PRODUCT DESIGN AND INTRODUCTION SUPPORT SYSTEMS

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Design decisions made early in the product realization cycle can have a dramatic effect on the manufacturability, quality, and ultimate marketplace success of a product. The features of CAE/CAD systems must ensure that, as designs progress, they adhere to design rules that codify manufacturability and quality. But that is only the start. For successful introduction of a product into the factory, computer-aided systems must be integrated with the design aids to augment the design information with all the factory-specific information needed to reach the state where the product is ready to manufacture. All this information must be put under change, version, and configuration control so that the factory is assured of accurate and consistent information. Finally, the data must be made available to the ordering systems to ensure that the product is manufactured to specification. This article describes the AT&T computer aids that satisfy these needs.

Background

Product design and introduction systems provide the framework for automating the early phases of the overall product realization process (PRP) in AT&T. These systems span the computer-aided engineering (CAE), computer-aided design (CAD), and engineer of manufacture (E of M) disciplines in supporting a smooth integrated flow of design information into manufacture. (Panel 1 identifies the acronyms used in this paper.) In addition, they help coordinate this data with the customer order systems to ensure that the desired system is shipped. This paper focuses on the AT&T computer aids that fill this role, as applied to the manufacture of products in AT&T's factories that build electronic systems (called assembly, wire, and test—or AWT—factories).

Goals of Computer Aids. The use of product design and product introduction systems throughout the overall product realization cycle significantly affects the quality, manufacturability, and reliability characteristics of the resultant product. Product design must account for manufacturability as well as functionality, and quality and reliability must be "designed in," rather than "inspected in."

Given this opportunity for impact, the overall goals for achieving an effective suite of computer aids are:

- Incorporation of design for manufacturability (DFM) features into CAE/CAD systems to ensure that designs—as they evolve—meet factory reliability, testability, assembly, and quality requirements.
- Integration of the design information that CAE/CAD systems produce with the factory-specific process information necessary for manufacture.
- Provision of a mechanism to manage change effectively by implementing version and configuration control to ensure accurate and consistent product information.
- Support for AT&T-specific assembly and interconnection technology[1] requirements.

Functional Architecture. Figure 1 shows the overall functional architecture for the AT&T computer aids that support product design and introduction. The diagram depicts the individual software systems as rectangles; their use in a process sense flows from top to bottom.

Because this paper focuses on the process that leads to the manufacture of products in AT&T's AWT factories, we will describe the top and right portions of the figure in more detail. The remaining processes support the design of integrated circuits (ICs) and hybrid integrated circuits (HICs) that are used in assembling the end product and are treated as components here.

Circuit design engineers typically use SysCAD—a suite of common CAE applications for ICs, HICs, and circuit packs (Figure 1)—for design capture and verification. SysCAD capabilities include schematic capture, synthesis, functional simulation, timing simulation, fault simulation, and physical prototyping.

Once the prototype design is acceptable, it is passed to a CAD system: silicon CAD, hybrid circuit CAD, mechanical CAD (MCAD), and interconnection design system (IDS). These CAD systems, which physical design engineers or drafters use for doing the physical design, are matched to the particular physical packaging designated for the circuit.

MCAD and IDS are targeted at AWT factories, and are used for the physical layout of circuit packs, backplanes (one or more shelves of circuit packs), and frames of equipment. To present the details of the complex physical

Panel 1. Acronyms in this Paper

AWT	assembly, wire and test (factories)
CAD	computer-aided design
CAE	computer-aided engineering
CDF	common design file
DFM	design for manufacture
DFT	design for test
DR	design rule
E of M	engineer of manufacture
FOCUS	factory interface system
HIC	hybrid integrated circuit
IC	integrated circuit
IDS	interconnection design system
LAN	local area network
MCAD	mechanical computer-aided design
MIPS	million instructions per second
MLR	manufacturing layout record
MPCS	manufacturing process control system
MRP-II	manufacturing resource planning systems
PRISM	productivity improvement systems for manufacturing
PROP	product realization operations plan
PRP	product realization process
SM	surface mount
SysCAD	set of common CAE applications (for ICs, HICs, and circuit packs)
WAN	wide area network

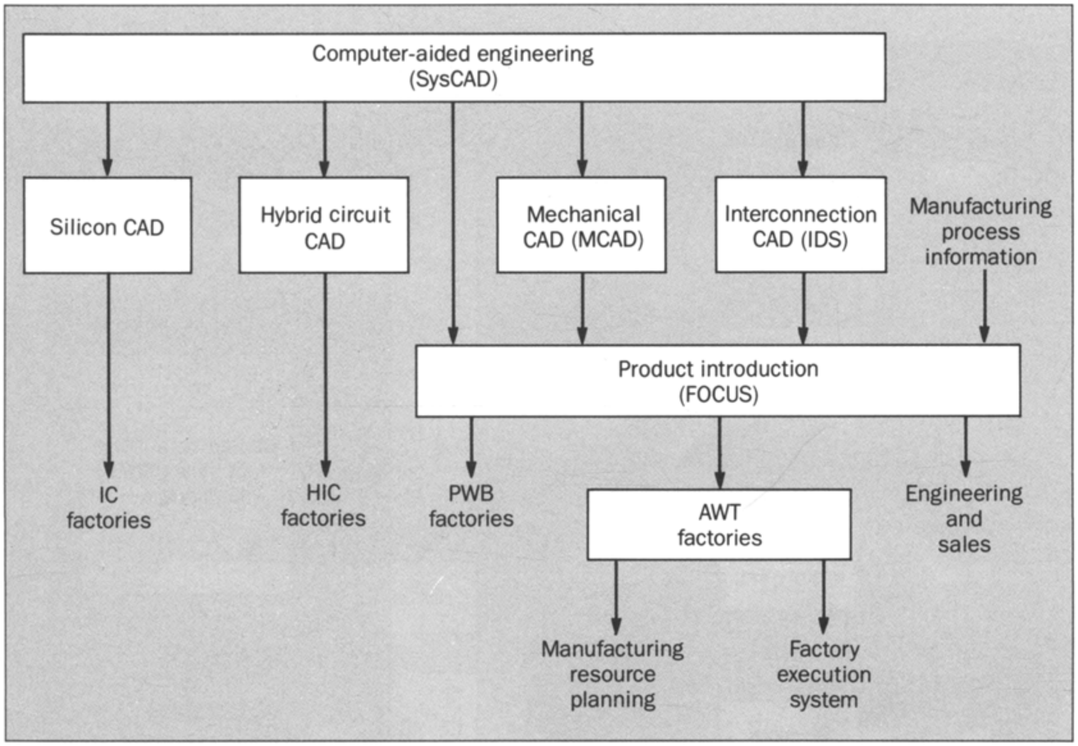


Figure 1. Computer aids architecture. SysCAD is a product design system, and FOCUS provides manufacturing design specifications. AWT = assembly, wire, and test; CAD = computer-aided design; HIC = hybrid integrated circuit; IC = integrated circuit; IDS = interconnection design system; PWB = printed-wiring board.

layouts, these systems require high-resolution color graphics.

IDS is used to design etched interconnection layouts for circuit packs and etched and discrete wire interconnection layouts for backplanes. It provides capabilities for automatically placing components and routing interconnections, and includes an extensive set of physical and electrical audits.

