# DESIGN FOR *X* (DFX): KEY TO COMPETITIVE, PROFITABLE PRODUCTS

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A key to competitive, profitable product realization is design for *X* (DFX); i.e., design for manufacturability, testability, installability, compliance, reliability, and other downstream considerations. DFX is a philosophy and practice that ensures quality products and services, reduces the time to market for a product, and minimizes life-cycle costs. Therefore, it is crucial to achieving customer satisfaction. This paper introduces DFX as a strategic concept for product realization, provides a framework and examples of techniques for supporting DFX, and gives an overview of the other papers in this issue of the *AT&T Technical Journal.*

## The DFX Concept

Over the past several years, AT&T and many other companies have made significant strides in reducing both costs and product realization intervals and improving quality by reevaluating and streamlining individual functions and processes. However, we are reaching a point where additional cost reductions and efficiency improvements will be increasingly difficult to achieve by concentrating solely on specific functions and processes.

Although we continue to strive for incremental improvements in unit processes, we now need to move to the next logical plateau of competitive advantage: integration and optimization of the entire product realization process, or PRP. (See Panel 1 for a list of acronyms.)

Integrating and optimizing the PRP is especially critical for large companies whose competitive advantage relies on vertical integration. Further, the success of these companies depends on how well they integrate the various functional areas along the PRP and business-operation chain. In the future, only those companies that recognize the implications of end-to-end integration—and are able to capitalize on it—can be competitive leaders. For example, the integration of research and development (R&D) with production is an essential step for U.S.-based companies to retain or regain technological preeminence in global markets.[1]

In the sections that follow, we elaborate on the DFX environment and describe how DFX ensures quality products and services, reduces time to market, and minimizes life-cycle costs. Then, we discuss DFX trade-offs and the electronic packaging hierarchy.

**The DFX Environment.** In a noncompetitive environment, designers of electronic systems have focused primarily on product performance and features without always considering downstream needs, i.e., the needs of the processes and operations that follow design.

True, a product's primary operating characteristics and functionality are essential. But the lack of integration between product design and other functions resulted in products that were difficult to manufacture, install, service, and maintain. In addition, environmental, safety, and reliability considerations sometimes were not considered in product and process designs. The price of this lack of forethought was often redesign, production and deployment expense, and market-entry delays. Figure 1a depicts this nonintegrated, pre-DFX environment.

DFX is an integrated approach to designing products and processes for cost-effective, high-quality downstream operations from manufacture (including fabrication, assembly, and test) through service and maintenance. [The X in DFX stands for manufacturability, installability, reliability, safety, serviceability, and other downstream considerations beyond performance and functionality. In AT&T and elsewhere,[2] DFX has also been called *designing for the "ilities."* The term DFX is an extension of the well-known terms DFA (design for assembly), DFM (design for manufacturability), and DFT (design for testability) and preserves the *design for* concept. It is flexible enough to accommodate all downstream considerations—some of which do not have an *ility* suffix, e.g., safety and compliance.]

As Figure 1b shows, product and process design are integrated from end to end in the DFX environment. This integration across PRP and business-operation functions permits the design of products and processes for easier manufacture, distribution, installation, operation,

service, and maintenance—while considering reliability, environment, and safety. The integrated DFX environment leads to higher quality, reduced time to market, and lower cost.

**Quality.** A quality design is one that meets or exceeds the full range of design objectives required to satisfy a company's customers—i.e., performance and features, as well as DFX considerations. A key concept in AT&T for process-quality management and improvement is the customer-supplier model (Figure 2).[3]

