Role of electronic measurement systems in new product development
by Adwait Prabhakar Ayare

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Industrial and Management Engineering
Montana State University
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Abstract:
Firms increasingly compete on their ability to develop high quality products at lowest cost possible and introduce them into the market in the shortest possible time. Much has therefore been written about new product development (NPD) practices, but few researchers have attempted to highlight NPD issues related to electronic industries even though they are one of the major drivers of the US economy. Also few have investigated the role of test equipment in NPD, though it plays a crucial role in assessing design performance.

This thesis attempts to study NPD in electronic industries, especially understand the role of electronic measurement systems1 (EMS) in NPD. A qualitative research approach, namely grounded theory, was adopted to guide data collection and analysis. Four sites were chosen for collecting data, which were then analyzed using data coding techniques.

Rigorous data analysis uncovered two major themes, the Hardware-Firmware-Test integration triad and information transformation. The Hardware-Firmware-Test integration triad results from the common practice of breaking down the development effort into separate hardware and firmware development cycles that must then be integrated, often with great difficulty. This integration problem gets compounded because these two groups must also simultaneously develop EMS to test their designs.

Information transformation, the process by which test data is transformed into useable design knowledge, results from a complex interaction between the human design engineer and other participants in the development process. Information transformation activities consume 70% of testing time.

This thesis investigates these two deeply rooted issues that all electronics manufacturers face, and proposes alternative approaches. The new models hold significant potential to improve product development effectiveness by simplifying the integration problem and speeding up the transformation processes.

1EMS: system consisting of data acquisition, analysis, presentation and related tools.

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A thesis submitted in partial fulfillment
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Master of Science

in

Industrial and Management Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

April 2002

N378
Ay159

Approval

Of a thesis submitted by

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Dedicated to the people I love:

Mom, Dad and Yasuko

Acknowledgements

I owe a lot to my advisor, Dr. Durward Sobek II, not only for being my graduate advisor but also my mentor at MSU, Bozeman. Only with his guidance and thought provoking insights, was I able to do this research and write my masters thesis. I am ever grateful to him and my other committee members, Dr. Paul Schillings, Dr. Don Boyd and Dr. Joe Stanislao for sharing their knowledge and experience and always inspiring me.

Mr. Sudhir Joshi and Mr. Chris Martinez of Tektronix Inc. (Instrumentation Division) were the inspiration behind this research. In developing strategies for their future generation products, Tektronix wanted to inform their decisions with an in-depth understanding of how engineers use electronic measurement systems in actual engineering processes, especially new product development. I would therefore like to thank both of them for nurturing this idea, providing direction and the necessary funds. I would also like to thank Ms. Tatyana Voronyuk for gaining access to the research sites and setting up interviews. I would further like to thank all the participants for their willingness to be interviewed and for providing invaluable information.

On a personal note I would like to thank my family, friends, M&IE dept. head Dr. Vic Cundy and office staff, especially Carol Anderson, Terry Kennedy and Eileen Baker for their continual support that has helped me finish my graduate studies at MSU.

But I am most grateful to God, for without his blessings I would have never tread this path.

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ABSTRACT

Firms increasingly compete on their ability to develop high *quality* products at lowest *cost* possible and introduce them into the market in the shortest possible *time*. Much has therefore been written about new product development (NPD) practices, but few researchers have attempted to highlight NPD issues related to electronic industries even though they are one of the major drivers of the US economy. Also few have investigated the role of test equipment in NPD, though it plays a crucial role in assessing design performance.

This thesis attempts to study NPD in electronic industries, especially understand the role of electronic measurement systems[1] (EMS) in NPD. A qualitative research approach, namely grounded theory, was adopted to guide data collection and analysis. Four sites were chosen for collecting data, which were then analyzed using data coding techniques.

Rigorous data analysis uncovered two major themes, the Hardware-Firmware-Test integration triad and information transformation. The Hardware-Firmware-Test integration triad results from the common practice of breaking down the development effort into separate hardware and firmware development cycles that must then be integrated, often with great difficulty. This integration problem gets compounded because these two groups must also simultaneously develop EMS to test their designs. Information transformation, the process by which test data is transformed into useable design knowledge, results from a complex interaction between the human design engineer and other participants in the development process. Information transformation activities consume 70% of testing time.

