AT&T *5ESS*® SWITCH HARDWARE DEVELOPMENT METHODOLOGY: A PROCEDURE FOR ENSURING QUALITY

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Hardware design for AT&T's 5ESS® digital switch is governed by a methodology that provides a common design approach for all hardware development engineers on the 5ESS switch project. It enables engineers to produce quality hardware designs that are completed in a timely way, are cost effective, and are easily introduced into manufacturing. The methodology uses the concept of a *design team* that addresses all issues of product design and manufacturing. It streamlines the design process by eliminating redundant tasks and paperwork. The methodology focuses on early reviews and minimizing changes late in the development process. Although the framework of the methodology is shared among all 5ESS switch organizations, it still allows flexibility to encourage engineers to apply their own initiative and creativity to the design process.

Introduction

In an ever-increasing competitive environment for digital central office switching equipment, timely, reliable, and cost-effective quality designs are essential to customer satisfaction. AT&T's candidate for digital central office switching equipment is the 5ESS switch. During the development of the 5ESS switch, a new hardware development methodology was implemented that enhanced AT&T's ability to respond to the demands of the competitive switching market. The methodology focuses on improved communication and well-defined parallel efforts among hardware development, manufacturing, and software development organizations. As a result, most hardware faults are identified early in the development cycle, significantly improving overall product quality, availability, and cost.

The new methodology improves the design development process to maximize quality, cost-effectiveness, innovation, and productivity, while minimizing development time. The key elements of this

Panel 1. Terms and Acronyms in This Paper

DFM	design for manufacturability
DFT	design for testability
PDI	product design information
PQMI	process quality management and improvement
RTB	ready-to-build

methodology, the 5ESS Switch Hardware Development Methodology, are:

- *Design teams* that include all disciplines from design conception to product realization.
- *A test team* to manage all aspects of both design verification testing during development, and initial product testing during manufacture and deployment.
- *Requirements and design reviews* that are early, frequent, and thorough to minimize change activity late in the product development cycle.
- *Development phases and benchmarks* that are well defined to allow detailed and common project tracking.
- *A formal hardware-software interface definition* reviewed and documented early in the process.
- *A project notebook* that uses informal documentation to allow parallel design and documentation while ensuring complete final product documentation.

These key elements form the framework of the new methodology used by all 5ESS switch hardware development organizations. The methodology is flexible to encourage initiative and creativity by development engineers. This creativity is critical to the design realization of technically advanced switching products.

Team Concept

The design team concept is essential to providing quality switching products. In this era of complex designs, a team approach to design, and extensive use of design reviews, can greatly reduce design iterations late in the development cycle. The team approach to design development fosters cooperation among designers of various disciplines because the entire team shares developmental responsibilities. This open-communication approach requires the early involvement of all team members, and reduces the risk of misunderstanding and error. Design teams are formed for each of the following functional 5ESS switch hardware project partitions:

- Project teams
- Multilevel design teams (all levels named below may not be required)
- Cabinet level
- Unit level
- Circuit pack level
- Device level
- Test teams

Figure 1 shows the hierarchy of the development teams.

Project Teams. The project team is the first team formed. As project requirements are received and understood, the project is partitioned into functional elements, e.g., cabinets, units, circuit packs, and devices. The project team forms the design and test team rosters, and ensures open communication within and among these teams. Members of this team develop and track the project schedule, and serve as development project managers.

Project team membership is project-dependent and includes representatives from all affected disciplines. A typical project team consists of management representatives from the following areas:

- Hardware design
- Software design
- Manufacturing
- Highest hierarchical design team leader (non-management member)
- Test leader (non-management member)

Members may be added as required by the scope of the project.