In the DFX environment we show in Figure 1b, the

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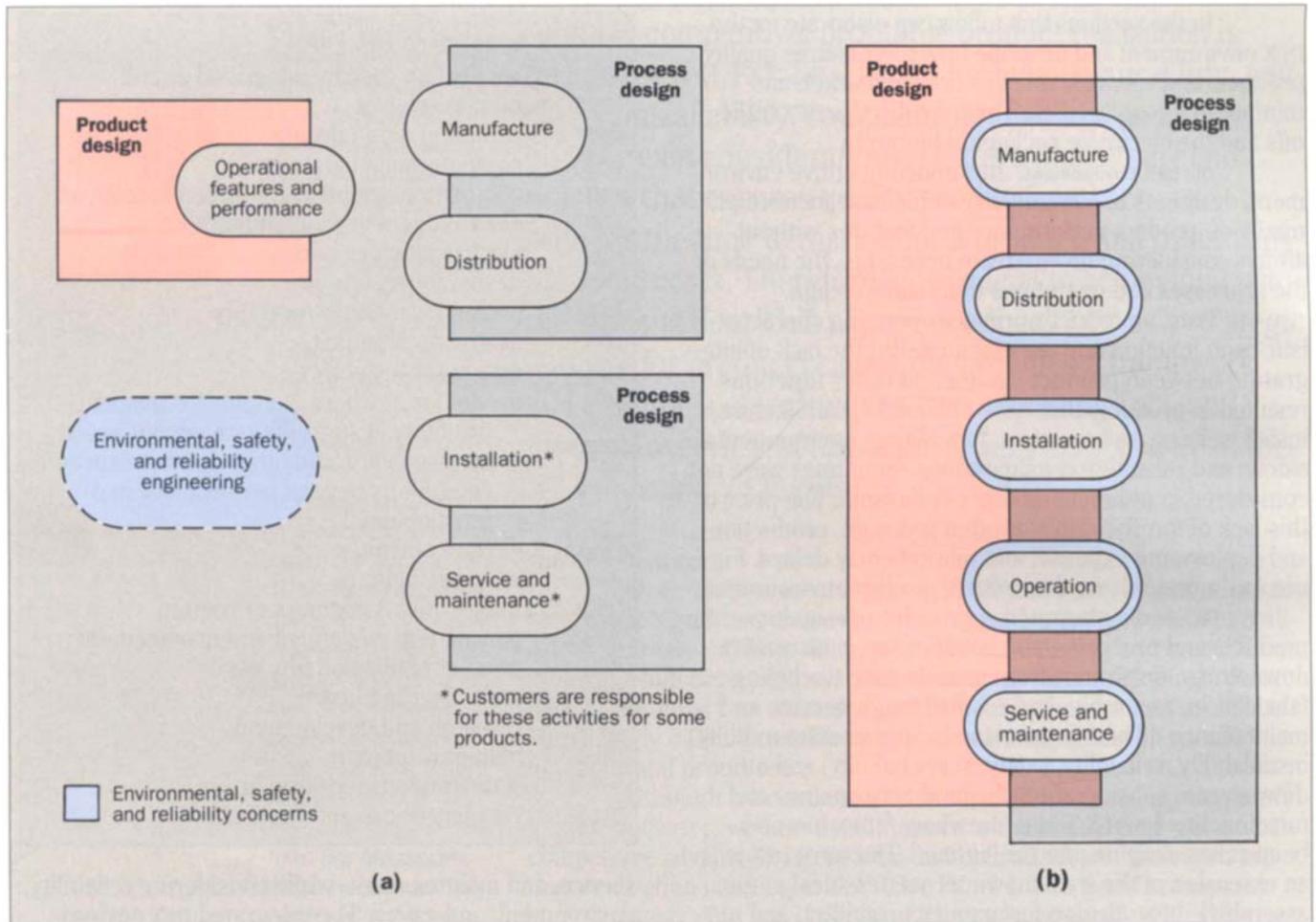
Figure 1. The design environment. (a) Before DFX principles were used, product designers focused on product features, functions, and performance (operational characteristics) and were decoupled from manufacturing, installation, and service engineers. Environmental and safety specialists and reliability engineers were often decoupled from designers and other engineers, as well. (b) In the DFX environment, product and process design are integrated end to end. Products and processes are designed for downstream *X* considerations (ease of manufacture, distribution, installation, operation, service, and maintenance, each with associated reliability, environmental, and safety concerns), as well as for operating features and performance.

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functions are linked through customer-supplier relationships and are driven by the customer's quality requirements, as well as by internal business objectives. DFX requirements and feedback are key elements in each of the customer-supplier relationships in the PRP.

The fourth phase of the quality-systems evolution—that is, *quality by design*—goes beyond the first three phases (*inspection, process control,* and *quality improvement*).[4] In this phase, quality is designed into the product and into the manufacturing process, starting with the initial concept of the product. Designed-in quality is a primary characteristic of the DFX approach. In terms of the cost of quality (i.e., the costs to prevent, appraise, and correct defects), the emphasis of DFX is on preventing defects early in the PRP rather than finding them downstream. DFX helps to achieve many of the attributes of the broad definitions of quality—e.g., *fitness for use,* which includes reliability, and ease of installation, service, and maintenance.[5]

**Time to Market.** Through DFX, we can reduce the PRP time-to-market interval by minimizing the number of design iterations and changes, instituting parallel processes, and eliminating activities that do not add value.

In previous years (the pre-DFX days), there was little dialog between design and manufacturing during product development. A product's designers rarely considered manufacturing's needs in their designs. Process designers were forced to tailor their processes around a product design that often was not compatible with existing processes. In the DFX environment, that is no longer true. For existing downstream processes, DFX is sometimes viewed as designing into fixed process windows. When neither product nor process designs are fixed, or when new products are designed into new process technologies, major opportunities exist for concurrent product and process design. DFX techniques are key enablers for this concurrency.

