DESIGN FOR ASSEMBLY: A CRITICAL METHODOLOGY FOR PRODUCT REENGINEERING AND NEW PRODUCT DEVELOPMENT

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Design for assembly (DFA), a methodology which improves the manufacturability of assembled products, has gained significant attention in recent years. DFA serves a critical role in reengineering existing products and in supporting effective design and development of new products. The increased competitive significance of rapid and highly effective new product development efforts continues to increase [13], highlighting the need for managers and engineers from both manufacturing and design engineering areas to gain a better understanding of DFA and related tools [12].

WHAT IS DESIGN FOR ASSEMBLY?

DFA is a systematic analysis process primarily intended to reduce the assembly costs of a product by simplifying the product design. It does so by first reducing the number of parts in the product design, and then by ensuring that remaining parts are easily assembled [5, 10]. This close analysis of the design is typically conducted by a team of design and manufacturing engineers, although other functional groups such as field service and purchasing may also be involved. DFA techniques can be applied manually or with software. Both approaches lead to a simpler product structure and assembly system [9]. DFA is used for discrete manufacturing products, and primarily for durable goods, but occasionally for consumer products. DFA is typically applied to subassemblies or small discrete products such as tape recorders, computer printers, and gunsight assemblies [7].

DFA goes by many names, such as DEM (design for economic manufacture), DFMA (design for manufacture and assembly), or PDFA (product design for assembly). DFA is often confused with, but is actually a subset of, DFM (design for manufacture). DFM describes a class of techniques to improve product manufacturability for all types of products, not just assemblies.

DFA was developed with the assumption that the bulk of manufacturing costs are set in the design stage, before any manufacturing systems analysis and tooling development is undertaken [5, 10]. DFA provides a quantitative method for evaluating the cost and manufacturability of the design during the design stage itself. DFA analysis roughly calculates expected unit material and labor (and / or equipment) assembly cost, and also finds an "efficiency rating" which is a relative measure of the product's ease of assembly [9]. Many products have efficiencies as low as 20% before DFA analysis is applied, and then achieve efficiencies higher than 70%. These product cost and efficiency figures can then be used to evaluate alternative design and assembly approaches early in a new product development effort.

DFA algorithms build on many earlier industrial concepts including group technology, producibility engineering, product rationalization, and time and motion studies. In many ways DFA is a structured, automated approach to time and motion industrial engineering, combined with a bit of design philosophy via design axioms and guidelines [1, 14].

Traditional industrial engineering concepts such as producibility engineering and value engineering are sometimes called qualitative approaches. Producibility engineering focuses on the efficient manufacture of piece parts, and so focuses on cost minimization. Value engineering considers part functionality, performance, and cost. Exclusive focus on piece parts can lead to usage of many individual parts that are individually less complex and less expensive; however, this leads to higher system costs due to part proliferation. DFA moves beyond this to consider effective *system design*, and does so by rationalizing and improving the assemblies [1, 14]. By integrating design rationalization theory, design axioms, engineering time study methods, and conventional wisdom on effective design practices, DFA "allows holistic [quantitative] analysis of design, materials, costing, and manufacturing processes [9]."

Primary Design-for-Assembly Applications

There are two uses of DFA. It may be used to redesign a product already in manufacture (or a product being "remarketed," or reverse engineered). In this case, the product is disassembled and reassembled with special consideration of parts handling (feeding and orienting) and attachment (insertion) times and costs. These times and costs are found in data tables, via software or by empirical observations.

DFA may also be used for analysis of a product while it is in design. Some firms may choose to apply the analysis later in the design stage, while others may do so early when major design alternatives for the proposed new product are evaluated. In either case, there are several steps in the analysis:

- First, an initial design is developed or proposed.
- Second, this design alternative is assessed penalty points for each feature of the design.
- Third, these points are aggregated to determine the "design score" efficiency of assembly for the design.
- Fourth, the product is "redesigned" using part and product level design rules coupled with consideration of annual volumes and existing manufacturing processes.

A typical design guideline is achieved by software queries asking these questions for the case of two parts connected by a fastener: "Does the fastener part move? Does it have to be a different material from the two parts? and, Does it have to be removed for servicing?" If the DFA team's response to all three questions is "no," then the software would advise the team to make the assembly as a single part, thus eliminating two parts [4]. Even with DFA's rules, guidelines, and measures, the last analysis step often requires considerable engineering creativity. DFA, to some degree, is still an art.