Design Teams. As the project is partitioned into functional elements, the design teams are formed for each level of hardware partitioning. The design teams translate the high-level requirements generated by the hierarchical teams into detailed design requirements. Each design team manages the design, development,

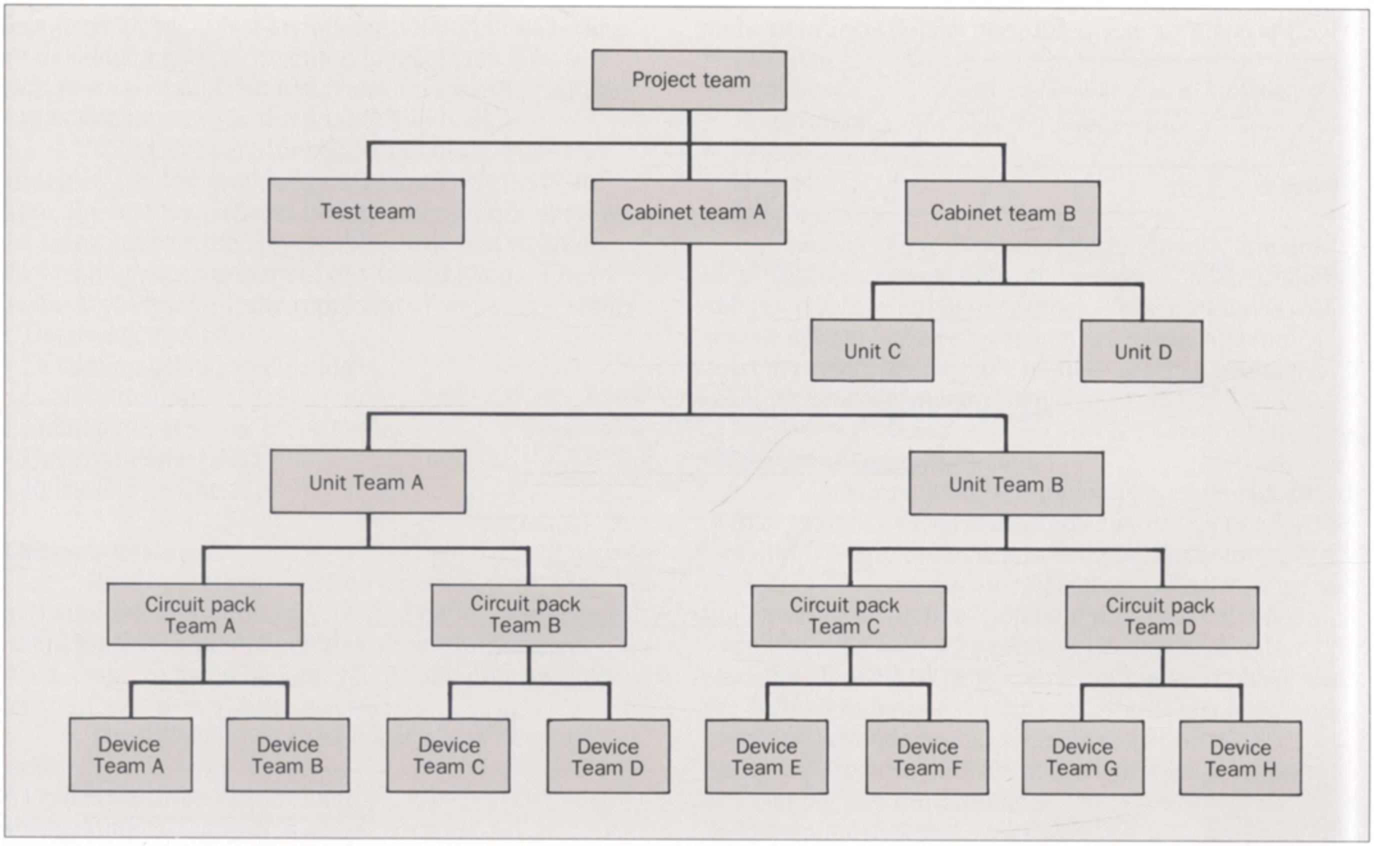

Figure 1. The hierarchy of development teams as used in AT&T's 5ESS® switch development organizations.

manufacturing, and testing of its portion of the hardware project. Requirements and design reviews are held regularly to verify that the design meets the specified requirements. These teams also ensure that detailed requirements, hardware and software interface information, design, and test results are documented in a project notebook that will be described later in this paper.

The design team consists of the development disciplines needed to design, test, and manufacture the product. While a design team is being formed, the composition of any subordinate team is also being considered. Team leaders from the subordinate teams and members of the test team are both members of the design teams; this dual role fosters interteam communications. The following areas typically are represented on the design team:

- Hardware design
- Software design
- Design support
- Test design
- Subordinate design team leaders

Membership disciplines may vary among the different levels of hardware design depending on the specific expertise needed.