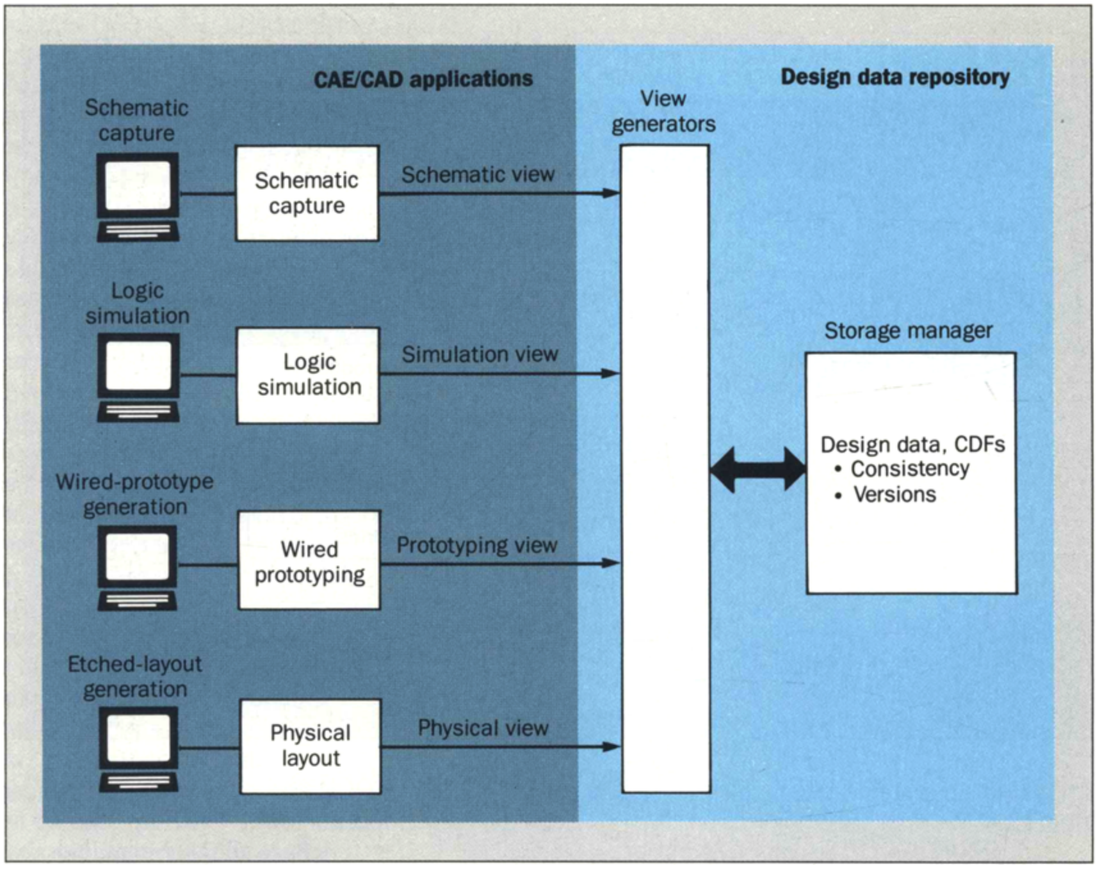
MCAD is used for the mechanical design of hardware pieceparts, molded units, and frame assemblies. It also supports structural and thermal analysis, two-dimensional drawings, and three-dimensional modeling.

The collective output from IDS and MCAD defines the design of an entire product, which is then formatted and organized by FOCUS, a factory interface system. FOCUS provides two related and interdependent functions.

- It defines all the design information needed to build a product and correlates the design data versions that are compatible for assembling the final product. The system gathers, organizes, audits, appropriately formats, and electronically transmits all required data to the factory.
- It supports a set of engineering of manufacture functions to generate process information that the factory uses to control factory operations such as the sequence for insertion of components, progressive assembly, and electrical testing of the product on a specific assembly line.

The functional architecture supports the process flow from SysCAD to IDS and MCAD for design, through

Figure 2. Relationship of application tools. They use design data accumulated and stored in databases, called the common design files (CDFs).



FOCUS for preliminary factory information and for final design information to the AWT factory. Throughout this process, design information is added, refined, and transferred to the factory to provide the detail necessary for manufacture. Also, process information about manufacturing is generated.

Common Environment

This section describes the method for storing process information and emphasizes change management's role in the overall process.

Data Storage. As Figure 2 shows, design data is accumulated and stored in databases called common design files (CDFs). The CDF is a collection of CAE/CAD application-specific (e.g., schematic capture, simulation, layout) design views for a circuit (e.g., a HIC, circuit pack, or backplane).

A storage manager passes the view to the application, which maps the data into its internal working structure—for modification or additions—and returns the updated view to the storage manager. The storage manager provides data consistency between views, and is

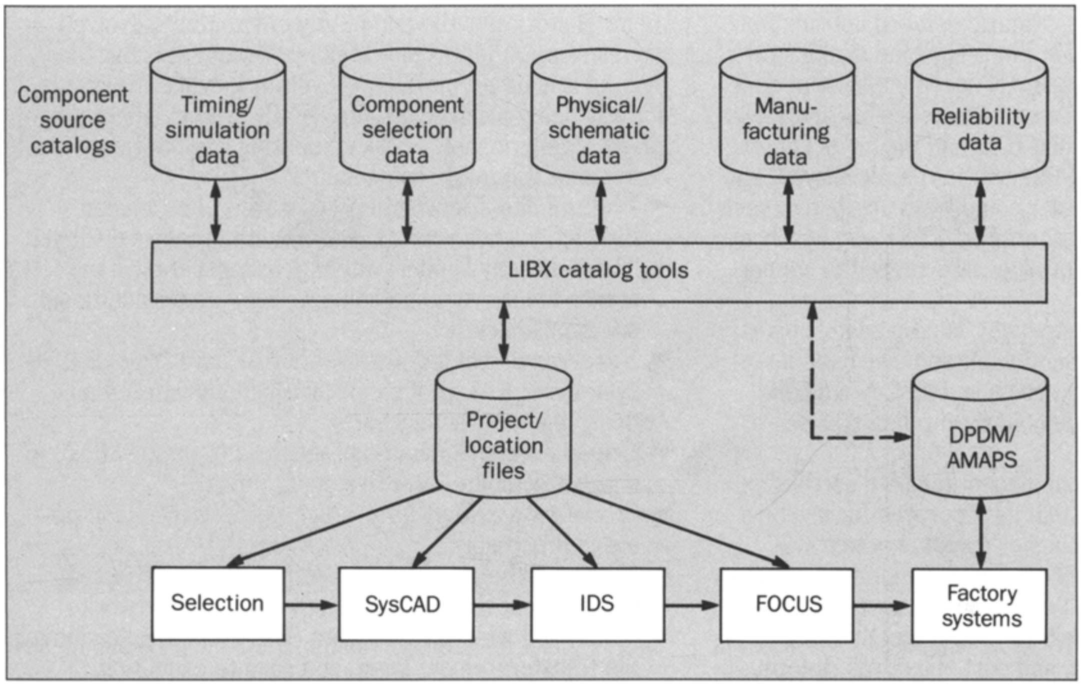


Figure 3. Corporate catalog information management system. SysCAD is a product design system. FOCUS provides the factory with manufacturing design specifications, while the DPDM/ AMAPS database provides mapping information. IDS = interconnection design system.

being enhanced to maintain "versions" of the circuit. The design data is stored in a central repository for later extraction of manufacturing-specific information required in the factory.

Change Management. When not managed properly, design "changes" can lead to schedule slips, cost overruns, and poor quality products. Even from early PRP stages, circuit engineers iteratively refine a circuit's design to meet function, cost, and reliability parameters in the product requirements. With each iteration, some design aspect changes, so each iteration must be labeled to ensure the design is properly integrated in the total product.

As mentioned previously, all design data for a single circuit is stored in a CDF, which is referenced by circuit name and version identification to provide specific product-configuration information for manufacture. Thus, each orderable configuration of a product is specifically defined by the collection of appropriate CDFs and auxiliary equipment files.

