line the two machines are indistinguishable.

external contamination, recycling processes may degrade the materials; for instance, paper fibers degrade with each successive reuse.

If designers are to use recovered materials more extensively, they must have confidence that these materials can provide similar performance and properties as virgin materials. This may be best achieved if their accustomed materials suppliers offer recovered materials with guaranteed properties alongside their offerings of virgin materials.[27]

Design for Comporting and Incineration

Apart from recycling and remanufacturing, there are two other materials management options that designers can consider: comporting and incineration.[28] Designers can facilitate comporting by making products entirely out of biodegradable materials.[29] For example, starch-based polymers and films can substitute for plastic in a variety of applications.[30] These starch-based polymers are inherently biodegradable, and easily composted.[31] Similarly, products could be designed for safe

27 Charles Burnette, Chairman, Industrial Design Department, The University of the Arts, Philadelphia PA, personal communication, Sept. 1, 1992.

28 Composting refers t. the process of biological decomposition of solid organic materials by microorganisms (mainly bacteria and fungi). "Compost" is the stabilized, humus or soil like product of this process.

29 As an illustration, Procter & Gamble's Pampers and *Luvs* brands contain about 80 percent compostable material. But the plastic backsheets On the diapers are not compostable. Thus, the compostable material must be separated from the backsheetbefore comporting. To eliminate this separation stage, P&G is currently developing backsheets made from compostable material. See the comments of Edward L. Artzt, Chief Executive Officer, Proctor & Gamble in *Beyond Compliance: A New Industry View of the Environment,* Bruce Smart (cd.) (Washington, DC: World Resources Institute, April 1992), pp. 36-40.

30 One company, Warner-Lambert, recently opened a large-scale manufacturing facility to produce such agriculturally derived polymers. The trade name of the polymer is Novon.

31 See Ramani Narayan, "Bioremediation/Biodegra&tion of Plastic Wastes by Composting," Proceedings of the Global Pollution Prevention Conference and Exhibition, Washington DC, Apr. 3-5, 1991.

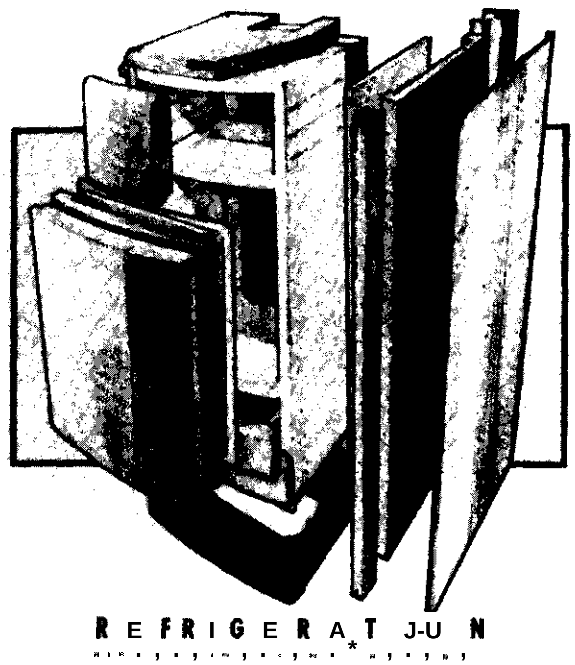


Photo credit: GE Plastics

The modern-day refrigerator is typically not designed for recyclability, and consequently is almost impossible to disassemble. Refrigerators use large amounts of polyurethane foam (this foam contains CFCs) that cannot be easily separated from different metal components. New refrigerator designs are beginning to incorporate modular concepts, as well as alternative forms of insulation such as silica aerogels or vacuum-based insulation.

incineration by avoiding the use of heavy metals and chlorinated organics.

For these opportunities to be realized, though, requires that product design changes be coordinated with new *systems* of product disposal and integrated waste management (see ch. 4). If products are designed for comporting or safe incineration, but end up being landfilled, the design improvements are effectively nullified.[32] Historically, there has been little, if any, coordination between the stages of design and waste management. This situation needs to change if society is to benefit from the environmental leverage afforded by design. Promoting greater coupling between manufacturing and waste management is a major challenge for policymakers (see ch. 6).