This thesis investigates these two deeply rooted issues that all electronics manufacturers face, and proposes alternative approaches. The new models hold significant potential to improve product development effectiveness by simplifying the integration problem and speeding up the transformation processes.

[1] EMS: system consisting of data acquisition, analysis, presentation and related tools.

CHAPTER 1

INTRODUCTION

New Product Development (NPD) activities, which involve conceiving new ideas, designing and testing them, then creating a manufacturing system to produce them are viewed as a major strategic competitive weapon (Wheelwright and Clark, 1992). Firms increasingly compete on their ability to develop new products faster and cheaper. Studies have shown that firms who are successful in NPD, irrespective of the industry type, set similar strategic goals: develop high *quality* products at lowest *cost* possible and introduce them into the market in the shortest possible *time*. The ultimate goal of this thesis is to help firms develop better product development (PD) systems and processes to meet these quality, cost and time (QCT) goals, as they are commonly referred to.

To help industries develop better PD systems and processes, numerous studies have been carried out and multiple streams of research have developed. But few researchers have viewed PD as a system and most of the studies tend to prescribe tools or techniques to improve some aspect of PD. Few studies provide a combinations of tools, techniques and processes that will optimize the PD system as a whole.

This research therefore takes a holistic view of the PD process and attempts to first understand NPD systems and processes at electronics industries. It then attempts to highlight issues related to design-test and manufacturing of electronic components in light of PD systems and processes. Understanding processes and trying to improve them is important, as Deming said, process control not product control. On a similar note the

basic premise of this thesis is to attempt to improve NPD processes so that the products therefore will be that much better, be made on time, involve minimal waste and ultimately be more profitable.

Why study NPD at electronic industries?

Much of the literature on PD has been born from case studies from automotive and software industries. Few researchers have attempted to address NPD issues related to electronics industries. Another reason for choosing this industry was many components in automobiles, airplanes, consumer electronics; PC's are electromechanical devices. The industry as a whole has also grown tremendously and is one of the major drivers of the US economy. Just like other industries it faces competition from firms from EU and Asia. Firms from all over compete on their ability to develop innovative products. Improvements in NPD systems and processes will potentially offer huge gains to these firms. Thus much could be gained from the study of NPD at electronic industries.

Contribution to recent NPD literature

Design, build and test (D-B-T) cycles have been given considerable importance in PD literature and some recent studies have also shed light on them (Loch, Terwiesch and Thomke, 2001; Thomke, 2001). But almost no one has attempted to look at the role that test equipment plays in the PD process. Studying this role is important because in a typical D-B-T cycle a design engineer designs the part, prototypes it and then tests it using test equipment, which then enables evaluation of the design performance against product requirements. Once a proper determination is made the design engineer can

improve the design and attempt to meet customer needs effectively. Carrying out such tests and making a determination of the design performance consumes a major part of the development time and engineering effort and therefore making this task simpler or faster could make the overall PD process faster.

Research questions

One of the major goals of this research is therefore to understand the role of electronic measurement systems[2] (EMS) in NPD. The questions addressed by this research are:

- What is the role of EMS in PD processes especially D-B-T cycles?
  - What are the data usage patterns?
  - What is the relationship between the data generators and users?
  - What is the role of software used in testing? and
  - What is role of EMS in experimental strategies?
- What is the role of EMS in management of engineering information at these firms?

These findings will help to prescribe in a limited way what new capabilities should be and how EMS could help these firms improve their PD systems and processes.

The scope of this thesis was to understand the role of EMS in NPD, therefore data collection concentrated on understanding when and how the EMS are designed and used. This included understanding of how EMS are used to generate test data, analyze it, store

[2] EMS: system consisting of data acquisition, analysis, presentation and related tools.

it and transfer it. Also data about all engineering activities leading to and resulting from the use of EMS was also collected.