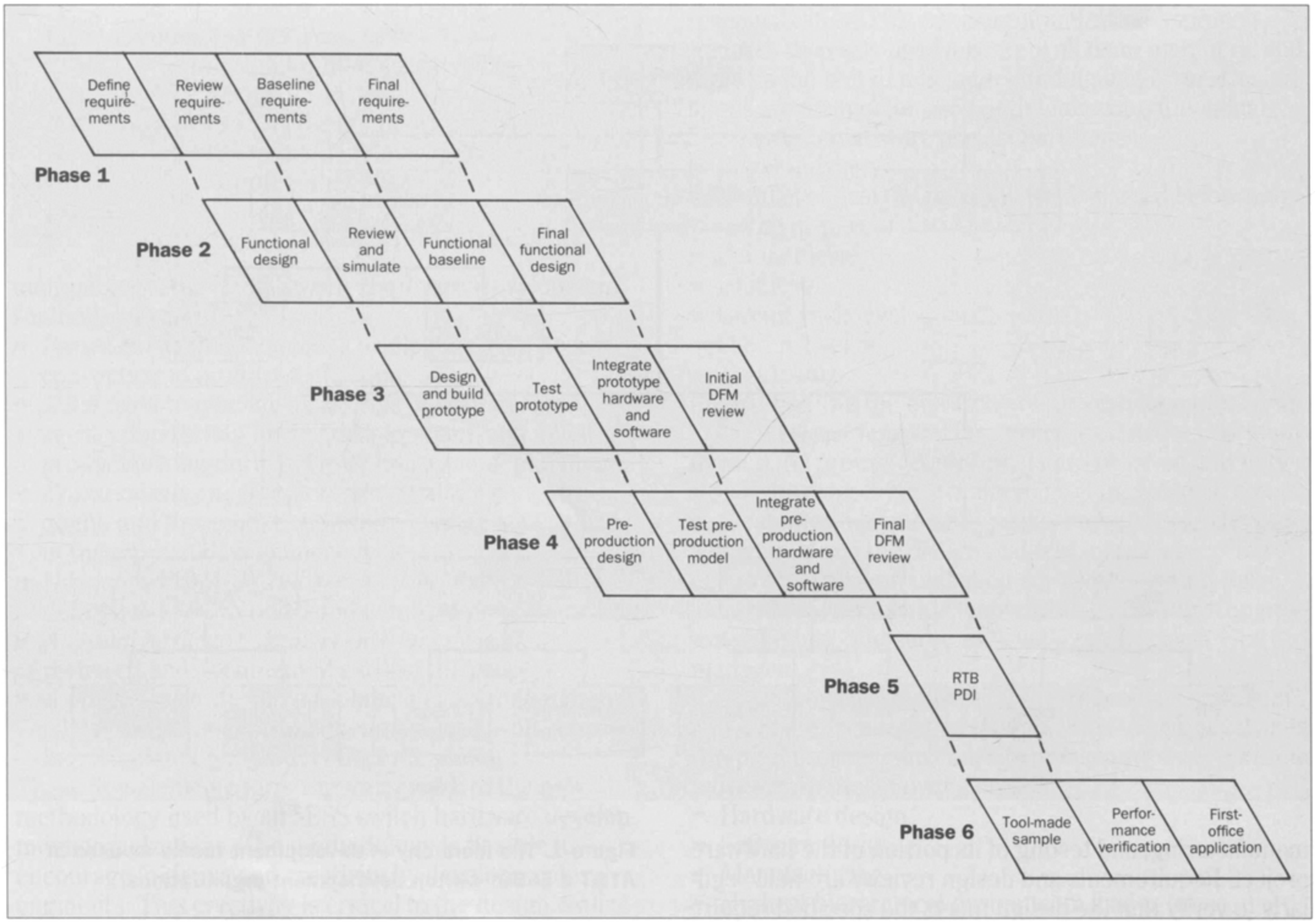

Figure 2. A high-level view of the hardware development process for 5ESS® switch development organizations. Note that exit criteria have been established for each phase to identify the phase status of the project, and to ensure that critical quality activities within the phase are completed.