HISTORY OF GREEN DESIGN

The idea of green product design is not new. It was developed in the late 1960s and early 1970s, along with the explosion of environmental consciousness that led to the creation of the Environmental Protection Agency and to the passage of laws such as the Clean Air Act, Clean Water Act, and the Resource Conservation and Recovery Act.[33] During the 1980s, ideas such as design for remanufacturing and design for recycling were developed in technical journals and conferences, but the concept did not receive much attention from policymakers or the public.[34] Perhaps because of recent alarming headlines about global climate change, ozone depletion, and overflowing landfills, the issue has enjoyed a renaissance in the past few years. Several recent books and articles have explored how architects, engineers, industrial designers, packaging designers, and graphic designers can incorporate environmental attributes into their designs.[35]

Despite this 20 year history, however, the concept of green design has not yet been integrated into engineering education or practice. Indeed, until recently, "design for the environment" meant a design that protects the product against the effects of

32 Approximately half of the material currently disposed in landfills is potentially compostable. But even the most readily compostable portions of the waste stream, like yard clippings, are rarely composted because of poor public education and inadequate waste management. (See OTA, *Facing America's Trash,* op. cit., footnote 9.)

33 The idea was already well developed in 1970, the earliest year of OTA's literature search. See Jacob Friedlander and Merril Eisenbud, "Environmental Dangers Challenge Design Engineers," *Mechanical Engineering, November 1970,* p, 15, A discussion of environmentally sound product design and policy options to encourage it appears in the Second Report to Congress, "Resource Recovery and Source Reduction," U.S. Environmental Protection Agency, 1974. See especially appendix B: "Product Design Modifications for Resource Recovery, Source Reduction, or Solid Waste Purposes."

34 Charles Overby, "Product Design for Recyclability and Life Extension," American Society for Engineering Education Annual Conference Proceedings, 1979, p. 181; Robert T. Lund, "Remanufacturing," *Technology Review,* February/March 1984, p. 19.

35 See Avril Fox and Robin Murrell, Green *Design* (London: Architecture Design and Technology Press, 1989); Dorothy Mackenzie, *Design for the Environment (New York,* NY: Rizzoli International publications, Inc., 1991); David Wann, *Biologic: Environmental Protection by Design* (Johnson Books, 1990); Charles Overby, "Design for the Entire Life Cycle: A New Paradigm?' American Society for Engineering Education Annual Conference proceedings, summer 1990, and references therein; The World Wildlife Fund and Conservation Foundation, "Getting at the Source: Strategies for Reducing Municipal Solid Waste," Washington, DC, 1991; Tedi Bish and Suzette Sherman, "Design To Save the World," *International Design,* November/December 1990, p. 49.

Photo credit: Office of Technology Assessment

Consumers sometimes can leave separated materials at igloos or other containers placed in conspicuous areas by communities or firms running recycling programs.

moisture, corrosion, or weather. Designers' use of materials have undergone dramatic changes over the past 50 years, but these changes have evolved independently of environmental concerns, being driven primarily by technological innovation and economic competition among materials (see ch. 2).

This situation is changing rapidly, however. Many companies, large and small, are starting to change their process and product designs in ways that reduce both their own waste disposal problems and those of their customers.[36] Several government-funded projects are underway in the United States and Europe to develop environmental handbooks or checklists for designers (see chs. 5 and 6). For example, researchers in the Netherlands have developed computer software to assist designers in making environmentally sound choices.[37]

ALTERNATIVE VIEWS OF GREEN DESIGN

The idea of green design seems straightforward, but there is no rigid formula or decision hierarchy for implementing it. One reason is that what is "green' depends strongly upon context. While there are some environmental design imperatives that are sufficiently compelling to apply to many different products (e.g., avoiding the use of chlorofluorocarbons), in general green choices will only become clear with respect to specific classes of products or production networks. What constitutes green design may depend on such factors as the length of product life, product performance, safety, and reliability; toxicity of constituents and available substitutes; specific waste management technologies: and the local conditions under which the product is used and disposed. For example, designing a product to be recyclable makes little difference if the infrastructure for collecting and recycling the product do not exist.