But to understand this data, contextual information was needed. Therefore data collection was broadened to include product development organizations and processes. This included information about the role of management, structure and communication within teams, PD phases, activities performed within the phases, milestones, and detailed information on D-B-T cycles.

Thesis overview

The backbone of this thesis is data collected about PD systems and processes from four firms involved in development and manufacturing of electronics. The first is a large corporation developing electronic test systems. Two of the firms are mid-size corporations, involved in manufacturing hybrid chips and fiber optics respectively. The fourth firm is a small company making dynamometers.

These four firms are diverse in terms of their products, size and competencies. Consequently the PD organization and processes they have in place to design, test and manufacture new products were also slightly different. But this diversity was advantageous because it made it possible to generalize across the firms and investigate PD issues that were common across all four firms. The themes that emerged and discussed in this thesis are grounded in PD issues common across all four firms.

Chapter 2 reviews PD literature, which serves two purposes. The first is to enable us to understand and appreciate current PD practices, including PD organizations, processes and strategies. The second purpose of reviewing current NPD literature was to

understand world-class PD practices pertaining to the goals of this research such as flexible PD systems, information and knowledge management strategies, Concurrent Engineering and Set-Based practices.

Chapter 3 describes the research methodology adopted to guide data collection and analysis. It justifies the choice of qualitative research methods over quantitative methods and describes the qualitative methods adopted, mainly grounded theory. It explains in depth how this research was carried out, including choice of sites, data collection through semi-structured interviews, and data analysis using various types of data coding.

Chapter 4 describes the four cases from a standpoint of PD organization, processes and experimental strategies adopted by these firms including and the use of EMS in D-B-T cycles. This chapter not only explains the subtle differences in the PD processes followed by these four firms, but also generalizes across the sample and highlights PD issues common across these firms. This chapter also provides the reader contextual information for understanding the two themes described in chapters 5 and 6.

Chapter 5 describes a major integration issue faced by management at these four firms. The Hardware- Firmware-Test integration problem occurs because these firms choose to break down the PD effort into hardware and firmware development groups and then have to integrate the efforts of these two groups. This problem gets further precipitated because these two groups have to develop EMS to test their designs and also coordinate development activities with manufacturing engineering. To resolve this issue

set-based concurrent engineering practice has been prescribed instead of the point based concurrent engineering approach.

Chapter 6 describes issues related to information transformation that occurs after testing a prototype. The most critical aspect of any design, build and test cycle is the transformation of test data into useful information so that design performance can be evaluated. This chapter explains the information transformation process, and shows how it consumes a significant amount of PD time. To improve the information transformation process a new information management system is proposed that supports NPD.

This thesis is a result of intensive data collection and rigorous data analysis but yet should be treated as a preliminary investigation into the research questions. There are still many issues to be investigated and many other themes might emerge if more data is collected from many more firms.

CHAPTER 2

LITERATURE REVIEW

Literature on new product development (NPD) is extensive, fragmented and ever growing. Several researchers have attempted to classify NPD literature into different streams. Brown and Eisenhardt (1995), for example, have classified literature into three streams: PD as a rational plan, communication web and disciplined problem solving. But in view of understanding the role of Electronic Measurement System (EMS) in NPD, no one stream of NPD literature was pursued, rather literature prescribing best practices in NPD was reviewed. As the grounded theory study progressed certain issues of NPD became more relevant to the research problems and so literature relating to information and knowledge management, new PD practices and experimental strategies was also reviewed.

Rather than presenting a comprehensive review of the literature this chapter highlights important issues and concepts considered for this research. The first section of this chapter establishes the need for NPD and outlines measures of successful NPD. The second section explains how these success factors contribute towards establishing world-class PD systems. The third section outlines how this research contributes the current body of knowledge on effective NPD practice.