The configuration-control-module entries identify all necessary design information files and specify the versions of a specific circuit to be used in a configuration. A configuration encompasses both hardware (e.g., circuit packs) and optional firmware (e.g., microcode by device instance on a particular circuit pack).

In addition to the specification of changes in product descriptions, changes in process data, requests for approval, and approvals must be managed. When the design changes after a product is in manufacture, the configuration control system is queried to determine the products affected. It then guides the regeneration of the appropriate set of changed design information to be sent to the factory.

Component Data. All systems used in the design and product introduction process require detailed information about the components used in the design and manufacturing process. For example, SysCAD needs component data for schematic capture, simulation, and reliability analysis. The CAD systems, MCAD and IDS, and the factory interface system, FOCUS, need the data for physical layout and manufacturing assembly. Other component attributes, such as which devices are manufactured by AT&T and which are acceptable for use on each product, are needed to support selection of components.

To manage this component data, catalog support software tools are used to administer and distribute a set of electronic catalogs to the design and factory support systems. Figure 3 shows the component data system architecture.

Typically, project component files are established to identify the components that are approved for use on a project (e.g., 5ESS™ switches or common power systems). In general, the use of approved components ensures their availability in the designated assembly factory and that they comply with overall project strategies about reliability, technology, and cost objectives. Information for project component files comes from corporate catalogs, which include all AT&T manufactured components as well as commercial components that AT&T does not manufacture.

The project component files are aligned with material procurement systems in the project's assembly, wire, and test factory. SysCAD, IDS, and FOCUS use these files to drive the design process. The component data system ensures that:

- Information available from various AT&T sources is provided to the design systems.
- Information on AT&T manufactured components is provided during the selection process.
- Component information specifically required for manufacture is aligned with material resource systems in the factories.

Computing Environment. The product design and introduction system uses a distributed computer environment. Historically, the computing environment evolved from several different operating environments. But today, most of it is based on UNIX® System V, while the rest is actively being converted to the UNIX system. Figure 4 shows a generic view of the computing environment, which consists of five major components:

- *Workstations*—dedicated processors (1 to 4 million instructions per second, MIPS) with graphics displays. These directly support interactive applications, and access file servers and compute servers for additional specialized needs.
- *File servers*—shared processors that have large disk file systems (1 to 8 gigabytes), usually administered on a department or factory basis.
- *Compute servers*—shared processors (5 to 30 MIPS), to support compute-intensive applications.
- *Special-purpose hardware*—high-performance task oriented processors.
- *Network*—the unifying component of the distributed environment that provides both local area network (LAN) and wide area network (WAN) communication for file transfer, remote login, and remote execution.

The product design systems, SysCAD/IDS, are deployed on workstations, file servers, and compute servers and use accelerators for simulation and automatic routing functions. The product introduction system, FOCUS, is primarily based on file servers located in factories. However, many E of M applications use the same computational base as the product design systems.

Product Design Systems (SysCAD/IDS)

The product design systems, SysCAD and IDS, are CAE/CAD systems that were developed internally to support AT&T's advanced technology and vertical integration of the design and manufacturing process. They also support the common CAE/CAD functions of:

- Design capture via interactive schematic layout
- Design verification through simulation and hardware modeling
- Automatic and interactive physical layout.

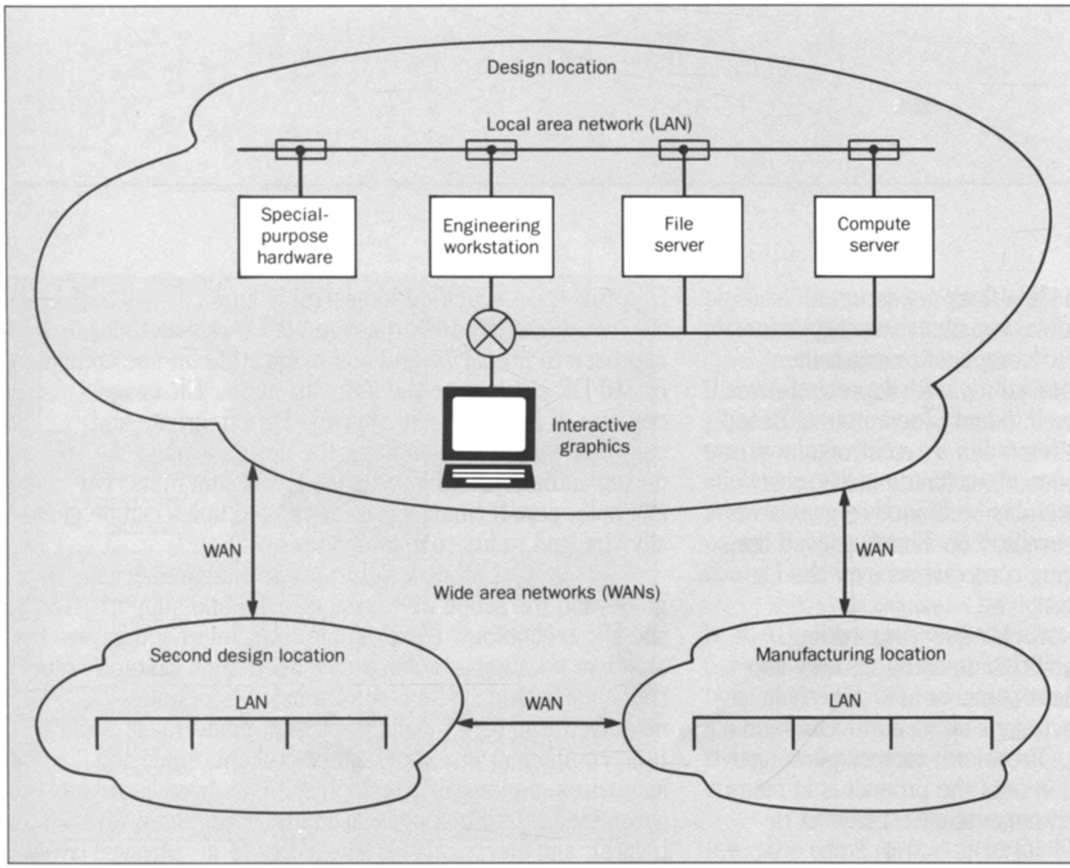


Figure 4. Computing environment. The local-area network (LAN) at a design or manufacturing location is connected to other LANs via wide-area networks (WANs). The major components of a generic distributed environment are identified.

The unique AT&T features ensure manufacturability at low cost, high yields, and quality early in the PRP. Therefore, this paper emphasizes those functions in the product design system that support design for manufacture.

The AT&T-specific features include:

- Component management and early interface to the component procurement systems.
- Analysis tools to allow design trade-offs to ensure manufacturing quality and decreasing costs.
- Innovative automated use of design rules throughout the design process to ensure the product is within the project's design criteria. The automated design rules also ensure that the product design takes advantage of the target factory's manufacturing efficiencies.

A robust set of dynamic and batch audits are available to verify the pre-established design rule and manufacturing criteria. Besides ensuring quality and manufacturability in the design process, SysCAD/IDS supports design and manufacturing teleconferencing. This feature allows E of M personnel and R&D circuit and physical engineers, located in dispersed geographic sites, to display and change product design in real time.

Project Design Aids. Computer aids have been developed for managing components and design rules and ensuring product design consistency.

Component management. Electronic components (e.g., integrated circuits and discrete devices) account for well over half the cost of most AT&T products. In addition, they have a major impact in determining post-assembly yield in manufacture and, more important, the reliability of the product for the customer. The availability of components is a dominant issue in "just-in-time" manufacture and must be managed appropriately to ensure adequate lead times for suppliers.