Although simultaneous product and process design (sometimes referred to as *concurrent engi-*
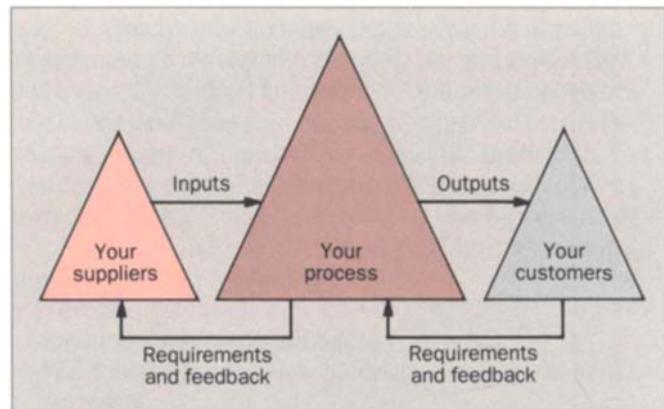


**Figure 2. In this customer-supplier model, customer requirements and feedback—as well as internal business objectives—drive the process as it converts supplier inputs into outputs delivered to customers. These customer-supplier relationships link all functions in the DFX environment, Figure 1b. (Reproduced from *Process Quality Management and Improvement Guidelines.*[3])**

*neering*[6]) embodies inherent risks, the benefits of parallelism can be substantial when this approach translates into getting products to market faster.

**Cost.** From 80 to 90 percent of the total life-cycle cost of a product (e.g., manufacturing, distribution, installation, and servicing) is determined during the design phase. But as Figure 3 shows, the design-phase efforts represent only about 5 percent of the life-cycle costs. The downstream functions contribute a sizable percentage of the total business-cost and expense base. Thus, products that have not been designed for downstream needs have not been designed to optimize our business objectives.

**Tradeoffs.** For a DFX methodology to be successful, the development team that is formed must consist of designers and individuals from the other functional areas that are part of the PRP.

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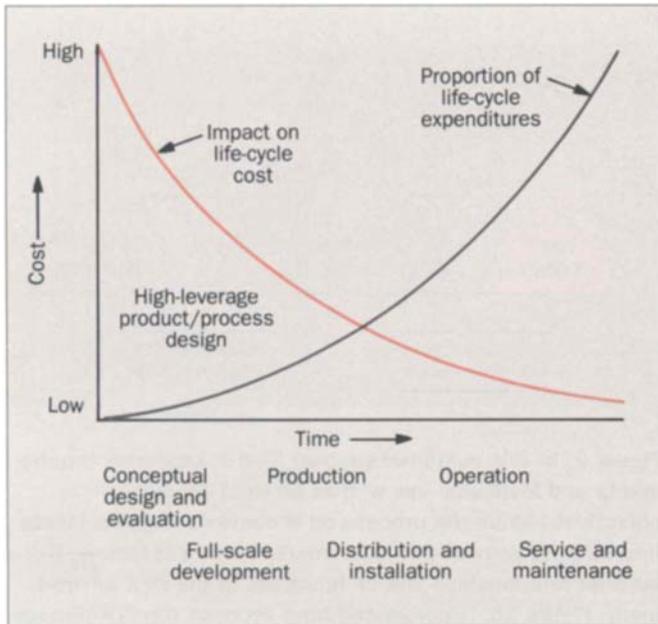
Figure 3. Design and life-cycle costs. The earliest stages of product realization have the greatest effect on life-cycle costs, yet they represent the smallest proportion of life-cycle expenditures.

The team needs to understand how a design's attributes affect all the $X$s, so that one DFX concern is not inadvertently optimized at the expense of another. For example, suppose a development team wants to combine or integrate parts to improve assembly operations and reliability. The team also needs to consider:

- Manufacturability from a parts-fabrication viewpoint.
- Repairability and serviceability.
- Material-logistics overhead for introducing additional, unique parts. (*Material logistics* is the planning, managing, and movement of materials needed to manufacture a product and deliver it to customers.)
- The effects on purchasing volumes of existing parts.

These parts-reduction DFX considerations are important for mechanical piece-parts and housings,[7] as well as for silicon integrated circuits (ICs) and printed-wiring boards (PWBs).

Similarly, the team must consciously evaluate tradeoffs between DFX and performance or functionality considerations. For example, an assembly that has fewer parts is usually much easier to manufacture. However, one criterion for eliminating a part is that its elimination does not affect the assembly's function. Alternatively, the assembly's function could be reengineered, so that the part could be eliminated or combined with another part.