Need and measures for successful NPD

The current electronics environment is perhaps best described as 'turbulent', very intense and dynamic. The major factors or forces causing this are (Wheelwright and Clark, 1992):

- Intense competition: Just like in all other businesses the numbers of competitors that are capable of competing on a world class level in electronics and hi-tech have increased multifold. The list of a firm's toughest competitors now includes firms from Europe and Asia thus making the competition is more intense and less forgiving.
- Fragmented and demanding markets: The target markets for electronics are not limited to developed nations but also developing nations, which have now become more accessible and hold huge potential. Firms now have to serve customers with diverse expectations who need quick and easy solutions to their problems.
- Diverse and rapidly changing technology: Rapidly developing and changing technology also creates options to meet the needs of the changing markets. The challenge lies not only in the development of these technologies but also in being able to commercially harness them.

To survive and grow in this turbulent environment firms compete on their ability to meet customer needs faster and efficiently. NPD has therefore become a focal point of competition and a potential source of competitive advantage (Clark and Fujimoto, 1991,

as quoted in Brown and Eisenhardt, 1995; Anderson, Tushman and Reilly, 1991). Designing, developing and marketing a new product involves an integrated effort from all functions within the firm and also its customers and suppliers. Management also has to radically rethink the firm's systems, structures and values and establish NPD systems and processes that can help meet customer needs effectively and efficiently (Wheelwright and Clark, 1992).

Measures of successful NPD

Success in the market is judged by how well a new product meets cost, quality and time (CQT) goals. Quality refers to total product quality encompassing reliability, functionality and customer satisfaction. Developmental processes have a great bearing on the budget needed for developing the product which taken together with cost of manufacturing the product makes up the total cost of the product. The total cost of the product should be competitive with that offered by other firms. Consideration of time to market is crucial to the success of the product because there is always a window of opportunity within which the market needs can be fulfilled profitability. The time span from product concept to market should therefore be as short as possible to enable a firm to take advantage of the opportunity.

Conventional thinking would call for tradeoffs between the three imperatives, but that is no longer feasible in the current environment. All three imperatives need to be optimized to succeed in NPD and ultimately in the marketplace.

Factors associated with successful NPD

Figure 2.1 depicts the key factors that research has shown to be associated with highly effective NPD. The center box represents the transformation process (PD process) from customer needs to a finished product. The transformation process is facilitated by five sets of supporting systems: customers, suppliers, manufacturing, technology and organizational structure and leadership. Many critical and revolutionary issues have been included in the transformation process including flexible stage gate PD process, early and rapid prototyping, set based concurrent engineering and use of engineering checklists.