Extensive effort has gone into developing a comprehensive set of computer aids to help projects manage components. These aids support product design activities starting with component selection; continuing through auditing component usage on designs; and culminating in providing component stocklists to meet procurement, materials management, and shop floor needs.

The key to successful component strategy is for each project team to define a "component management" process. Typically, this is done jointly with representatives from engineering, manufacturing, and procurement. Based on this strategy, the project team defines a list of "approved components" screened for functionality, cost, reliability, manufacturing assembly technique (e.g., water-soluble flux tolerance), and availability. This approved list is the mechanism for managing components over the entire product design cycle.

The computer aids provide querying, adding, deleting, and reporting capabilities. In addition, they support the concept of "equivalent components." For each design code, several manufacturer's equivalent codes can be listed in order of priority. Therefore, factory personnel can defer component selection until the product is in manufacture and then choose components based on cost or availability.

As detailed circuit-design activity begins, circuit designers can query the project's approved component list and audit usage to ensure adherence to the list. On a project basis, accumulation functions are also available to monitor overall component use. Preliminary stocklists prepared from this analysis can be sent electronically to manufacturing and procurement personnel for use in planning and review activities.

Design rule management. A design rule (DR) is a guide or criterion that defines established physical and physically determined electrical constraints to ensure that the product meets performance, cost, manufacturability, testability, and quality objectives. A classic example of DRs is conductor path width and clearances that depend on bare-board fabrication and board assembly process.

The SysCAD/IDS systems incorporate automated design-rule management that they use to reduce design and design-to-manufacturing intervals, eliminate costly design errors and manufacturing problems, and ensure design and manufacturing quality. Predefined sets of DRs are specified for AT&T interconnection technologies and factories (i.e., specified to assembly line).

Automated DR management is a structured approach to preparing and communicating on-line computerized DR catalogs to the software tools. DR usage consists of automatically applying DRs to create and change a design, and auditing the design against the DR during automatic and interactive layout functions. For example, part terminals, via lands, and holes can be globally changed to improve fabrication.

SysCAD/IDS design rules are unique because they go beyond the scope of "classical" DRs and support AT&T-specific technology. For example, one set encompasses the standard packaging technologies of AT&T's Fastech® electronic packaging system. Additional DRs define manufacturing (e.g., drilling, plating, soldermask application, component insertion and placement, soldering, inspection, and repair); testability (e.g., bare-board and assembled-board testing, placement of in-circuit test points); and electrical characteristics (e.g., physical layout-dependent crosstalk, parallelism, net length).

Automated DR management and usage have a significant positive effect on the cost effectiveness of the design process that supports a product's manufacturability. Through attention focused early in the design process to manufacturing and testing requirements, the designs are tailored to a specified manufacturing and testing process. The result is ease of manufacture with no manufacturing or testability changes.

Product design consistency. During the design of AT&T products, the initial requirements are translated into a functional architecture and then successively refined to the physical realization on which the manufactured product is based. On a project-wide scope, a structured design methodology is required to enable several designers to work synergistically in creating a consistent product design.

Designers create the overall functional architecture in a top-down hierarchical structure, continually decomposing the functional design into lower-level functional blocks. This process is on the left in Figure 5. When

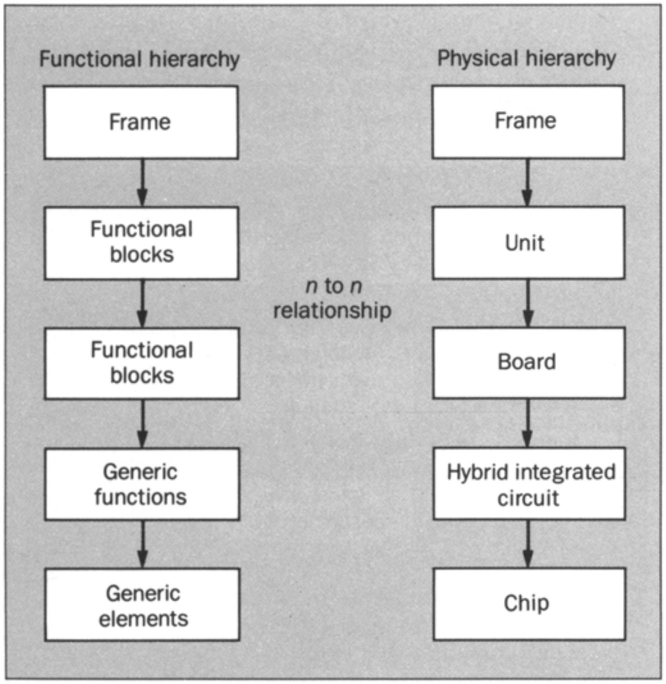


Figure 5. Functional hierarchy versus physical hierarchy.

several levels of hierarchy are created, functional blocks are decomposed into generic circuit elements. As decomposition proceeds, interconnections of lower level blocks are continually validated against their parent block to ensure that product requirements are met.

The functional hierarchy drives the product's physical design. The right side of Figure 5 shows a typical physical hierarchy. The design methodology is based on mapping (i.e., physical partitioning) the functional entities on the left in the diagram to the more-common-term physical entities (e.g., silicon chips, HICs, or circuit packs) on the right.

Computer aids have been extended to help automate parts of this architectural process. In particular, the CAE application functions for designing entities in the physical hierarchy are now being applied in the earlier phase of product design to create the functional hierarchy.

Design Process. Figure 6 shows the major steps in the design of a physical entity (e.g., circuit pack or backplane). As already explained, decomposition and partitioning of the overall product drive this process, which allows the design to proceed in a consistent way. The hierarchical levels above the backplane are still designed on paper, but the data is entered into computer systems for control and dissemination.

Design capture. The design process begins in SysCAD with capture of the circuit. Typically, an engineer uses an interactive graphical schematic editor to add symbols and construct the interconnections between symbols. The output of this process step is termed circuit "connectivity," and becomes the circuit's definition for later design steps.

Traditionally, designs were captured as schematics (i.e., the same format as in final-product documentation). SysCAD now has aids for specifying designs initially in terms of behavioral language descriptions, functional primitives, Boolean equations, or finite-state machines. These higher level formats allow engineers to concentrate on the circuit's function, and delay the need to add more detail until the design is functionally correct.

In addition, automated synthesis aids are available to generate the more detailed designs from the higher level definitions. By using the higher level capture techniques and applying design synthesis aids, engineers now can try several alternative design approaches in the same amount of time that traditionally would have been required to generate just one. Thus, they can evaluate "design tradeoffs" by comparing the effect of different alternatives on product requirements (e.g., cost, reliability, area).

Another aspect related closely to design capture is the "reuse" of portions of previous designs on new products. To do this, engineers reference another design from within a functional block on the new design (e.g., custom chip) or copy portions of the schematic (e.g., usually one or more sheets) into the new design.

Overall, the design capture step is interactive. After the initial capture, design verification and testability steps are executed and changes, when needed, are incrementally applied using design capture aids.

Design verification. The goal of this process step is to verify the design's functionality. To verify a design, one traditionally built prototypes (e.g., breadboards or models) of the product in the lab. Although this is still done on some products, the preferred approach today is to use simulation to evaluate designs.

With simulation, a designer can analyze "worst-case" conditions and better reflect the environment in large-volume manufacture, where the "design margin" is critical. Therefore, designs must have adequate margins for tolerance variations in device parameters (e.g., setup time, hold time, intrinsic delay) and signal level (e.g., noise immunity, capacitive loading, rise times).