Similarly, reducing the number of gates on an IC could lead to a lower cost chip. But maintaining the required functions, while reducing the gate count, can be a challenge. For example, when circuits that generate dual-tone, multifrequency signals for dialing were combined with those that produce the telephone's ring, a cost-effective, single-chip implementation of a telephone circuit was achieved. The gate count was halved, compared to separate dialing and ringing circuits.[8]

These types of DFX relationships and tradeoffs, their inherent interdisciplinary scope, and rapid changes in many technologies all make DFX complex. Product development teams must work together to understand the breadth of design objectives, including DFX considerations, and make the appropriate tradeoffs to ensure profitability as well as customer satisfaction.

**Electronic Packaging Hierarchy.** DFX considerations are important for all levels of the electronic packaging hierarchy. For example, design for testability (DFT) techniques[9] are applied to devices, PWB assemblies (also known as circuit packs), and units and systems.

Designing for electrostatic discharge (ESD) protection[10] and for electromagnetic compatibility (EMC)[11] also requires DFX for every packaging level. For example, we must design for ESD protection at the:

- Device level—e.g., apply CMOS (complementary metal-oxide semiconductor) protection-circuit design rules.
- Board level—e.g., select devices with the highest possible ESD thresholds.

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- Unit and system levels—e.g., provide grounding and circuit-isolation arrangements.

Similarly, designing for EMC is necessary at the:
- Device level—e.g., minimize IC emissions.
- Board level—e.g., apply filtering and grounding techniques in the layout.
- Unit and system levels—e.g., use shielded enclosures and cabling.

Even design for assembly (DFA), a well-known DFX approach for mechanical assemblies, is important for device-packaging and circuit-pack design.

DFX must be integral to product realization to achieve high quality, rapid product introduction, and profitability. This integration must be driven into educational programs, product realization processes and information systems, and organization and reward systems.

The next section describes DFX-related techniques in each of these areas.

### Supporting DFX in Product Realization

DFX considerations should be built into every design *early* in the product realization process. In this section, we describe the mechanisms for supporting DFX in the PRP:
- The technical core: knowledge base, development processes, and information systems
- Education and training
- Managerial considerations, such as organization and reward systems.

Communication and teamwork, which underlie all these support mechanisms, are also briefly discussed.

**Knowledge Base.** DFX knowledge is the understanding of how a design's attributes affect downstream operations, and how the characteristics of a downstream process constrain a design's attributes. For example, the characteristics of the fabrication process for ICs or PWBs determine the minimum clearances between interconnections on an IC or PWB. Similarly, the capabilities of an injection-molding or sheet-metal-forming process determine the bend radii for features on a mechanical part.

One usually acquires DFX knowledge through experiments with test vehicles (e.g., IC and PWB interconnection features), failure-mode and effects analyses, or experiences with designs and downstream operations (e.g., servicing or maintaining electronic products). The systematic acquisition of DFX knowledge is a first step toward implementing DFX in product and process designs.

Once understood, DFX knowledge can be communicated in several forms:
- Verbal—e.g., in dialogs with DFX experts or in multifunctional development teams
- Written—e.g., in design guidelines, rules, standards, or practices
- Digitally encoded—e.g., in computerized databases of components and design rules.

The mode of communicating DFX knowledge influences its effectiveness. For example, rule-based tools can be a must for some applications. However, DFM experts have observed that some product-design techniques depend too much on rules and that these rules are no substitute for experienced people.[12]

Throughout the PRP, clear, continual communication of DFX knowledge is essential.

**Development Process.** Here, we discuss methods for applying DFX knowledge in development processes.

A carefully formulated and documented PRP description or methodology is needed to achieve productivity and quality improvements, especially for complex electronic products, such as computers and network-systems equipment.

Process definitions include DFX-related tasks at key points in the development process. Among these tasks are:
- Establishing DFX rules, guidelines, checklists, and targets
- Team design or redesign activities
- Team inspections, evaluations, and reviews of a design relative to DFX considerations
- Tracking DFX performance (e.g., the conformance to rules, and the results in target $X$ processes).

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Procedures for executing these tasks are also important. For example, disciplined processes for design reviews[13] and inspections[14] are considered *best practices* that reduce design defects.

Teamwork is essential to achieve DFX. Selecting the right team for each activity is crucial to an effective process. Integrating information systems into the process is also important. For example, on-line design systems at several locations can be networked, so that designers and manufacturers at those sites simultaneously view designs and jointly improve DFX in real time.

**Information Systems: CAE/CAD.** Here, we discuss computer-aided engineering and computer-aided design (CAE/CAD) support of DFX.