Test Teams. Each new development project requires a test team. The team members must be familiar with the cabinet, unit, circuit pack, and device requirements, and must have technical knowledge of the hardware. This knowledge is necessary to develop effective and efficient tests. The main function of the test team is to develop and execute two critical testing functions in the project: *design verification* and *product verification.*

Test strategies and test scripts for both types of testing are developed and documented in test plans. The test team ensures that these test plans are executed and the results documented in the project notebook.

To ensure early development of rigorous test strategies and the availability of resources to execute them, the test team leader is also a member of the project team. Individuals responsible for design partition level testing are members of the design teams. The following areas are typically represented on the test teams:

- Diagnostic design
- Design partition level testing
- Factory testing
- Simulated customer office testing
- Environmental testing
- Reliability testing

Hardware Reviews

Hardware reviews are an essential part of this methodology. Although reviews add effort at the busiest part of the development process, their downstream result—e.g., reduced design change and improved product quality—is worth the investment.

The following types of hardware reviews are conducted:

- Project-partition requirements
- Functional design
- Hardware-software interface
- Design verification test plan
- Design for manufacturability (DFM)
- Design for testability (DFT)
- Product verification test plan.

The project team leader is responsible for ensuring the completion of individual reviews for a project. This includes scheduling the reviews in the overall project plan, identifying and allocating resources for the reviews, selecting review moderators, and assisting them to ensure the reviews are conducted as planned.

There are six basic steps in the review process. They occur in each review, although specific entrance and exit criteria details may differ. The six steps are:

- Planning
- Overview
- Preparation
- Review Meeting
- Rework
- Follow-up.

Each review requires different inputs, amounts of preparation, review time, and numbers of participants and reviewers. Hardware reviews also are an important source of data for in-process metrics to manage the current project and provide input to process management for process improvement.

Project Development Phases

The hardware development process is composed of many subprocesses in a complex interdependent relationship. To help projects proceed effectively through all necessary processes in an efficient and effective way, six high-level hardware development phases are defined. Each phase focuses on a primary product realization objective. Individual benchmarks within each phase also are defined to measure progress toward the phase's primary and secondary objectives. Every 5ESS switch hardware project conforms to the following six phases:

1. Planning and requirements
2. Functional design
3. Prototype development
4. Preproduction development
5. Ready-to-build (RTB)
6. Manufacturing and deployment support

Figure 2 represents a high-level view of the hardware development process. Exit criteria have been established for each phase to identify the phase status of the project, and to ensure that critical quality activities within the phase are completed. They emphasize localized defect identification and resolution within the current phase. However, the transition between phases is not serial, and phase overlap exists for non-dependent subprocesses of different phases.

Both in-process and end-process metrics have been defined to help manage hardware projects and processes within the structure of this methodology. In-process metrics provide quality measures of intermediate design deliverables and process steps that affect end-product quality. End-process metrics of the final design and product are used with the in-process metrics of multiple projects to measure and improve the process and methodology.

Planning and Requirements. The planning and requirements phase begins after a project has been approved. Initially, the high-level project requirements are supplied by systems engineering and architecture design organizations. Project requirements consist of the customer feature requirements, switch architecture evolution requirements, high-level system interface requirements, and any general requirements necessary for the project.

During this phase, the hardware project team is established. This team is responsible for managing the entire hardware development project. After the project team is established and project requirements are available, the project is partitioned into physical hardware elements (i.e., units, circuit packs, custom devices). As this partitioning progresses, design and test teams are formed.

The project, design, and test teams meet to determine appropriate benchmarks, staffing, and schedules for the overall project. This meeting has become known as an *estimeeting*. It allows the developers to have input into the project's staffing and scheduling. At this time, partition-level schedules are also developed by the design and test teams.

The partition design requirements are derived from the project, the next higher hierarchical level design team, and general design practice requirements. Reviews are held for each design partition to ensure that the design team understands and can produce detailed design requirements from the project and general requirements. Requirements issues and defects are identified, and responsibility for resolution is assigned. Issues and defects are tracked to resolution by using a computerized design configuration management system.

The design requirements form the foundation of project success. Early resolution of all requirement issues will eliminate design changes in later phases because of incomplete or inaccurate requirements. This will lead to on-time delivery of high quality hardware.

Functional Design. In this phase, the electrical design process begins. It may begin before the previous phase is completed, but all requirements issues must be resolved before any Phase 2 review activity.