DFA Objectives and Intended Results

The primary objective of DFA is to minimize part counts [3]. This leads to fewer parts that must be manufactured and assembled, fewer parts that can fail, and fewer interfaces between parts. For example, each part has a "tolerance," or allowable error, in its specifications. The compounding of tolerances across many parts in an assembly leads to "tolerance stackup" which can greatly reduce product quality. Further, each part interface is a potential source for failure [15]. Individual part failures, tolerance stackup, and part interface problems are reduced as the number of parts is minimized. DFA's second objective is to have remaining parts of a nature that they are easily assembled together [3]. These objectives lead to the ***primary expected DFA results*** for the assembly:

- Reduced material cost
- Reduced labor and / or automatic assembly cost
- Reduced assembly cycle times
- Higher product quality and reliability.

A great number of beneficial secondary results also accrue from DFA usage. Often, the total product development time is reduced greatly because the design engineers only actually design the product once, since it is manufacturable on the first try. This avoids having multiple and time-consuming "build-test-fix" loops. Manufacturing systems analysis and tooling ramp-up are then much simpler, quicker, and cheaper. New capital equipment may be avoided or simplified, cutting development costs and times. Purchasing, documentation, and other manufacturing service aspects are easier and quicker, and the entire product development effort gains from simultaneous engineering aspects which cut time and increase product quality [9, 15]. With appropriate functional involvement, product serviceability is enhanced, as is shop-floor employee safety through easier (ergonomic) assembly [15]. DFA enables usage of automation due to simpler assembly requirements. In fact, DFA first became popular as a tool to facilitate product design for automated assembly.

Major but indirect results from DFA usage include cross-functional organizational integration [15]; data collection, synthesis, and analysis that benefits other projects; supplier integration [9]; and better understanding of the product development process, the product itself, and the primary design and manufacturing technologies the company uses. Other outcomes arise from reduced "complexity" due to having fewer parts. These advantages include: lower inventories, lower purchasing costs, reduced material handling, reduced documentation, and other reduced overhead; improved and orderly materials flows; reduced shop floor and inventory space; and simpler vendor, distributor, and service relationships [8]. Overall system cost reductions arising from sources other than direct labor and direct material can be hard to quantify, but may be much greater than the actual direct cost reductions [4, 8].

There are many DFA success stories. The classic example is IBM's 1985 redesign of a printer previously outsourced to Seiko Epson (Japan). This printer, the Proprinter, was intended for automated assembly. The DFA redesign resulted in 91 of 152 original parts being eliminated, with assembly time being cut from 30 to three minutes. Currently, the assembly is being done manually because the product is so easy to assemble [11]. A more recent case is that of NCR's model 2760 point-of-sale cash register terminal. Relative to the predecessor model, use of DFA cut assembly time by 75%, reduced assembly parts by 80%, and diminished the number of suppliers by 65%. This usage has cut an estimated $1.1 million in direct labor over the life of the product [11]. NCR estimates that "materials, labor, and overhead costs associated with one small screw used in the point-of-sale terminal would have amounted to over $12,500 over the life of the product [15]."

PREPARING FOR DFA ANALYSIS

The DFA Team

DFA is both an organizational and a technical tool. While champions for DFA can come from very high levels in an organization, the people who actually implement DFA tend to be subassembly and assembly design engineering section managers, senior manufacturing engineers, and individual engineers. A typical DFA team is composed of the design and manufacturing engineers dedicated to a subassembly. For large or critical subassemblies, many senior engineers and engineering managers may get involved in a DFA team. For smaller designs, such as a simple printed circuit board, a pair of design and manufacturing engineers may work together. Other development and manufacturing service functions can also be represented in the team, including test engineers, purchasing and vendor engineers, human factors people, materials planning, safety and quality people, and documentation specialists. Other downstream groups that may be involved include suppliers, distributors, field service, packaging engineering, and customers. These constituents can provide particular perspectives on the outcomes of various design choices. In some cases they may provide information leading to more and better design alternatives, and may aid in evaluation of the achievability of each alternative.

As with any team, there may be problems in gaining cooperation and consensus among individuals of widely different backgrounds and perspectives. This potential problem should be anticipated. Appropriate and acknowledged team leadership is required for effective DFA analysis to occur [15].

Training

Training in the techniques of DFA rules and software is required, and generally can be completed in a day. Use of DFA guidelines and software leads to recognition of areas that could profit from improvement. However, DFA cannot tell the designer exactly what to do to achieve improvements—it simply provides guidelines and design insight. The designer must still be creative in determining alternative approaches that might resolve or reduce problems. Accordingly, designers' creativity and experience help greatly in efficiently and effectively completing the analysis.