In a CAE/CAD environment, DFX can be supported in many ways. The CAE/CAD tools can:
- Manage DFX knowledge on line—e.g., in component or DFX-rule databases.[15]
- Build in DFX considerations automatically—e.g., incorporate testability into circuits and physical layouts.[9,15]
- Audit designs against DFX rules—e.g., design-rule checking of PWBs and of VLSI (very large-scale integration) chips.[10,15,16]
- Model or predict DFX performance or behavior—e.g., for manufacturing yields of chips[17] and for board- and system-level reliability.[18]
- Enable on-line DFX reviews—e.g., via networked CAE/CAD systems used for simultaneously reviewing and improving DFX of mechanical and PWB designs and documentation.

CAE/CAD support of DFX is closely coupled with the development methodologies and PRP definitions discussed in the previous section. Where DFX criteria are more subjective or qualitative (e.g., designing for *foreseeable misuse* to enhance product safety and prevent liability[19]), development processes and checklist procedures are the dominant means of DFX support.

Simulation and modeling techniques (e.g., for circuit and physical designs) are increasingly important to ensure proper design margins and robustness of designs—e.g., when combined with robust-design approaches.[20,21] Today's emerging design-automation systems are incorporating more DFX considerations into their on-line knowledge bases and algorithms. Examples include expert systems for PWB producibility,[22] synthesis tools that incorporate built-in self-test (BIST),[23] and optimization systems that use robust circuit design[24] to improve the yields of semiconductor manufacturing. DFX support is one advantage of in-house developed CAE/CAD systems.

**Education and Training.** Courses and workshops on the technical aspects of DFX knowledge, processes, and CAE/CAD systems are important for enhancing the DFX skills of the development team. Day-to-day teamwork with personnel from other functions is also an important part of the DFX education and training process.

Rotations and internships [across functions in the DFX environment (Figure 1b)] are excellent ways to accelerate DFX knowledge acquisition and appreciation. For example, the Inter-Entity Assignment Program (IEAP) at AT&T Bell Laboratories (a division of AT&T) enables Bell Laboratories designers to spend 6 to 12 months in manufacturing organizations. Designers who have participated in the IEAP have learned valuable DFM lessons that they have shared with their development teams. IEAP also gives manufacturing engineers the opportunity to spend 6 to 12 months in design organizations at Bell Laboratories. Internships in other functional areas, such as marketing, are also offered.

Personnel at all levels need to understand DFX concepts and the relationship of these concepts to productivity and quality improvement. And, they need to understand that DFX requires skills and discipline that may differ from those embedded in past, traditional corporate cultures. Top-management support of DFX is essential because DFX activities typically require increased efforts earlier in the PRP, with paybacks to be reaped downstream. Middle managers need to understand the reasons for changing their operations and allocating people for DFX-related activities. Personnel at the operational

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levels need an appreciation for DFX and its benefits to help motivate them to implement DFX in their work.

Universities have started to pave the way for DFX by emphasizing design and the interaction of multiple disciplines in engineering curricula and research. Examples include graduate-level DFM courses[25] for mechanical design, and research in IC design for enhanced yields and design centering.[26,27] A fundamental need at all levels of our educational system is to emphasize cooperative or team learning, not just individual learning. Team attitudes, methods, and communication skills need to be nurtured to lay a solid foundation for DFX practitioners.

**Organization and Reward Systems.** Success in high-technology markets cannot be achieved through technical solutions alone. People—the human resources of a business—have many nontechnical needs and dimensions that must be recognized and managed for DFX success. Some productivity experts contend that the major problems of our work are more sociological than technological.[28] This is especially relevant for the multifunctional teams required for DFX.

Organizational approaches and reward systems are people-oriented DFX support mechanisms that have tremendous leverage. But historically, they have received short shrift in high-technology companies.

For effective DFX, organizing the multifunctional team for development is critical. If we get the right people from the different PRP functions and "grow" them into jelled teams, we help enable the collaboration required for DFX implementation. Rewarding DFX teamwork, to ensure that the team's desirable behavior continues, can involve the application of psychological principles. For example, we should use nonfinancial recognition, avoid interfering with intrinsic motivation, and reward teams and the individuals in them—but tip the balance toward the team.[29]

Many successful companies have achieved DFX through functionally integrated, organizational structures.[30] For example, one approach to ensuring cooperation between product designers and manufacturing engineers is to combine them into a single organization that reports to a common manager. Thus, manufacturability becomes a common, high-priority goal that designers and manufacturers work on jointly from design concept through production. The Japanese have been particularly successful at the team approach. Their manufacturers are involved at product conception, and their designers are involved through the start of production. Variations on this approach have proved successful in many industries.[12,30] At the macro level, AT&T's recent restructuring into focused business units is helping us to achieve some of the end-to-end PRP integration that improves DFX.

DFX accomplishments need to be singled out and rewarded. For example, in determining team and individual performance, DFX should have equal or higher weight than fire fighting (i.e., solving an immediate problem), thus creating a balance between DFX and short-term needs.