SysCAD provides a comprehensive simulation capability that supports both functional and timing simulation. Devices can be modeled at transistor, gate, or functional levels. Mixed-level simulation can be done with combinations of these to localize effectively in detail where necessary. Hardware modeling [i.e., for VLSI (very-large-scale integration)] is also supported consistently, because the simulation includes the actual device, not software models. The results of a simulation run can be viewed graphically the same way a circuit designer would use a logic analyzer in the lab.

Because of increased use of microprocessor-based designs, SysCAD also supports aids for combining software and firmware in simulations of the underlying hardware to simulate the entire system. This allows software developers to verify their code without depending on the existence of a lab model (i.e., a hardware prototype assembled in the laboratory).

Where prototyping is desired, SysCAD provides circuit-pack discrete-wire prototyping aids based on wire-wrap, quick connect, or Kollmorgen, Inc.'s Multiwire™ technology. An AT&T Network Software Center service offers two-day turnaround to wire and verify a wire-wrap board from design information transmitted electronically from any AT&T design locations.

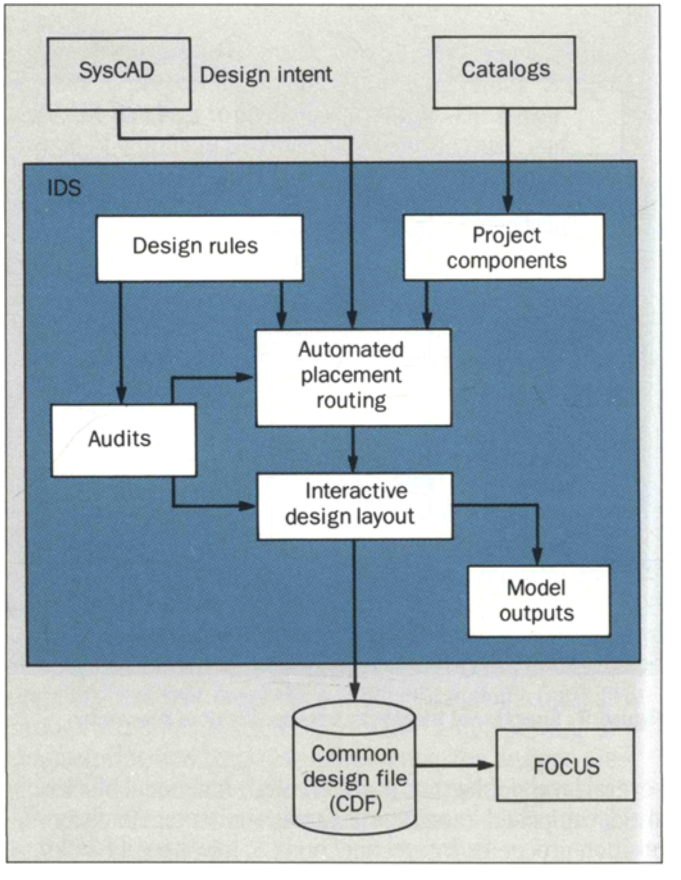


Figure 6. Physical layout design process. SysCAD is a product design system, and FOCUS is a factory interface system. IDS = interconnection design system.

Testability. About half the total cost of designing a product relates directly to developing the tests and associated test interfaces for use in manufacture. By addressing testability needs early in the design process, circuit designers can reduce the time and cost for test development.

SysCAD supports two approaches to testability:

- Functional test is based on driving the circuit from its access terminals (e.g., edge connector on a circuit pack) and sensing the resultant outputs at the same interface.
- In-circuit test is done by "probing" a device's terminals after it has been assembled (e.g., integrated circuit on a circuit pack).

Because of the increased complexity of designs and more dense packaging (e.g., surface-mounted components), generating and applying functional tests have become very difficult. As a result, the recent trend has been toward in-circuit test with its advantages in test modularity and reusability.

To support functional test, SysCAD provides fault simulation and test-vector preparation and editing tools. Typically, more than 90-percent fault coverage is required for a test-vector set to be effective in manufacture. To support in-circuit test, SysCAD also provides a comprehensive set of audits that detect design problems. In either case, the circuit description (e.g., connectivity) and required test vectors are processed through a standard interface[2] (developed at AT&T's Engineering Research Center in Princeton) to condition them for use by the specific test equipment in manufacture.

At this point, the design is fully captured and verified, and the testability criteria is well established. These three process steps have been exercised interactively to ensure that the design can proceed to physical layout without further functional or margin problems.

Physical layout. The interconnection design system provides a comprehensive set of software tools to support AT&T's complex electronic products and is the physical layout CAD system for hybrid ICs, printed-wiring boards, and backplanes. IDS contains functions for generating design rules, automatically and interactively placing components, routing conductive paths, auditing design and manufacturing criteria, and documenting and generating manufacturing data.

As Figure 6 shows, the physical-design-realization process begins after the circuit has been captured and verified in SysCAD. IDS acquires the circuit connectivity and stock list information from the design database, CDF, via SysCAD. Analysis software is available to help determine the required number of printed-wiring layers and the physical design-rule alternatives—such as path width and spacing—to ensure that the design can be packaged on the selected board size. A basic set of design rules is established for the project (based on board fabrication and AWT factory requirements), and these DRs are tailored, as needed, for the specific design. The board design outline, its layer stacks, and additional physical data on the selected components (e.g., size) are extracted from the corporate catalogs.

Enough data is now available to generate automatically an initial component placement for the board design, and placement may be modified interactively to meet critical parasitic requirements. The automatic router generates path traces that conform to circuit connectivity and design and manufacturing rules. Several iterations may occur, each altering the placement to achieve increasing routing completions. If 100-percent routing cannot be achieved by iterating the placement and routing process, the designer will interactively route the last few traces.

Throughout the physical layout cycle of placement and routing, the DRs established at the beginning of the design process are automatically applied, thus assuring the integrity of circuit connectivity and compliance with the DRs for manufacturability.

Besides supporting AT&T's integrated design and manufacturing product-realization process and technology, IDS supports specific features for surface-mount (SM) devices:

- Dynamic device fan-out routing to SM integrated circuits. This ensures that SM devices can be interconnected using minimum board spacing.
- Ability to display components on both sides of the board.
- Specific SM device design rule audits.

IDS also includes automated design generators for power and ground planes that can mesh large copper areas.

The mesh avoids trapped gases, which often occur during plating of large copper areas, and improves the manufacturing quality. Automated generators also design soldermasks used to protect the board printed areas during the soldering process in component assembly. The mask ensures high quality and low defects in the assembly, wire, and test factory.

Finally, IDS's automated generators are used to design in-circuit test pads. Using the testability data generated in SysCAD, IDS ensures that enough probing points are included in the physical design so that each component is testable after assembly.

The IDS audit system was developed to ensure high design quality, reduce time-consuming and error-prone manual checking, ensure design conformance to manufacturing standards, and reduce manufacturing design changes after products are released to the factory. The audits are run dynamically during the design process or as a batch process after the design is complete.

Manufacturability audits ensure that the design conforms to specific AT&T factory fabrication and assembly requirements. The available electrical-performance audits include critical circuit analysis, connectivity, crosstalk, circuit loops, net length, and parallelism. Fabrication audits include nonconductive and conductive nomenclature, soldermask, bare-board tests, and clearances. Assembly audits are hole and part audits and in-circuit test. IDS capability to drive the design process via design rules and the manufacturing audits has significantly improved printed-wiring board manufacturability and quality and reduced the manufacturing interval.

After the design has been audited, corrected, and modified, IDS generates outputs for manufacture that are delivered via FOCUS. Typically, these include bare-board test, printed-wiring masks, drilling information, part insertion and placement data, and assembly documentation.