Data Requirements

DFA requires a substantial amount of data on the exact nature of the individual parts in the subassembly, materials used, tolerances, etc. Further, detailed assembly characteristic information on the types of assembly motions, task times, and labor and equipment costs are also required. Some of this data can be found in DFA handbooks, in traditional manufacturing and industrial engineering handbooks and tables, via software support, by empirical time and motion studies, in cost accounting and MRP data, from group technology parts databases, and other sources. Costs and efficiency scores cannot be determined unless data is complete. To the degree that data is not conveniently available, the time to conduct DFA analysis is lengthened while data is gathered or estimated. Yet, once data is collected, it tends not to outdate rapidly, and so can be stored in databases to support future DFA usage. NCR, IBM, Ford, and others have accumulated "years of research data on assembly times, material properties, machine rates, and manufacturing processes [15]."

Analysis Steps

DFA costing and efficiency scoring is tabulated manually on evaluation worksheets or via computer software evaluation support using simple algorithms. For a given design, each assembly step is broken down into time and motion primitives such as part orientation, feeding and insertion times, and motions. Costs are attached to these times and motions, and materials costs are added. This stage of analysis leads to estimates of unit cost and statements of design efficiency. A powerful benefit of DFA usage is this quantification of assembly efficiency the scoring methods facilitate. It provides a figure on which to focus, gives manufacturing engineers something to point to when they complain about lack of manufacturability, and quite tangibly shows levels of improvement achieved through alternative designs [15].

In the next stage of the analysis, the DFA team actually redesigns the product following a number of design rules [5, 15]. For piece parts, such rules include:

- Avoid projections and holes that lead to tangling
- Make parts symmetrical to avoid extra orientation efforts
- If symmetry cannot be achieved, provide asymmetrical features that can be used for orientation.

Product-level rules include:

- Combine and eliminate parts whenever possible
- Design for solely bottom-up (or top-down) assembly
- Improve access to assembly locations in the product
- Optimize part handling and avoid separate fasteners.

Figures 1, 2, and 3 illustrate steps in the DFA analysis process. Figure 1 shows a pressure recorder device, a small electro-mechanical assembly, as it was originally designed. Figure 2 contains the evaluation worksheet for this design. Notice (in the lower right corner) that this design has an assembly efficiency of 6%. The DFA team applied DFA guidelines and resulted in the improved assembly design shown in Figure 3 [5].

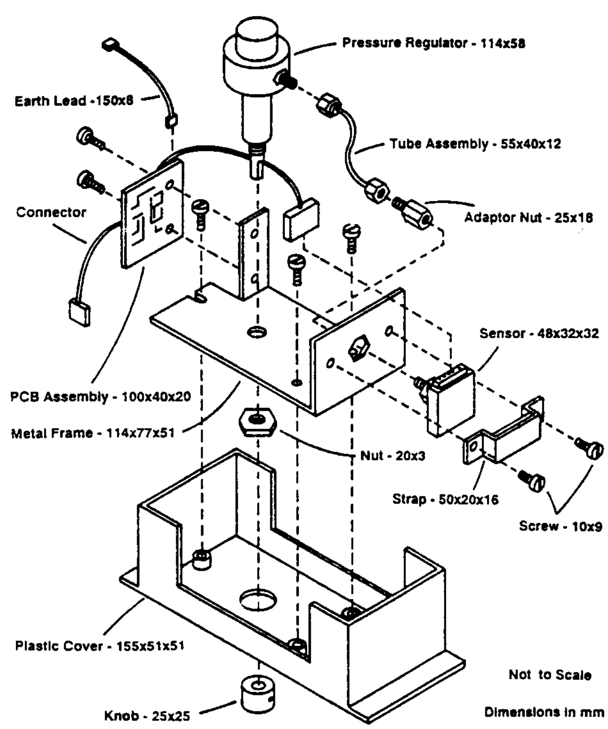

FIGURE 1: Pressure recorder assembly [5]