DFX innovations must be highly valued, just as functional innovations have been in the past. These values should be reflected in reward systems, because both DFX and functional innovations translate into profits—the bottom line.

**Communication.** A common thread through the DFX support mechanisms is communication. Effective communication is essential for teamwork, for developing and using the DFX knowledge base, and for making DFX processes work. In a DFX environment, a premium is placed on interpersonal communication skills. Information movement and management (IM&M) technology is also valuable for enhancing communications on DFX.

AT&T successfully applies its voice, data, and video IM&M technology to overcome many of the problems of doing DFM when both design and manufacturing are geographically separated. For example, liberal use of IM&M technology helped an AT&T R&D organization in New Jersey and a manufacturing organization in Colorado to achieve DFM at a distance.[31]

DFX technology, trials, tribulations, and triumphs

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**Table I. Profile of Downstream Impact for DFX Papers**

| DFX paper | Downstream activity | | | | |
| --- | --- | --- | --- | --- | --- |
| | Manufacture | Distribution | Installation | Operation | Service and maintenance |
| Design for simplicity[7] | √ | √ | √ | √ | √ |
| Design for multinational EMC[11] | √ | √ | √ | √ | √ |
| Computer-aided design for quality[20] | √ | — | — | √ | √ |
| Design for material logistics[33] | √ | — | — | — | — |
| Design for ESD protection[10] | √ | √ | √ | √ | √ |
| Automated BIST in ASICs[9] | √ | — | √ | — | √ |

NOTE: Each downstream activity also has associated reliability, environmental, and safety considerations. Also see Figure 1b, the DFX environment.

should be shared throughout a corporation. AT&T, for example, holds an annual DFX conference where employees share experiences on implementing DFX.

Industry-wide conferences on DFX (e.g., on DFM) have also been valuable sources of information on DFX experiences and techniques. One added benefit of these external activities is that they enable us to take the pulse of progress in DFX. Over the past five years, the scope and intensity of DFX-focused activities in industries and universities have increased dramatically.

### Summary and Future Directions

This paper has given a broad view of DFX— designing for downstream considerations from manufacture through service and maintenance. We have discussed knowledge bases, development processes, CAE/CAD information systems, education, and managerial approaches for supporting DFX in product realization.

For U.S.-based electronics companies to become more competitive, their level of DFX commitment in product realization and PRP support technologies needs to increase. DFX specialists (e.g., in designing for EMC, ESD, safety and liability prevention, reliability, and maintain-

ability) and personnel from all PRP functions are becoming better integrated into mainstream PRP activities. They are also becoming more influential in the development of PRP support technologies like CAE/CAD.

Although much progress has been made, DFX knowledge bases and educational programs must be extended, DFX tools and processes must be improved, and DFX technologies and experiences must be shared and leveraged. Those who focus on prevention in the PRP, which is synonymous with DFX and quality by design, will successfully compete—and profit.

### Some DFX Experiences at AT&T

This issue's papers provide a sampling of recent and ongoing DFX work in AT&T. Their authors are a blend of representatives from product development teams who have implemented DFX, and technologists who work with the teams to develop and deploy DFX methods and tools.

The papers contain a blend of pragmatic, experience-based information, as well as technical principles and results. Therefore, the issue should appeal to a broad audience: product management, marketing,

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design, manufacturing, installation, and service people who are directly involved with bringing a product to the marketplace; and R&D people who work on the underlying technologies of products, productivity, and quality. The papers cover these DFX disciplines:

- *Design for assembly and simplicity*—Watson, Theis, and Janek describe[7] a successful DFX method—design for simplicity (DFS)—that AT&T has applied to mechanical equipment. This equipment represents the mechanical and electromechanical portions of our electronic products, such as computers and telecommunications networking systems.
- *Design for electromagnetic compatibility (EMC)*— Heirman, Morris, and Crosby address[11] the development of products that satisfy regulatory compliance requirements in a multinational environment. They describe a successful design process for EMC compliance, testing considerations, and quality metrics for the EMC-compliance design process.
- *Design for manufacture (DFM)*—A paper by Liu, Nazaret, and Beale discusses[20] a computer-aided, robust-design approach that has been successfully applied to integrated circuits. They describe their sample-approximate-optimize method, give an optimization example using a gallium-arsenide (GaAs) IC circuit, and compare their method to other robust-design approaches (e.g., the Taguchi method).[21,24,32]

  A paper by Foo et al. highlights[33] design-documentation considerations for the planning, management, and control of materials. Designing for material logistics is an important dimension of DFM because the cost of materials dominates the total cost of manufacturing a product.
- *Design for reliability and maintainability*—Welsher et al. report[10] on designing for ESD protection in telecommunications products. They review ESD models and effects, describe factory and field ESD-control procedures, explain designed-in protection for all levels of the electronic packaging hierarchy, and

discuss industry standards and future trends.
- *Design for testability (DFT)*—Aadsen, Scholz, and Zorian describe[9] efforts on BIST for regular structures [e.g., read-only memory (ROM) and static random-access memory (SRAM)], embedded in application-specific IC (ASIC) devices. They provide some historical background on BIST; describe fault models, test algorithms, and access for BIST (e.g., interfaces for boundary scan); present some specific applications; and share their views on future directions for BIST.