On a deeper level, though, one's philosophical view of the relationship between the economy and the environment strongly conditions one's view of green design and the environmental "problems" it should address. One taxonomy of this relationship employs a set of five paradigms, ranging from "frontier economics' to 'deep ecology. ' '[38] Here we will discuss alternative views of green design for the three intermediate paradigms: "environmental protection, ' "resource management, " and "eco-development."

Paradigm I: Environmental Protection

In this paradigm, the environment is recognized as an economic externality that must be safeguarded through laws and regulations. Tradeoffs are seen between industrial competitiveness and protecting the environment (e.g., employment vs. protecting endangered species), and cost-benefit analysis is offered as a means of balancing the two. This view is fundamentally anthropocentric, with the principal concern being the effect of pollution on human health and welfare.

The "problem" in this case is that human society produces too much waste. This concept leads to policies that focus on reducing the quantity or toxicity of waste: e.g., waste prevention, recycling, or treatment. Similarly, the objective of green design should be to reduce the quantity and toxicity of

36 A diverse set of companies including 3M, Xerox, AT&T, Procter & Gamble, S.C. Johnson Wax, and Eveready have implemented programs of process and product reformulation to reduce levels of waste generation at both the manufacturer and post-consumer stages. See ***Beyond Compliance: A New Industry View of the Environment,*** op. cit., footnote 29.

37 The program, called SimaPro, is available from PRé Consultants, Amersfoort, The Netherlands.

38 One extreme, *frontier economics,* focuses on economic growth and emphasizes free markets and unbridled exploitation of resources. The other extreme, ***deep ecology,*** focuses on harmony with nature and emphasizes drastic reductions inhuman population and the scale of human economies. See Michael E. Colby, "Environmental Management in Development" World Bank Discussion Papers, Washington DC, 1990.

wastes requiring disposal, e.g., making products more recyclable, light-weighting, etc. Progress is measured in terms of increasing the efficiency of energy and materials use, i.e., reducing the quantity of energy and materials required per unit of production. This view does not concern itself explicitly with whether the physical flows of energy and materials through the economy are ecologically ''sustainable.

Paradigm 2: Resource Management

In this view, the environment is recognized as an economic externality that must be internalized in measures of economic performance and policy decisionmaking. The earth is seen as a closed economic system, and therefore the main challenge is to ''economize ecology. ' If those who use resources and generate pollution are made to pay the true price of those environmental services, this will lead to sustainable industrial development. Advancing technology is seen as an integral part of achieving more efficient use of energy and materials. Technologically advanced countries should aggressively transfer new, more efficient technology to developing countries, and assist them in stabilizing their populations.

The "problem" in this paradigm is that human society is managing its resources poorly, generating pollution that threatens to undermine the ecological productivity upon which the economy depends. The solution is to "get the prices right' through taxes on resource use and pollution, or perhaps tradable permits to pollute within sustainable limits. Such economic incentives are seen as providing more flexibility than regulations, so that industry can respond in the most cost-effective way.

This view assumes that environmental services can be monetized, and that functioning markets for these services can be created. It does not address uncertainties in the valuation of these services or in the correct determination of the relevant ecological thresholds or carrying capacities. It is primarily anthropocentric, since it is concerned with the stock of 'resources' available for human use, but extends its concern to quality of life of future generations as well as the present generation. Sustainable development is defined as maintaining a nondecreasing stock of human plus natural capital, implying some substitutability between the two.[39]

In the resource management paradigm, green design involves choices that conserve resources as well as reduce wastes. Emphasis is on the materials inputs in products, e.g., avoiding the use of materials that are toxic or become dispersed in the environment. In principle, the prices of material inputs would reflect their demand on environmental services, thus providing the correct signals to the designer. The resulting price changes would cause reorganization of the production system toward cleaner technologies and discarded materials would have a higher value, thus encouraging recovery and recycling.

Paradigm 3: Eco-Development

The eco-development paradigm stresses the co-evolution of human society and ecosystems on an equal basis. The earth is seen as a closed ecological system and therefore the principle challenge is to "ecologize the economy. " This view is less anthropocentric than the resource management view, emphasizing that nature has an intrinsic value that is independent of the value placed upon it by the human economy. Thus, this view has a moral or ethical dimension that implies a transformation of societal attitudes toward nature (not assumed in the previous paradigms).