DESIGN FOR MANUAL ASSEMBLY WORKSHEET

1	2	3	4	5	6	7	8	9	Name of Assembly: PRESSURE RECORDER
1	1	30	1·95	00	1·5	3·5	1·4	1	Pressure regulator
2	1	30	1·95	06	5·5	7·5	3·0	1	Metal frame
3	1	00	1·13	39	8·0	9·1	3·6	0	Nut
4	1	–	–	98	9·0	9·0	3·6	–	(Reorient /turn over)
5	1	30	1·95	08	6·5	8·5	3·4	1	Sensor
6	1	20	1·80	08	6·5	8·3	3·3	0	Strap
7	2	11	1·80	39	8·0	19·6	7·8	0	Screw
8	1	–	–	99	12·0	12·0	4·8	–	Apply PTFE tape to sensor
9	1	10	1·50	49	10·5	12·0	4·8	0	Adaptor nut
10	1	91	3·00	10	4·0	7·0	2·8	0	Tube assembly
11	1	–	–	92	5·0	5·0	2·0	–	(fasten 2nd tube nut)
12	1	83	5·60	31	5·0	10·6	4·2	0	Earth lead
13	1	83	5·60	08	6·5	12·1	4·8	1	PCB assembly
14	2	11	1·80	39	8·0	19·6	7·8	0	Screw
15	1	–	–	98	9·0	9·0	3·6	–	(turn assembly over)
16	1	30	1·95	08	6·5	8·5	3·4	0	Plastic cover
17	1	30	1·95	08	6·5	8·5	3·4	1	Knob
18	1	–	–	92	5·0	5·0	2·0	–	(tighten set screw)
19	1	–	–	98	9·0	9·0	3·6	–	(turn assembly over)
20	3	11	1·80	59	12·0	41·4	16·6	0	Screw
						225 (TM)	90 (CM)	5 (NM)	design efficiency = $\frac{3 \times NM}{TM}$ = 0·06

FIGURE 2: Completed worksheet for pressure recorder [5]

IMPLEMENTING AND CONDUCTING DFA

A Short Case Study

Burke and Carlson [6] describe a multistep process for implementation of DFA in Ford's Transmission and Chassis Division:

- Provide a DFA overview to senior management
- Choose a DFA coordinator / champion
- Define design objectives (e.g., to reduce costs, to identify future development needs, etc.)
- Choose a pilot program (e.g., a given new or old product) and test a part (e.g., a subassembly) within that program
- Identify the team structure and individual members
- Coordinate training
- Have a first workshop
- Continue meetings as needed.

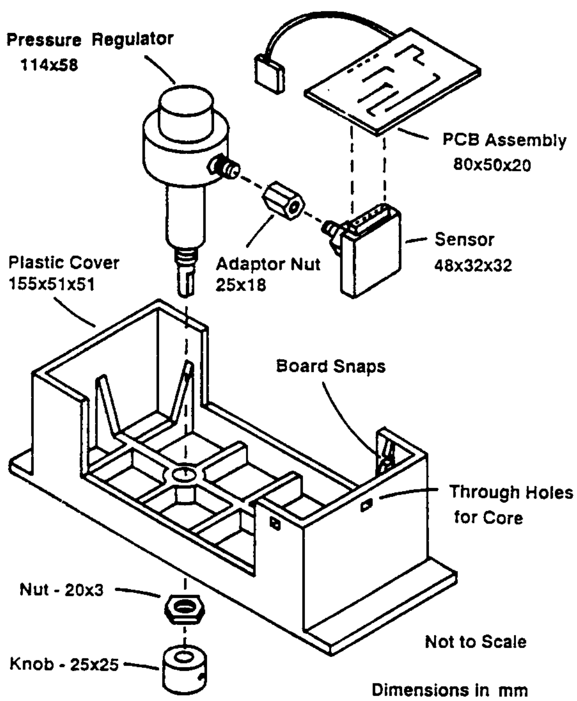

FIGURE 3: Proposed redesign for pressure recorder assembly [5]

Ford decided to apply DFA to an automobile transmission system. Activities at the first DFA workshop and subsequent meetings included:

- Review of DFA principles
- Review of parts lists and current assembly processes
- Assignment of subteams to analyze particular assembly sections, with at least two different teams looking at each section in order to provide multiple ideas
- Analysis of the existing design
- Analysis of proposed redesigns
- Comparison of the original design with proposed designs
- Prioritization of all new design ideas into A, B, and C priority categories
- Incorporation all of A and B design choices into one design analysis
- Assignment of design responsibilities
- Coordination of reviews and follow-up meetings.

Ford spent 2,500 hours over nine months on the design of this transmission, and has used learning from this project on subsequent designs [6]. In contrast, one firm applied DFA analysis to a relatively small subassembly and achieved a redesign in half a day. The firm then spent two days documenting the design changes [7].