Table I shows a profile of the downstream impact of the DFX techniques described in this issue's papers. Techniques in all the papers have a strong impact on manufacturability. Distribution material logistics are affected by DFS, EMC design, and ESD protection. DFS, EMC design, and ESD protection also affect installation procedures such as assembly; and BIST can streamline tests and diagnostic procedures during installation, as well as during service and maintenance. Techniques in four of the six papers (DFS, EMC design, CAD for quality, and ESD protection) influence both operational reliability or robustness and the ease and frequency of service and maintenance.

Although this issue's papers concentrate on hardware DFX, most of the DFX principles and techniques they describe have analogies in software. There are some fundamental differences between hardware and software (e.g., with respect to manufacturing variation and wear-out mechanisms), but both must be designed for $X$ to realize competitive products.

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**References**
1. R. B. Reich, "The Quiet Path to Technological Preeminence," *Scientific American*, Vol. 261, No. 4, October 1989, pp. 41-47.
2. B. Huthwaite, "Manufacturing Competitiveness and Quality by Design," *Proceedings of the 4th International Conference on Product Design for Manufacture and Assembly*, Newport, Rhode Island, June 5 to 6, 1989, Institute for Competitive Design, Rochester, Minnesota, 1989, pp. 17-25.
3. R. Ackerman, R. Coleman, E. Leger, and J. MacDorman, *Process*

*Quality Management and Improvement Guidelines*, Issue 1.1, Select Code No. 500-49, AT&T Customer Information Center, Indianapolis, Indiana, 1988.

4. E. Fuchs, "Quality: Theory And Practice," *AT&T Technical Journal*, Vol. 65, No. 2, March/April 1986, pp. 4-8.

5. C. L. Pettijohn, "Achieving Quality in the Development Process," *AT&T Technical Journal*, Vol. 65, No. 2, March/April 1986, pp. 85-91.

6. R. I. Winner, J. P. Pennell, H. E. Bertrand, and M. M. G. Slusarczuk, *The Role of Concurrent Engineering in Weapons System Acquisition*, IDA Report No. R-338, Institute for Defense Analysis, 1801 N. Beauregard Street, Alexandria, Virginia 22311, December 1988.

7. R. G. Watson, E. M. Theis, and R. S. Janek, "Mechanical Equipment Design for Simplicity," *AT&T Technical Journal*, Vol. 69, No. 3, May/June 1990, pp. 14-27.

8. P. Wallich, "Phone Chip: Shared Circuits Save Space," *IEEE Spectrum—Special Report: On Good Design*, Vol. 24, No. 5, May 1987, p. 54.

9. D. R. Aadsen, M. N. Scholz, and Y. Zorian, "Automated BIST for Regular Structures Embedded in ASIC Devices," *AT&T Technical Journal*, Vol. 69, No. 3, May/June 1990, pp. 97-109.

10. T. L. Welsher, T. J. Blondin, G. T. Dangelmayer, and Y. Smooha, "Design for Electrostatic-Discharge Protection in Telecommunications Products," *AT&T Technical Journal*, Vol. 69, No. 3, May/June 1990, pp. 77-96.

11. D. N. Heirman, R. C. Morris, and S. M. Crosby, "Design for Multinational EMC Compliance," *AT&T Technical Journal*, Vol. 69, No. 3, May/June 1990, pp. 28-45.

12. D. E. Whitney, "Manufacturing by Design," *Harvard Business Review*, Vol. 66, No. 4, July-August 1988, pp. 83-91.

13. AT&T Bell Laboratories, *Design Reviews Reference Guide*, Contract No. N00600-88-C-2307, Reliability, Maintainability, and Quality Assurance (RM&QA), Office of the Assistance Secretary of the Navy (Shipbuilding and Logistics), Washington, D.C., to be published 1990.

14. P. J. Fowler, "In-Process Inspections of Workproducts at AT&T," *AT&T Technical Journal*, Vol. 65, No. 2, March/April 1986, pp. 102-112.