The "problem" in this case is that the scale of human economic growth is inconsistent with the long-term coexistence of man with nature. Sustainability is defined as nondecreasing stocks of human and natural capital maintained independently; that is, no substitutability between technology and natural resources is assumed.[40] In the face of uncertainty about ecological thresholds and the world's carrying capacity, the "precautionary principle" applies: new technologies or development projects must demonstrate that they are consistent with sustainability as defined above before they are adopted. Progress is measured not in terms of efficiency, but in terms of the health of regional ecosystems as well as human health.

Policy objectives for development under this paradigm include moving toward a closed materials

39 This has been called the criterion of "weak sustainability. " See Herman E. Daly and John B. Cobb, ***For the Common Good: Redirecting the Economy Toward Community, the Environment, anda Sustainable Future*** (Boston, MA: Beacon Press, 1989).

40 This has been called the criterion of ''strong sustainability." Ibid.

cycle. The economy would rely principally on renewable sources of energy and materials, extracted at rates that would not affect ecological health. Nonrenewable resources would be recovered and recycled indefinitely. Instead of tradable pollution permits, tradable permits might be issued for the extraction of a freed quantity of nonrenewable materials.[41] The production/consumption system would be restructured to optimize the utilization of goods to satisfy essential human needs, rather than the ownership of goods to satisfy frivolous 'wants.' Green designs would avoid use of materials that are toxic to humans or ecological systems, substitute renewable for nonrenewable materials, and ensure that nonrenewable materials could be readily recovered for recycling.

Analysis

These three paradigms illustrate the different assumptions that underlie the environmental policy debate. They reflect different views of mankind's place in the natural world, and of its obligations to future generations as well as to other species. Present U.S. policy is most closely approximated by the environmental protection paradigm, while many environmental groups espouse the eco-development perspective. Resource management is the theme of reports such as the Brundtland Commission's "Our Common Future," the Worldwatch Institute's annual 'State of the World,' and the World Resources Institute's annual "World Resources."[42]

These paradigms also suggest different criteria for defining green design. In the environmental protection view, a product design maybe considered green if it results in 10 percent less waste than last year's design over its entire life cycle (waste prevention). The same design may be rejected from the eco-development perspective because it uses nonrenewable materials that are not recycled and do not biodegrade. Evidently, green product design within each succeeding paradigm involves satisfying a correspondingly broader set of criteria for compatibility with the natural environment.

In this chapter, we have defined green design as an extension of traditional design to include the goals of waste prevention and better materials management. This formulation might be criticized as being too conservative, since it suggests a narrow focus on the "outputs" of the production system that is characteristic of the environmental protection paradigm. Certainly, other formulations are possible. For example, an alternative definition focusing more on the "inputs" might involve reducing the use of toxic materials, and relying more on resources that are managed in a "sustainable" way. Such a definition might be more consistent with the eco-development paradigm.

In some cases, designers may have information about materials choices that bear directly on the destruction of irreplaceable resources, or the extinction of endangered species. An example might be avoiding the use of tropical hardwoods that are harvested from environmentally sensitive rainforests. In most cases, though, it will not be clear which choices are more ecologically "sustainable." It seems most practical to address global issues of ecological sustainability at the level of national policy, rather than at the level of the individual designer.

OTA chose a formulation of green design that suggests the most concrete actions available to the designer. A narrower focus on waste prevention and better materials management provides tangible criteria for evaluating the choices that designers make every day. The next chapter discusses various strategies that designers and companies can employ to reduce the environmental impacts of their products.

41 See Herman E. Daly, *Economics, Ecology, and Ethics: Essays Toward a Steady State Economy* (San Francisco, CA: W.H. Freeman, 1980), PP. 337-348.