During the initial part of this phase, the design requirements are converted into functional blocks. As the design progresses, computer-aided design tools are used to synthesize and simulate the design. Electrical schematics, waveforms, and timing diagrams are generated. Functional design reviews rigorously evaluate and examine the design for possible design faults. The interfaces between hardware and software are identified, documented, and reviewed. By detailed analysis of these interfaces, design changes are minimized during hardware-software integration testing.

The design is also reviewed for manufacturing testability (DFT) through formal reviews by factory test engineers and test developers. All testability improvement ideas generated at this review are tracked to resolution during prototype or preproduction development.

A thorough design verification testing strategy is developed to ensure that the implementation of the design meets or exceeds all requirements. Documented test plans are the foundation of the test strategy. They are developed by the test team to provide a set of tests used to verify each prototype and preproduction model. A formal review of the test plan is conducted with each design team to ensure that complete and robust tests have been defined for each test environment where the models will be tested. Test environments include the device laboratory, circuit laboratory, hardware-software system integration, environmental testing, electromagnetic compatibility testing, and others. A comprehensive test plan, provided early in the hardware development process, shortens test intervals and maximizes fault detection before manufacturing begins.

During the functional design phase, components are selected and approved for project use. The component management process used for this is rigorous to ensure the availability and reliability of the components used in the 5ESS switch.

Prototype Development. Prototype hardware models are an important method of design verification. Prototypes offer the first opportunity to examine the functional design converted into a physical and electrical reality. They supply an extra level of requirements validation and verify the results of earlier reviews and simulation. Any design changes required during model testing are formally documented for inclusion during the next design phase. The prototype design also provides the basis for an initial DFM review. The design team's manufacturing product engineer provides a comprehensive DFM review from an established set of manufacturability requirements. All DFM issues identified are formally tracked to resolution during the next phase. After design verification testing is complete, operational prototypes are given to software development for integration with initial software.

Preproduction Development. Preproduction development is the next phase in the development process. Where the functional design phase concentrated on the electrical attributes of the design, the preproduction phase concentrates on the physical attributes of the design, including component layout, reliability, power consumption, aesthetics, manufacturability, testability, and the projects's other physical requirements. As the electrical design was dependent on stable requirements, preproduction development (physical design) is dependent on stable electrical design from phases 2 and 3.

To ensure that manufacturability and factory testability issues are resolved before manufacture, final DFM and DFT reviews are held at the end of this phase. All DFM and DFT issues identified earlier must be resolved to complete this phase.

Preproduction hardware is produced from initial versions of the same design information that will be used for production. Any design faults identified during design verification testing of preproduction hardware are formally captured and tracked to resolution. All design changes necessary to resolve these faults are introduced into both the design source and the model with formal change procedures. The proven hardware is then delivered to the appropriate system laboratory to begin hardware-software integration testing. This fully functional preproduction hardware is also used to validate the factory tests developed in parallel with design.

Ready-To-Build. During the ready-to-build phase, all assembly and test information used for preproduction is reviewed and updated to reflect the final design established during the preproduction phase. All production design, test, and shop assembly information is then officially released to the manufacturing organizations. The process for releasing information primarily consists of certifying computer-based information stored in a shared design and manufacturing database system. Most computerized design information is transferred via wide area networks, although some traditional paper documents are also used. The official release of the production design is documented in a ready-to-build PDI (product design information) package. The release of this information package requires design team consensus and project team (management) approvals. Since manufacturing representatives were part of the design teams, this official release represents a consensus view by both development and manufacturing that the design is "ready to build." Including the manufacturing representatives in the design teams also allows the manufacturing location to get an early start on any critical path tasks (e.g., component procurement, process modifications) necessary to support manufacture of the design.