Product Introduction Systems (FOCUS)

Timely introduction of new products to the marketplace and enhancements to existing products are of major concern to AT&T. Shortening the introduction interval requires cooperation and uniformity, implying that design and manufacturing must be equal partners throughout PRP. Design must provide manufacturing with information from preliminary design through final design. Manufacturing must work with this design information to define the facilities and information-flow processes that will allow fast introduction of new products. Similarly, fast introduction of change to existing product requires close, synchronized cooperation between design and manufacturing.

The keys to making this a responsive process are discipline; adherence to cost-effective procedures; and electronic acquisition, analysis, maintenance, control, transformation, and distribution of all product and process data.

Functional Architecture. Most new product design data is generated and stored electronically, albeit in many design systems across many types of machines and operating systems. The objectives of computer-based product introduction systems, as illustrated by the functional architecture in Figure 7, are:

- Acquire electrical and mechanical design data from various design systems and correlate it (e.g., physical data from IDS corresponds to stocklist data from SysCAD for the same circuit-pack artmaster issue).
- Support extraction of particular design data views for manufacturing engineering functions and to generate process data.
- Manage the basic product and process data and changes that occur during the product life cycle.
- Distribute design and process data to other systems both inside [e.g., factory execution systems and manufacturing resource planning systems (MRP-II)] and outside (e.g., sales and engineering systems) the factory.
- Support integration of manufacturing and design by electronic sharing of DFM/DFT information (e.g., early design information and defect and yield data). Information that factory execution systems generate should provide feedback to the designers on how easy or diffi-

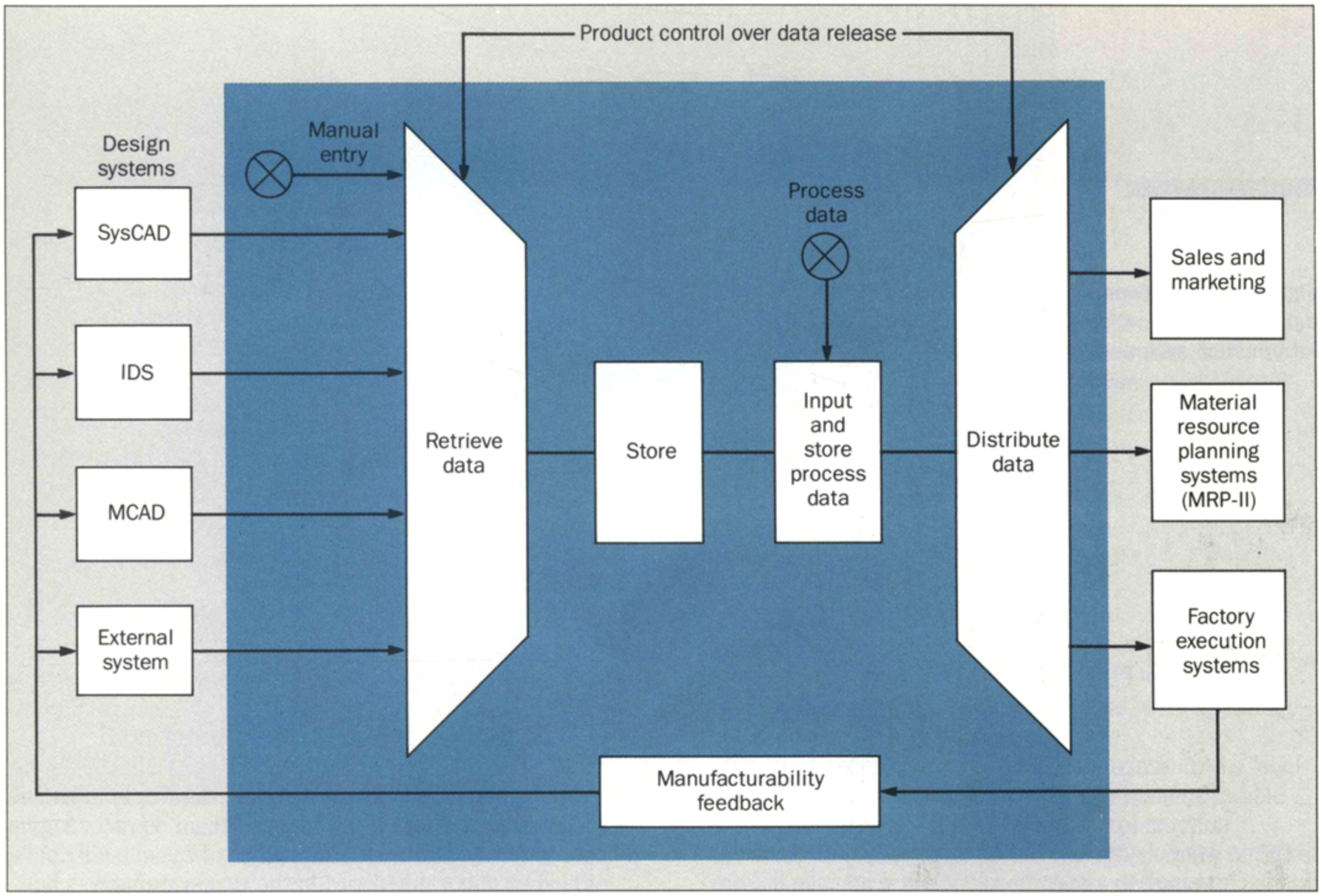


Figure 7. Functional architecture of product introduction system. SysCAD is a product design system. IDS = interconnection design system; MCAD = mechanical computer-aided design.

cult their design is to manufacture. Consequently, the information flow is bidirectional through the system.

- Support the sales and engineering organizations that interact with customers and provide for customer installation, support, and documentation.

The strategy adopted to realize this architecture is to provide a flexible interface between design and manufacturing to accumulate, control, and distribute all data, as shown in Figure 8. This interface provides an open architecture where design and manufacturing can evolve separately. The information is obtained from the various design systems to assemble a complete product description. The information managed is the fundamental data with redundancies removed. Process information is added to describe the operations needed to build the product. This data is then reformatted and distributed to the factory operations systems (e.g., PRISM).

The interface to the design systems is clearly defined so that information can be exchanged, controlled, and tracked. When a design is complete enough to be shared with downstream manufacturing processes, the information is securely stored so that it cannot be accidentally modified. Because the complete product definition must remain consistent, a version control subsystem is provided for all data that forms the product definition. The system must know where the stored files reside and what set of files go together to make up a complete definition. Furthermore, it must know which set of files must be updated when a change is made to provide a new consistent definition of the product.