42 Colby, op. cit., footnote 38.

APPENDIX 3-A: THE AUTOMOBILE DEVELOPMENT PROCESS[1]

Introduction

The automobile sold in the United States today is a complex product, not only in terms of the functions that it performs, but also in terms of the marketplace, and in terms of the wide set of goals, both private and public, that it is expected to meet. This appendix is intended to convey the many factors that influence automobile design decisions, and how environmental concerns enter the process. The following description of the automobile design process is necessarily generalized, but it captures the key issues and tradeoffs that govern contemporary automobile development.[2]

Automobile Product Development

Concept—The first stage in automobile design and development can be called "concept development." This stage in the process is essentially a strategic effort, which can take one of two forms. Most commonly, a particular set of market segments is identified, defined not only by demographics like age and marital status, but also by income, spending characteristics, and stylistic trends. The car concept that evolves from these considerations is a combination of appearance, features, and cost that is expected to attract enough purchases from the targeted groups to justify the development effort and to make the automaker money. As Charles Centivany, a Ford product planning manager, said, "In one sense we are looking for customer demand to pull us along, while looking for pockets not being filled, or that could be filled better. '

Another concept stratagem is to develop a product which can be used as a testbed for innovative vehicle technologies, either in manufacturing or in the product itself. The classic example of this kind of development in the domestic automobile industry has been the Chevrolet Corvette and, more recently, the Pontiac Fiero. Because the production volume is low, limited testing of innovative automobile technologies can be performed with low risk to the producer, and a wide range of innovations can be easily tested. For example, the composite automobile leaf spring was first introduced on the Corvette, although it now can be found in several other General Motors vehicles. Of late there has been considerable use of this stratagem at General Motors to develop manufacturing technologies. The Fiero introduced the space-frame vehicle manufacturing process, which has been considerably refined in two current General Motors products, the Saturn and the All Purpose Vehicles (APVs).

Whatever the original source of the ideas, the purpose of a vehicle concept is to supply an outline of the basic characteristics of the product under development, and a set of guidelines against which the results of the design process are to be measured.

Design Studio-The automobile concept is then passed to the design studios, where the concept is fleshed out on paper and, ultimately, in clay for review by the concept team and upper management. The focus at this phase of the process is to develop a vehicle shape that can accommodate the concept requirements while achieving those intangible characteristics known as "style." As a consequence, the studio draws upon a wide range of inputs in the course of developing the shape of the vehicle. These include past features of the product line as well as competitive product lines.

Although the design studio has historically drawn from U.S. sources, the recent globalization of the automotive market has led to international partnerships and outright acquisition of centers of styling excellence. In particular, the U.S. original equipment manufacturers (OEMs) have focused this effort on Italian and British design shops, although many elements of Japanese design have also been incorporated. Although the nation of origin of most designs can still be identified on sight, there has been a trend toward blurring the distinctions between the different schools of design. However, the Japanese have proven to be most mutable, as they have located many elements of their design effort in the United States, particularly California. For example, the

[1] This discussion is &awn from Frank Field, "Automobile Design and the Environment,'' contractor report prepared for the Office of Technology Assessment, May 1991.

[2] For a good overall view of the process, see James P. Womack, Daniel T. Jones, and Daniel Roos, *The Machine That Changed the World* (New York, *NY:* Rawson Associates, 1990).

[3] Christopher A. Sawyer; "It's All in the Planning," *Automotive Industries* (Radnor, PA: Chilton Co., January 1991), p.20.

popular Mazda Miata is the product of a U.S. design shop, and its appearance reflects these origins.

Frequently, the design studios will devise several potential vehicles for any one concept. These alternatives are winnowed down within the design studios and by corporate decisions until a single vehicle geometry is settled upon, usually following the presentation of a full-scale clay mock-up of the vehicle. Once the clay models have been approved by concept and the higher levels of management, car development is turned over to advance engineering.

Advance Engineering—Advance engineering is the stage in the vehicle development process where what most people think of as product design really happens. Here, the product of the design studios and the concept teams is converted into the first real engineering drawings of the automobile.

The classic approach to this problem is to divide the vehicle into functional subsystems, such as the body, the chassis, the powertrain, and the interior. The division of the vehicle into subsystems is a critical organizational simplification of the vehicle development process. These subsystems are defined to isolate engineering decisions within the subsystem design group. Without this isolation, the engineering problem is simply too large to be satisfactorily resolved. Instead, specific requirements (known as ''design bogeys' are developed at the advance engineering level which must then be implemented by the product engineers. Provided that these bogeys accurately reflect the objectives devised at the concept level, and are satisfactorily backed up with good engineering practice, the automobile can be successfully designed.