Manufacturing and Deployment Support. At this point, the design is completed and documented. Production samples are built to verify that the design information has been successfully transferred to and correctly

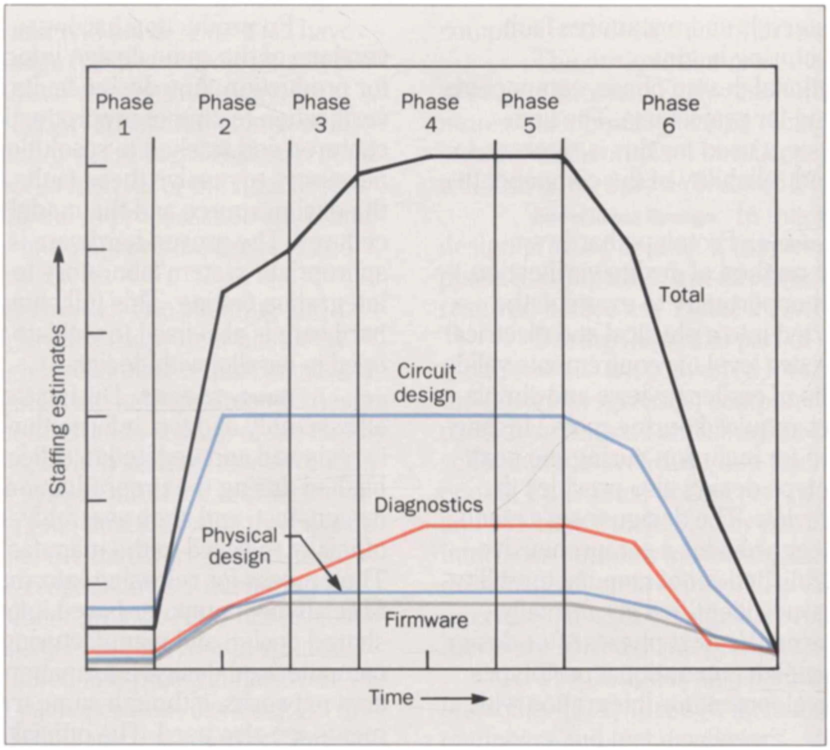

Figure 3. Typical hardware development staffing profile, showing the activities of the various development teams.

processed by the manufacturing systems. These samples are used to verify the capability of the manufacturing processes to build products that accurately reflect the design intent.

After the production samples are approved by the design team, initial manufacture can begin. The first products made are intended for performance verification testing and early product shipments to support first-office application. Performance verification testing is a combined hardware-software operation that uses initial production hardware and production software to ensure that the performance requirements of both the customer and AT&T are satisfied. This testing is performed by a test team separate from earlier hardware or software development teams.

Product yield is continuously monitored during initial manufacturing. In addition, product performance is monitored throughout both manufacturing testing and customer field use. If product yields or performance are inadequate, the design teams will be notified to take appropriate corrective action. When the performance verification test requirements are met, manufacturing yields are acceptable, and the first customer application is operating, approval for full production is granted.

Hardware Development Phase Staffing

During typical hardware development, the activities of the project, design, and test teams increase rapidly after the requirements review phase. The activities of these teams decrease rapidly after the ready-to-build

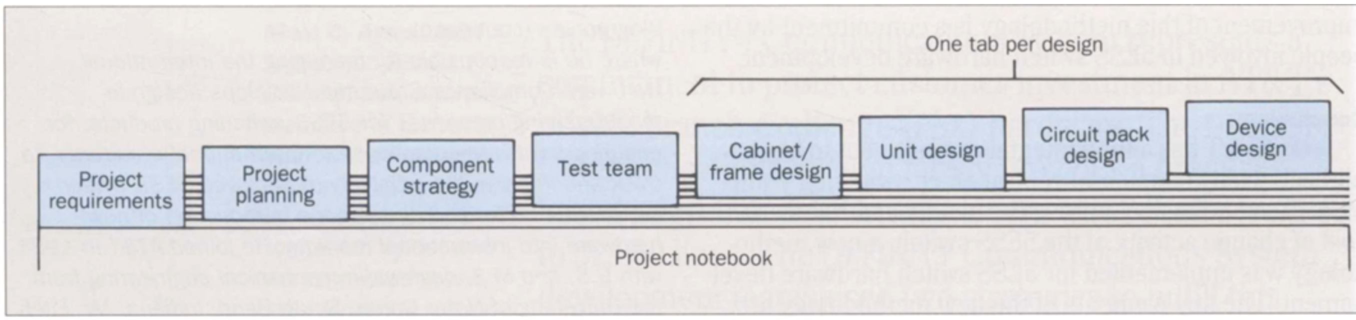

Figure 4. A representation of the project notebook structure and its various tabbed divisions.

phase as the design moves into manufacturing. When the product meets or exceeds customer expectations, the staffing of the teams can be reduced to a level commensurate with product support activity. A typical staffing profile is shown in Figure 3.