The Ford implementation provided many benefits. They were able to incorporate supplier experience and Ford manufacturing experience early in the design cycle. Teamwork was promoted and communication increased between product engineering, manufacturing engineering, and suppliers. A better understanding of the design's impact on manufacturing cost was gained. An easily modified database on the assembly of transmissions was developed which could be used to evaluate future designs and engineering changes. In addition, design engineers now have a much better sense of assembly requirements [6].

Organizational Issues and Implementation Problems

DFA needs, and builds, extensive databases and efficient cross-functional communication. To the degree that data and communication skills are already on hand, DFA implementation is likely to be more successful. A firm can "buy" data from consultants or other manufacturing firms who have accumulated large databases of manufacturing and design information. However, a firm cannot buy a new organizational structure to increase communication levels and facilitate DFA. Accordingly, new organizational structures must be initiated as soon as is reasonable.

A recent survey identified a number of problems firms experienced in using DFA and overcoming resistance to change [7]. These problems included:

- Not enough time to perform the analysis
- Uncertainty over DFA benefits
- The sense that DFA would not work on that firm's products
- Getting manufacturing involved in the design stage
- Lack of confidence in management for support.

Common implementation errors were:

- Accidental misuse of software and constrained access to it
- Analysis done too late in the product development effort
- DFA methodology objectives misinterpreted
- Not developing team-style experience
- Not gaining management support.

Other major barriers were: data availability problems, resource problems, and problems with understanding the technique. These problems were resolved by:

stressing the organizational benefits; increasing software training and personnel exposure to DFA; demonstrating other success stories; and gaining and showing top management support [7].

Inadequate access to resources is a major problem. In one implementation, team members included individuals from: product, assembly, manufacturing, and industrial engineering; design; production; quality control; price estimation; and part and machine tool suppliers. However, due to resource problems, not all functions were fully represented continuously.

Misinterpretation of DFA methodology can be avoided if adequate training is provided. Typically, Ford DFA team members initially learn the DFA philosophy and techniques in a two-day in-house class. This training session also provides the opportunity for the new DFA team to "play" by analyzing a simple, existing product first. This initial training is followed by occasional two-hour refresher courses [6].

One problem that can occur is design engineers complaining that DFA usage slows down their schedules. It is true that DFA lengthens the design stage; however, it cuts total product development time. It can be difficult for some people to see the "down-the-road" benefits [15]. A related problem is that traditional performance measures evaluate individuals, while DFA requires team performance. In an effort to devise new performance measures to support DFA usage, CalComp put in place goals that required engineers to do early analysis. Engineers were to beat old cost and performance targets and achieve the "three 20s," that is, have less than twenty parts, have less than twenty suppliers, and have suppliers located less than 20 miles from the plant [15]. Others have questioned the necessity for setting strict numerical goals since shooting for arbitrary numerical results does not always lead to the most desirable outcome [2].

DFA increases the amount of collaborative decision making and moves the decision activity down one level in the organization. DFA implicitly transfers authority from bosses to workers. This may be resisted by those unwilling to lose power [15].

Another problem is that many firms apply DFA after they find that a product is not producible [7]. While DFA can be used in this sort of remedial application, it gains the greatest benefits when used early in the development project, rather than after initial manufacturing has started.

DFA is not an instant fix. While training and consulting assistance can help, managers and engineers must have the right spirit for collaborative, cross-functional work. Prior cross-functional activity and a culture leaning towards such interaction is quite beneficial. The human barriers are great since there is a tendency for people to resist sharing knowledge and potentially losing power. In addition, "egos, sacred cows, territoriality, and fear are likely reactions" to initial DFA usage in some firms [15].

DFA'S LIMITATIONS

DFA has many application limitations. Since it is employed to optimize assemblies, it is often used for smaller and medium-size products, or for the numerous subelements of larger systems [7]. DFA does not specifically support system-level applications.

DFA specifically requires that design and manufacturing engineers work together. Yet, it is often too easy to leave out representatives from other functional areas, suppliers, and customers who should be involved in the process. While IBM's Proprinter is lauded for a fourfold increase in reliability, it is not considered easily serviceable. In this case, field service had limited involvement in the DFA team [2].

Increased product reliability and ease of use arise from utilization of DFA; however, DFA alone does not aid in assessing customer desires, setting product requirements or technical functional specifications, or conducting engineering functional analysis. Further, DFA does little to assist up-front product conceptualization in a product development effort [9]. DFA simply advises regarding manufacturability of a design, given that the design meets functional goals already. DFA can make radical changes in the product structure, but does not change function. Nonetheless, DFA does assist design and manufacturing engineers in using technologies other than ones they are most comfortable with since it helps them visualize alternative approaches to realizing the product [15].