Two of the most critical design bogeys established at advance engineering are cost and weight. Both of these are central to the success of the designers in meeting the requirements of the vehicle concept. Cost targets must be met in order to meet the pricing objectives that underlie the marketing strategy, and weight targets are critical to assuring that the vehicle performance (i.e., fuel economy and vehicle handling) will meet the concept goals.

Since 1978, fuel economy specifications have been principally dictated by Federal Corporate Average Fuel Economy (CAFE) requirements. No automaker can afford to ignore CAFE when devising its vehicle designs. CAFE enters into the automobile design cycle at its inception. The strategists, in the course of defining the vehicle concept and the product strategy, must establish a target fuel economy for the product. The design studios are not directly affected by this target, although aerodynamic drag and vehicle rolling resistance (two key factors along with engine performance that determine vehicle fuel economy) are a direct consequence of vehicle shape and weight, respectively. However, once the concept is passed to advanced engineering, the need to meet CAFE becomes one of the critical design parameters, probably second only to cost.[4]

Thus, weight bogeys become the primary way in which fuel economy is managed by the advance engineering departments. For a new design, the advance engineering groups will establish weight targets for each of the major vehicle subsystems. At the same time, the materials composing those subsystems are largely determined, particularly for the body and the chassis. CAFE has thus encouraged automakers to use more lightweight materials like plastics or plastics composites. This has raised a number of concerns about the recyclability of automobiles. With a decreasing metal content in cars, existing auto scrap dealers are finding it increasingly difficult to maintain business viability.[5]

Apart from CAFE requirements, designers must also give consideration to vehicle emission and safety regulations. The need to meet certain emission levels affects engine performance specifications,[6] while safety standards affect a number of design parameters including the choice of materials.

[4] CAFE regulations have a ripple effect all the way down to automobile suppliers. For example, Goodyear's new "environmental tire' is designed to improve fuel efficiency. The tire weighs less and has reduced rolling resistance.

[5] Automakers are working with the plastics industry to develop the technologies necessary to make the recovery of plastics economical, but difficult barriers remain to be overcome (see box 4-C, ''Design and Materials Management in the Auto Industry").

[6] The aims of limiting emissions and improving fuel economy have a peculiar interaction. On one hand, improved fuel economy implies that energy is more efficiently extracted from the fuel. If so, a greater fraction of the available fuel is burned (reducing hydrocarbon emissions) and a larger fraction of the fuel is completely combusted (reducing the amount of carbon monoxide released). On the other hand, this improvement in efficiency is generally achieved by operating the engine at a higher temperature, which unfortunately increases the amount of nitrogen oxides that are produced. Additionally, changes in the operating condition of the engine (higher speeds, acceleration etc.) require changes in the way in which combustion is affected (spark advance, timing, etc.).

Once the basic design bogeys are established, the advance engineering groups turn to developing the first engineering drawings of the vehicle subsystems. These drawings are fairly general, since much of the detail work requires more resources than are usually available at this level. However, it is at this stage in the design that the basic shapes of the critical vehicle elements are devised, and where the majority of the vehicle material specifications are made.

The most important element of engineering design at this and subsequent stages in the automobile design process is past experience. Vehicle designs almost always start with a consideration of past designs having similar requirements. Automobile designers rarely start from "blank paper" when designing vehicles, primarily because it is inefficient for them to do so. There are several reasons for this:

1. *Time pressure:* A crucial element of the automobile development process is the issue of time. Automakers have found that, like so many other industries, time to market is central to market competitiveness. While tooling acquisition and facilities planning are major obstacles to shortening the development cycle, they tend to be outside direct control of the automaker. Design time, however, is directly under the control of the automaker, and reduction of design time has been a major goal in vehicle development.
2. *Cost pressures: The* reuse of past designs also saves money. In addition to the obvious time savings described above, the use of a proven design means that the automaker has already developed the necessary manufacturing capability (either in-house or through purchasing charnels). Furthermore, because the old part has a known performance history, the product liability risk and the warranty service risk are also much reduced.
3. *Knowledge limitations:* Underlying factors 1 and 2 is the fact that the automobile engineering design community is still developing the information and analysis base needed to do analytical design of automobile components. This limitation does not arise from a lack of engineering talent, although some of the domestic OEMs have had a tendency to lay off engineering staffs when times get hard. Rather, the limitation is a consequence of a real lack of knowledge of the structural loads that the various automobile subsystems must be able to sustain. In other words, the automakers have only a rough idea of what loads a car will experience in service. Given this limitation, it is far more efficient to start with a past design which has proven to be successful, and to modify it to meet the geometric limitations of the new vehicle. Starting at this point, and backing up the design with prototyping and road testing, has proven to be far more efficient.