Hardware-Software Interface

The detail-level interface between hardware and software is a critical design element that must be established early in the project. This interface should be an output of the functional design process and should be formally documented and reviewed during Phase 2. This allows parallel development of hardware and software to occur with minimal design change when hardware-software integration testing is begun at the end of Phase 4. The project team is responsible for ensuring that the interface is documented and reviewed on schedule.

Project Notebook

The project notebook is a key design file or document associated with this methodology. All requirements and design decisions associated with the project are contained in this notebook. An advantage of the project notebook method of documentation is that all design information for a given project is centrally located and maintained. The project notebook approach allows team members to record pertinent information while the design is progressing. By documenting all design actions as they occur, all team members and other interested persons have an up-to-date account of the project.

A key feature of the project notebook is the inclusion of "informal documents." Informal design data, such as graphs, pictures, drawings, flow charts, text, or other pieces of information describing part of the design, can be entered as they are created.

A standardized two-level tab structure is used to create a common information structure for all project notebooks. Figure 4 shows the high-level tab structure for each project. This primary tab structure closely parallels the team structure. The project notebook approach to documentation guarantees that important information is completely and accurately documented without the delays associated with formal documentation.

Methodology Evolution

This methodology was developed by many individuals who participated in hardware development during the 5ESS switch project. Their experience and knowledge from early 5ESS switch projects is the foundation of this methodology. Although the methodology has seen four revisions, it is not final. Continual development process improvement through PQMI (process quality management and improvement) techniques will both evolve and re-engineer its key elements.[1] The continuing improvement of this methodology is a commitment by the people involved in 5ESS switch hardware development.

Conclusions

AT&T has a fundamental commitment to be the highest quality supplier of central office switching equipment. To continually improve the quality and reduce the cost of change activity of the 5ESS switch, a new methodology was implemented for 5ESS switch hardware development. The key elements of the new methodology are:

- Using cross-functional design teams
- Early, frequent, and thorough requirements and design reviews
- Well-defined development phases and benchmarks
- Detailed hardware-software interface document
- Structured project notebook.

The framework of this methodology is sufficiently flexible to foster innovation and creativity by designers.

This methodology has proven to be an effective structure to ensure quality during 5ESS switch development, and has met with great success. Significant reductions in change activity have been achieved by using this methodology. Recent project audits support the contribution this methodology has provided to achieving the demands of project schedule and product quality.

An attitude that *we all own the product and product quality* is becoming prevalent in 5ESS switch development. AT&T will continually improve this hardware development methodology to satisfy the changing needs of the competitive switching equipment marketplace. Customer satisfaction is paramount to the quality commitment of AT&T.

Reference

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Biographies (continued)

where he is responsible for managing the International Hardware Compliance Group that develops design-to-manufacturing processes for 5ESS switching products, for ensuring hardware compliance to international standards, to track and improve the reliability of deployed 5ESS Switch hardware, and for coordinating the introduction of new hardware into international markets. He joined AT&T in 1981 with B.S. and M.S. degrees in mechanical engineering from the University of Notre Dame, South Bend, Indiana. Mr. Fitch is a member of technical staff, also in the International Systems Hardware Design Department, where he is a hardware designer of central office switching equipment for the international market. He joined AT&T in 1984 with B.S.M.E. and M.S.M.E degrees from the University of Illinois, Urbana-Champaign. Mr. Graff is a supervisor in the 5ESS Switch Module Development Department at Indian Hill South, and is responsible for hardware quality, methodology, and system physical design for the 5ESS switch and the Service Net-2000, Release 1 project. He joined AT&T in 1965 with an A.A.S. in electronics from the DeVry Technical Institute, Chicago, Illinois. Mr. Groszczyk is a distinguished member of technical staff at the Indian Hill South facility, also in the 5ESS Switch Module Development Department. He is working in the 5ESS Hardware Development Laboratory, and is currently responsible for hardware project management for the Service Net-2000, Release 1 project. He joined AT&T in 1969 with B.S. and M.S. degrees in mechanical engineering from the University of Illinois, Urbana-Champaign.

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