After the complete information has been obtained

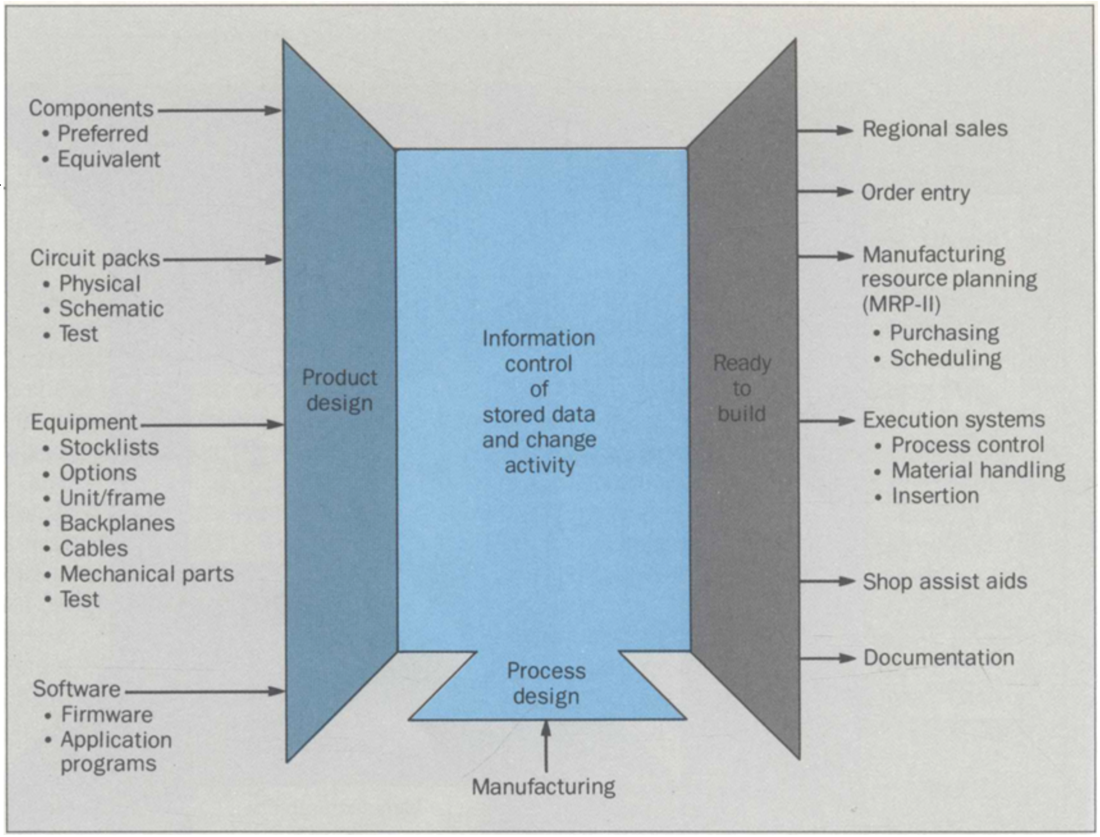


Figure 8. Data coverage of product introduction system.

from the design systems, the factory-independent information is converted to a specific factory or a specific line to build the product. For example, factory engineers generate the information needed to order each component specified in the design and feed this information to the factory's material management systems. The engineers generate routings, digital test programs, and numerical control information—for insertion machines that match the manufacturing line where the product is to be built. The components to be assembled and the information used to control the assembly process must arrive simultaneously on the floor for "just in time" manufacturing.

Status of Product Introduction

Historically in AT&T, separate systems managed information about circuit packs and the equipment constructed from them. A goal of the FOCUS project was to combine these systems, which ran under different operating systems, into a single logical architecture that would span the complete set of product and process data. Then the capabilities could evolve together to handle all information consistently and more efficiently.

The major difference in the two systems was how they use the information. The circuit pack system was concerned primarily with transferring complete sets of design and process data to the factory. But sales and engineering organizations used the equipment system to configure a product to meet a specific customer's needs and then sent the factory the information needed to manufacture each configuration.

Circuit Pack Information. Figure 9 shows the logical architecture of FOCUS that realizes the functional architecture. It explicitly identifies the system's components, whose functions are described here.

Information control. This module provides security, notification, data location resolution, and data archival and retrieval. The objective is to give the design system user and factory engineer controlled access to all necessary design, process, and yield information. Controlled access ensures that all users who need to view data can do so, but only authorized personnel can alter the data. This bidirectional accessibility to the data improves the DFM process

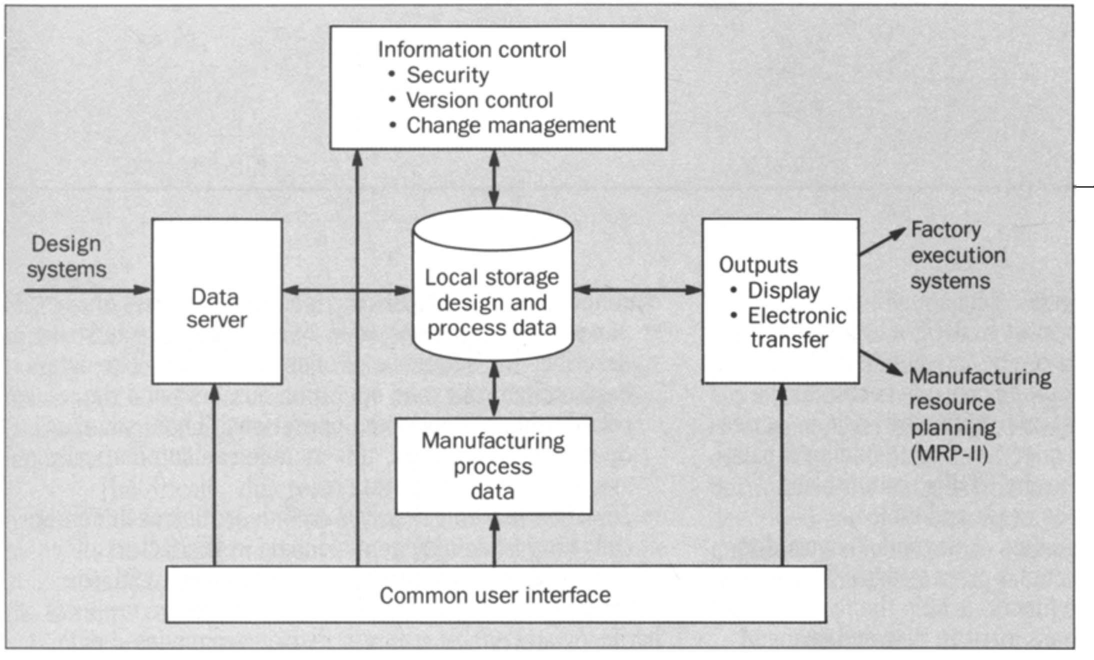


Figure 9. Logical architecture of product introduction system.

by making the yield information accessible to the design community.

Three levels of security—data, function, and person—control access to information. Access to data and functionality is limited on a per-user basis. The system's integrity can be maintained by carefully defining the ability of individual users to access particular functions and data.

Notifications are real-time events that signal the occurrence of an event or change (e.g., receipt of final design data for a particular artmaster issue). Within the system, predefined events that users cannot alter cause a notification message to be sent as UNIX system mail.

To record the storage location of all product data, a configuration control module stores the name of the CDF or other source that contains the design data. The configuration control system understands the causal relationship (changes that require other items to change) and temporal relationship (set of items that define a product at a specific time) between the various data entities (e.g., test information file, artmaster file). Thus, it permits users to examine the status of information and identify the set of data files that form a consistent product definition.

The version control subsystem uses the configuration control module to manage the source data files so that consistent set data can be assembled for any operation. The subsystem's two basic functions are:

- A data entity can be labeled so that it can be identified throughout its product life cycle. The FOCUS hierarchy of labeling currently is: artmaster issue, series, vintage, and revision.
- Data can be amalgamated (which is intrinsic to the labeling function) to form a view of a single manufacturable entity. For example, this version control function enables the user to define which design changes must be combined to form a complete product definition.

The change management subsystem provides a way to specify changes to the product definition, request approvals of changes, and approve submitted changes. The user can enter and display changes either as text or graphics. The functionality will evolve from its current implementation in FOCUS to a function that is shared with the appropriate design system. This will ensure that all design information is created, maintained, and tracked in the design systems and transmitted for introduction of product changes to the factory.

Data server. This module provides for the acquisition, synchronization, and amalgamation of needed design and manufacturing information. Using information from the configuration control module about where to retrieve the needed data, this module provides the intelligence to determine what distinct pieces of data need to be pulled together to form a complete, consistent view of a manufacturable entity. The data server must retrieve information from the design systems and factory execution systems as needed.