This normative design process has been central to automobile design for decades. While it may seem to be an unsophisticated way to design, it is important to recognize that designing a car is not the same as designing an airplane. The scale of production, the cost of the product, and the manufacturing technologies demand a completely different approach to the problem, particularly in the absence of inexpensive, widely distributed computing power. With the availability of such tools, the automakers have begun to incorporate more analytical design approaches, but the normative approach has continued to serve automobile engineering well, in the main.

Product Engineering/Manufacturing Engineering—The advance engineering group subdivides the automobile into functional subassemblies, which are passed to individual product engineering groups for final, detailed designs. The broad outlines of the advance engineering drawings are filled in, and the details of tolerance and material are worked out in the product engineering groups.

Again, past designs play a large role in defining these designs, but a harder look at the individual elements can be taken at this level. This effort will be taken, for example, when design bogeys prove difficult to meet using the historical designs. The changes may involve changing a material specification, although they usually focus upon changing the geometry of the part.

Manufacturing engineering becomes a major part of the work done by the product engineers. Although all phases of product development are geared to maintain manufacturing feasibility, the product engineers have to work closely with manufacturing engineering, not only to assure that the components that they design can be manufactured, but also to guarantee that the assembly of the rest of the car is not compromised. For example, while the engineer designing the inner panel of an automobile door might want to reduce the thickness of the panel to reduce weight, the production engineers require that the inner door has enough openings to assure that the door mechanisms can be easily installed, thus requiring a thicker, stiffer panel.

Non-OEM Contributions to Product Development— There are two major classes of actors in the automobile product design and development process who are not directly a part of the automobile companies. The first of these is the custom design house. These houses offer freelance services which support the design studios or the engineering designers. In the former case, these groups are called upon to bring particular knowledge or awareness of the automobile marketplace to enhance the appearance of the studio product. Although these operations can exist almost anywhere, they have historically been located either in Michigan, near the OEMs, or, more recently, in California, near the largest market.

Engineering support has become an increasingly important supplement to the OEM product development cycle. This is a consequence of the increasing engineering difficulty associated with the increasing demands being placed on the performance of the automobile, and the decline in the amount and breadth of engineering talent within the OEMs who have been forced to trim engineering and development effort to maintain financial goals.

These specialty engineering shops are not the only manifestation of this development. The other major actors in this area are the material and parts supplier industries. All of the major material supplier companies have followed the lead of the plastics suppliers and have made engineering, manufacturing, and design support of their material an integral part of their material selling efforts. Today, most of the major material suppliers not only offer their materials, but also finished designs of components which use these materials, backed up with complete engineering analyses. Similarly, major component and subassembly suppliers have also taken on many elements of product development and design that have traditionally been associated with the automobile companies.

In conjunction with this change has come the trend toward what has come to be called “modular design. ” Essentially, modular design focuses on the idea that the automobile is composed of components of definable functionality which can be designed and developed in isolation from the rest of the vehicle. Although this strategy has really only come to full expression in the electrical system and in parts of the powertrain, the idea has particular attraction in the current design framework. By adopting such a strategy, a number of subassemblies or modules can be easily mixed or matched, thus retaining economies of production while offering a diverse family of products.

Summary

The process of automobile design and development is a complex endeavor that takes a product concept through stages of increasingly detailed engineering and manufacturing specifications, based on product performance and cost goals. But these performance and cost targets are affected by a number of external constraints. Because of federally mandated fuel economy and emissions requirements, environmental considerations are a major factor underlying almost every stage in the vehicle development process. This inevitably results in design tradeoffs among such factors as performance, fuel efficiency, and recyclability.