TECHNOLOGIES AND PRACTICES WHICH COMPLEMENT DFA

The full potential of DFA is achieved when it is employed with other tools and approaches, some of which compensate for its limitations or complement its capabilities. For example, DFA is used with quality function deployment (QFD) techniques to determine the feasibility of achieving customer requirements for a new product. DFA may be used with design of experiments or "robust engineering" techniques to determine cost-efficient and high-performance product configurations and manufacturing processes. DFA is an essential part of concurrent engineering and life cycle costing analyses since it provides early product cost estimates and an early view of manufacturing requirements.

Xerox and others have used DFA as a method for competitive benchmarking in addition to analysis of their own products [2]. It is a tool for coordination, selection, and integration of suppliers [9]. DFA data can be input into spreadsheets or MRP II information systems to perform business and manufacturing planning. DFA analysis results can be input to manufacturing simulations for extensive costing and materials flow analyses. Similarly, part data may be electronically communicated to computer-aided manufacturing tools.

The extensive part and manufacturing process data which DFA requires may already be available in MRP files, in group technology databases, purchasing, or cost accounting records. This data can be taken and used immediately, avoiding the need for time-consuming empirical analysis and information generation. Alternatively, the data gathered to support DFA can help these other functions. DFA data can be used to particularly great advantage via group technology principles to generate part families, control part proliferation, design manufacturing cells, etc. DFA's benefits are magnified when used in conjunction with such complexity reduction and information intensive applications.

CONCLUSIONS

DFA may be employed in product reengineering or new product development. The primary results of DFA usage are reduced unit costs, shortened manufacturing lead times, and increased reliability. In addition, DFA aids reduction of product development time and cost, helping speed products to market. DFA is applicable in many contexts, but requires appropriate organizational support and linkage with other tools to achieve the greatest benefits. Today's extraordinary level of international competition, coupled with the increased competitive significance of high quality new products that reach market quickly, point to the need for understanding and applying critical new methodologies such as design for assembly.

REFERENCES

1. Andreasen, M. M., S. Kahler, and T. Lund. *Design for Assembly.* New York: Springer-Verlag, 1983.
2. Bebb, H. B. "Implementation of Concurrent Engineering Practices." *Concurrent Engineering Design Conference Proceedings.* Society of Manufacturing Engineers, Dearborn, MI (1990).
3. Boothroyd, G. *International Journal of Advanced Manufacturing Technology* 2, no. 3 (August 1987) Bedford. U.K.: IFS Publications Ltd.
4. ———. "Making It Simple: Design For Assembly." *Mechanical Engineering* (February 1988): 28–31.
5. ———, and P. Dewhurst. *Product Design for Assembly.* Wakefield, RI: Boothroyd Dewhurst Inc., 1989.
6. Burke, G. J., and J. B. Carlson. "DFA At Ford Motor Company." *Proceedings of the 4th International Conference on Product Design for Manufacture and Assembly* (1989).
7. Dewhurst, P. "DFMA and Team-Working—A Cultural Revolution in U.S. Industry." *Concurrent Engineering Design Conference Proceedings.* Society of Manufacturing Engineers, Dearborn, MI (1990).
8. Hagel, J. "Managing Complexity." *McKinsey Quarterly* (Spring 1988): 2–23.
9. Kirkland, C. "Meet Two Architects of Design-Integrated Manufacturing." *Plastics World* (December 1988).
10. Nevins, J. L., and D. E. Whitney, eds. *Concurrent Design of Products and Processes.* New York: McGraw-Hill, 1989.
11. Port, O. "Pssst! Want A Secret for Making Superproducts?" *Business Week* (October 1989): 2.
12. Rosenthal, S. R., and M. V. Tatikonda. "Competitive Advantage Through Design Technologies and Practices." In *Integrating Design and Manufacturing for Competitive Advantage,* edited by G. I. Susman. Oxford: Oxford University Press, 1992.
13. ———. "Time Management in New Product Development: Case Study Findings." *Journal of Manufacturing Systems* 11, no. 5 (1992).
14. Stoll, H. W. "Design for Manufacture." *Manufacturing Engineering* (January 1988): 67–73.
15. Welter, T. R. "Designing For Manufacture and Assembly." *Industry Week* (September 4, 1989).