From the CDF or other data source, the server retrieves data needed to support FOCUS's utilities and applications, so applications can be independent of the storage schema. The data server controls access to the data and provides storage of information by issue or series and incremental change. A query and value-adding capability permits users to examine the CDF's contents and enter additional data, such as notes and tables.

Manufacturing process data. This module is used to capture both specific product and process data. These engineering of manufacture functions help the factory's product and process engineers manage new and changed circuit-pack product definitions. The engineers must precisely define the parts used in an assembly and the exact sequence of steps to be performed. At a high level, the engineers specify the sequence of operation codes for the circuit pack's manufacture, develop insertion machine programs, and create setup sheets and operator graphical aids. When changes occur, the engineers must evaluate what parts of the circuit-pack process definition are affected and update those data items.

These E of M functions are available:

- *Assign operation codes.* This is the sequence of operations for each item on a circuit pack.
- *Generate insertion machine programs.* These are pattern programs for through-hole insertion and surface-mount pick and place machines.
- *Generate shop aids for manual assembly.* The shop aids consist of the hand and progressive assembly layouts and the bin labels used for operators' trays.
- *Generate component preparation assignments.* Certain components must be prepared (e.g., putting them on a sequence tape) before they can be assembled onto the circuit board.
- *Create a manufacturing layout record (MLR).* The term MLR denotes all textual information that is distributed for use on the shop floor.

To provide the E of M functions, certain data that describes the operations in the factory must be maintained in an engineering support database. This data, which is factory-dependent and circuit-pack independent, consists of:

- *Master sequence of operation codes*—specifies and describes the sequence of operation codes. The database contains all valid operation numbers and the relationship of dependent operations. Thus, when an operation is identified, this module can automatically assign dependent operations.
- *Insertion machine descriptions*—describes each numerically controlled insertion machine in the factory.

Outputs. This module is the interface with the other systems to provide on-screen customized reports or hardcopy and enable users to display accumulated data. This feature's display aspect supports retrieval of design definition and value-added data. For example, engineers can examine the design data for DFM review and develop the engineering value-added data.

The outputs module allows FOCUS to send gathered information to the end-user systems that needs it. Some examples of these interfaces are:

- *Manufacturing resource planning systems*—stocklist data for an explicit product to be manufactured so MRP-II can create the bill of materials.
- *Factory execution systems*:
  - Shop floor control—operation code assignments that define the assembly sequence order
  - Manufacturing process control system—insertion machine programs and shop aids that can be downloaded to the shop floor as needed.

User Interface. This module provides common, consistent, and friendly access to the data and the application programs of, for example, the manufacturing-process-data module. The goal is to be consistent with design systems and factory execution systems.

Equipment Information. The FOCUS operational features that support the manufacture of product configurations (equipment) are similar to the circuit pack process. However, the scope of the data covered and its application are significantly different.

Configurable equipment is needed because the telephone network must be operational even during changes in customer demands, traffic volume, government regulation, and technological developments. This evolutionary process required that the equipment be manufactured and documented for each installation site to facilitate engineering for growth and interfacing to new functions.

Historically, different computer-based systems handled the various functions in the manufacture of equipment, its installation, and sales. One of our primary objectives is to provide consistent data electronically to all the systems to reduce ordering and manufacturing intervals. Thus, the architecture integrates the process from design through field sales and installation.

The capture of the complete set of design information is performed in several steps that correspond to the equipment hierarchy. These steps are:

1. *System description* (the highest level)—Major functional entities are defined, systems concepts are developed, and orderable options are determined.
2. *Bay, frame, or cabinet*—Systems are made by defining functional entities within options for assembling bays with the proper interconnections and parts required to support those functions.
3. *Shelf, unit, or panel*—Here the options for a bay are defined and shelves are assembled with the proper interconnections and parts required to support those options.
4. *Equipment assembly*—Shelves are made by defining the options and assembling equipment subassemblies with the proper interconnection wiring.
5. *Nonoption equipment assembly* (the lowest level)—This is similar to the circuit pack process.

Many of these design steps are documented on paper, and the data is entered as text into computer support systems. Some of the information (related to mechanical parts, cabling, and mechanical assemblies) is captured using product design systems not discussed here. The goal is to acquire all the information from design sources and extract the textual information needed to describe the equipment.

All the information control concepts already discussed (version control, configuration control, notification of users, and archival and retrieval of data) are equally appropriate when discussing equipment. But the problem is more complicated for equipment because a complete data model—such as the CDF—that gives the relationships between all the entities (mechanical and electrical) described does not exist for equipment. The product configurations are managed as correlated sets of files that represent the documents used to perform the various functions.

All product descriptions for AT&T manufactured equipment are currently available in an on-line electronic format where the design community enters the information and the user community accesses it directly via drawing descriptions. The version control over this information is the drawings that are produced from this information. Because so much information is needed to describe all AT&T products, a centralized, mainframe database management system is used for storage. The information on product changes is stored incrementally, and the user can obtain reports that list the differences between two issues of a drawing.

Equipment data usage. In the factory, the processes described for circuit packs apply equally well at the equipment level. That is, all E of M functions, the transfer of material information to the MRP-II systems, and the distribution of data to the execution systems on the floor for assembly and test are similar. In addition, because optioned product is sold in specific configurations, this data is also used to take the order for a configured product and expand it into a complete list of the manufacturable items that must be assembled. Thus, it is the major input to the factory scheduling systems in the MRP-II systems.

This information is also used to engineer a specific configuration for a customer, providing forecasts of sales and orders for the product, and determining price and cost estimates for new products. These activities occur, not in the factory or the design community, but in the regional sales and engineering organization, which makes electronic transfer critical to provide timely information.

Impact of Product Introduction Tools

Although the benefits of a fully integrated process are self-evident, we have included two examples to show typical gains.

The availability of accurate product descriptions to the factory and the sales organizations is critical if the desired product is to be delivered to customers in the shortest time. When microfilm was used, access to vaulted data required four to six weeks. The introduction of on-line equipment configuration data has reduced the interval to a few hours.

Electronic data transfer from the design systems to AT&T's Dallas Works has reduced the time to develop and prove in component insertion machine programs from 18 days to less than two hours. The process eliminated manual reentry of data from paper documents and provided error-free information. Furthermore, availability of the data in machine readable form has made it possible to automate the sequencing operations for the specific insertion machines.

Summary

This article has described AT&T's product design and introduction systems. Although these systems provide automated aids for most phases of the product realization process, there is still much to be done.

Three major thrusts are driving the future development. First, as the product realization process continues to evolve, the operations plan calls for new and modified computer aids. Second, the tools used for design and product introduction systems must be consistent for all parts of the product hierarchy to ensure that all data is managed correctly. Third, because a larger number of people (many of them casual users as opposed to full-time, dedicated ones) are using the computer aids, the "user-friendliness" of applications must be continually improved. This will be done both through better integration of AT&T's systems and by taking advantage of new functionality offered via workstations for building user interfaces.

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Biographies (continued)

State University and an M.S.E.E. from Columbia University. Mr. O'Neill, head of the Manufacturing Engineering Systems Planning Department at Holmdel, New Jersey, joined the company in 1967. He is responsible for systems engineering of FOCUS, which provides software that interfaces design and manufacturing data. Mr. O'Neill has a B.S.E.E. from the University of Maryland, an M.S.E.E. from The Catholic University of America, and a Ph.D. in electrical engineering from The Johns Hopkins University. Mr. Pennino, head of the Computer Aided Design Department in Holmdel, New Jersey, joined the company in 1960. He is responsible for software development of the interconnection design system, a CAD tool for physical design of printed-wiring boards and backplanes. Mr. Pennino has a B.S. in mechanical engineering from New Jersey Institute of Technology, and an M.S. in engineering from Stevens Institute of Technology.

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