15. W. A. Burling, B. J. Bartels Lax, L. A. O'Neill, and T. P. Pennino, "Product Design and Introduction Support Systems," *AT&T Technical Journal*, Vol. 66, No. 5, September/October 1987, pp. 21-38.

16. C. R. Bonapace and C.-Y. Lo, "An $O(n \log m)$ Algorithm for VLSI Design Rule Checking," *Proceedings of the 26th Design Automation Conference*, Las Vegas, Nevada, June 25 to 29, 1989, Institute of Electrical and Electronics Engineers, New York, 1989, pp. 503-507.

17. C. M. Drum and D. L. Gerlach, "Yield Model with Critical Geometry Analysis for Yield Projection from Test Sites on a Wafer Basis with Confidence Limits," *Proceedings of the 1989 IEEE International Workshop on Defect and Fault Tolerance in VLSI Systems*, Tampa, Florida, October 23 to 24, 1989, Institute of Electrical and Electronics Engineers, New York, 1989, pp. 197-208.

18. B. F. Gundaker, D. E. Martinich, and M. J. Tortorella, "Quality Technology in Product Realization Systems," *AT&T Technical Journal*, Vol. 66, No. 5, September/October 1987, pp. 5-20.

19. J. F. Thorpe and W. H. Middendorf, *What Every Engineer Should Know About Product Liability*, Dekker Publishing, New York, 1979.

20. L. Liu, W. A. Nazaret, and R. G. Beale, "Computer-Aided Design for Quality (CADQ)," *AT&T Technical Journal*, Vol. 69, No. 3, May/June 1990, pp. 46-60.

21. M. S. Phadke, "Design Optimization Case Studies," *AT&T Technical Journal*, Vol. 65, No. 2, March/April 1986, pp. 51-84.

22. R. Hawiszczak, "Integrating Producibility Tools into a CAE Design Environment," *Proceedings of the 3rd International Conference on Product Design for Manufacture and Assembly*, Newport, Rhode Island, June 6 to 8, 1988, Troy Conferences, Rochester, Minnesota, 1988, pp. 79-84.

23. C. E. Stroud, "An Automated BIST Approach for General Sequential Logic Synthesis," *Proceedings of the 25th Design Automation Conference*, Anaheim, California, June 12 to 15 1988, Institute of Electrical and Electronics Engineers, New York, NY, 1988, pp. 3-8.

24. C. C. McAndrew, S. R. Nassif, K. Singhal, and V. Visvanathan, "The CENTER Design Optimization System," *AT&T Technical Journal*, Vol. 68, No. 3, May/June 1989, pp. 77-92.

25. J. Freckleton, "Graduate Level Training in DFM for the Practicing Engineer," *Proceedings of the 2nd International Conference on Product Design for Manufacture and Assembly*, Newport, Rhode Island, April 6 to 8, 1987, Troy Conferences, Rochester, Minnesota, 1987, pp. 141-145.

26. S. W. Director, "Designing for Enhanced Yields," *SRC Workshop on Design For Manufacturing*, SRC Report No. P89002, Semiconductor Research Corporation, Tampa, Florida, January 9, 1989, paper II.2.1.

27. A. J. Strojwas, "Design For Manufacturability and Yield," *Proceedings of the 26th Design Automation Conference*, Las Vegas, Nevada, June 25 to 29, 1989, Institute of Electrical and Electronics Engineers, New York, 1989, pp. 454-459.

28. T. DeMarco and T. Lister, *Peopleware: Productive Projects and Teams*, Dorset House Publishing Co., New York, 1987.

29. J. C. Mower and D. Wilemon, "Using Psychology to Reward Teamwork—Four Important Principles," *Proceedings of the 1987 IEEE Conference on Management and Technology*, Atlanta, Georgia, October 27 to 30, 1987, Institute of Electrical and Electronics Engineers, New York, 1987, pp. 294-299.

30. J. W. Dean and G. I. Susman, "Organizing for Manufacturable Design," *Harvard Business Review*, Vol. 67, No. 1, January-February

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1989, pp. 28-36.
31. J. W. Wesner, "DFM at a Distance," *Proceedings of the 1990 International Computers in Engineering Conference*, Boston, Massachusetts, August 5 to 9, 1990. American Society of Mechanical Engineers, Chicago, Illinois, to be published 1990.
32. R. N. Kackar and A. C. Shoemaker, "Robust Design: A Cost-Effective Method for Improving Manufacturing Processes," *AT&T Technical Journal*, Vol. 65, No. 2, March/April 1986, pp. 39-50.
33. G. Foo, J. P. Clancy, L. E. Kinney, and C. R. Lindemulder, "Design for Material Logistics," *AT&T Technical Journal*, Vol. 69, No. 3, May/June 1990, pp. 61-76.

Biographies (continued)
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