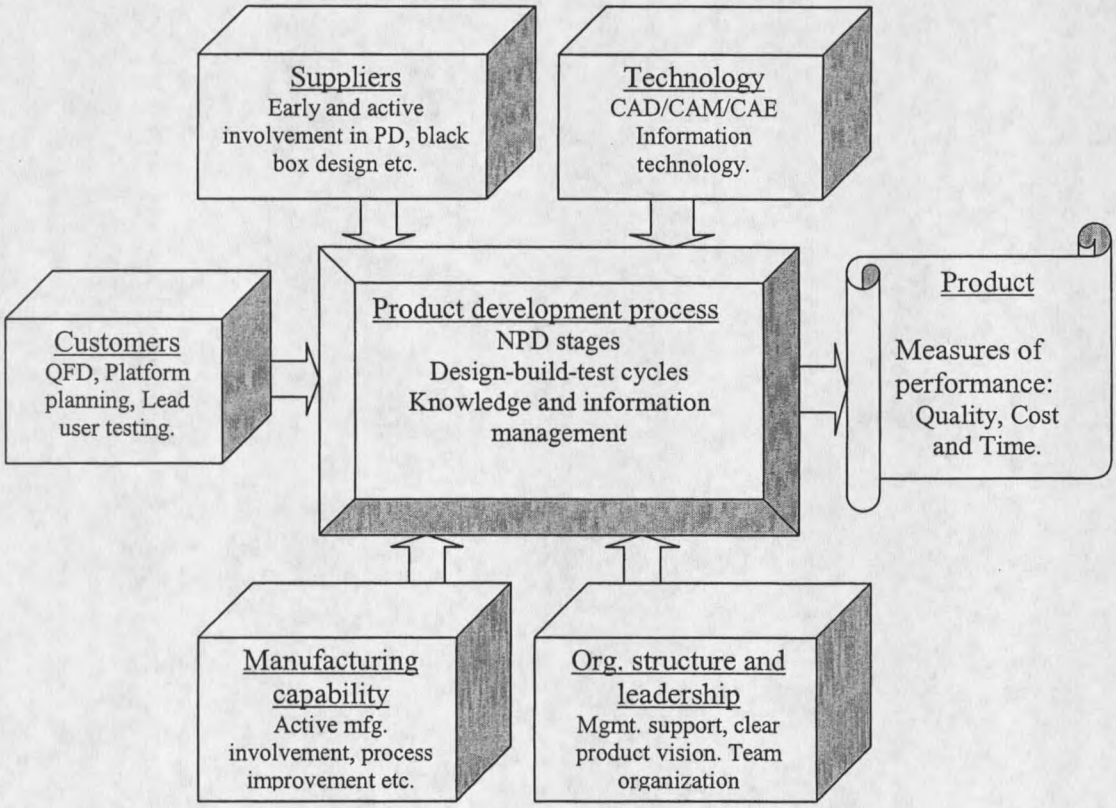


Figure 2.1: Transformation model

Organizational structure and leadership

The organizational structure for NPD commonly consists of top management providing the vision and resources and middle management directing and coordinating the activities of a cross-functional team that carries out the design and development activities.

Top management: Top management plays the primary role in the development of organizations and has a similar role to play in the NPD effort. If any firm has to position itself in a way that it is capable of designing and developing products that meet QCT goals consistently, then the change should happen first at the organizational level. This organizational redesign has to be led and managed by top management (Nadler and Tushman, 1997).

New role of top management: Literature in NPD directs top management towards two crucial tasks in organizing for NPD. They are defining a clear vision and communicating that vision through the organization.

- Clear vision and charter: Every effort needs a clear vision and the best way to capture the mission precisely is to have an explicit and measurable project charter. This charter should set broad performance based goals and a timeline for these goals (Clark and Wheelwright, 1992). Every function or development team should be able to translate the overall goals into targets, work plans and set their own evaluation criteria.
- Communication of the vision: Communication of the vision to each individual in the firm (or development team) is important and this should be done through

multiple media, and should be thought of as both a telling and selling activity. The vision should be communicated as real, visible and concrete long-term goals and not as the program of the month. This provides leverage points for changing individual behavior. The communication should not be a one-time event but should occur repeatedly to prove the commitment of top management towards the set goals.

Role of Middle management: The role of middle management also changes with the change in the organization structure. From being heads of functional groups in the past, middle level managers faces new challenges as team and project leaders.

- Link between customer and team: The team leader should be the direct link between the market/customer and the development organization. This involves knowing the market well, studying market data and being a multilingual translator (Fleischer and Liker, 1997). Multilingual translator means being able to translate the market data to information understood by all functions involved in development effort.
- Project management: The team leader should be able to translate the overall goals into team goals and accordingly initiate, direct and coordinate team activities, and maintain schedules.
- Concept champion: Success stories at many leading firms have highlighted a new role for project managers; that of a concept champion. Team leaders have been found to be most effective when they were working engineers and

guardians of the new idea or concept under development (Clark and Wheelwright, 1992). They should ensure that decisions made are consistent and harmonious with the concept goals and themselves act like mentors to the other engineers involved in the development effort. This requires team leaders to have a blend of leadership, engineering and mentoring skills, which not only ensure that the goals are met but also that the other engineers grow in experience.

The new roles of top and middle management discussed above are consistent with a new concept called 'compressive management' (Nonaka, 1988). In compressive management, top management is responsible for determining the overall direction of the firm, establishing the vision and setting time limits. They also select the middle managers to head the projects and lay the foundation for the lower organizational structure (teams). The middle management organizes the project team, breaks the overall goals into team goals and sets a timeline. The team is given autonomy in its working while being constrained by targets and a timeline (Nonaka, 1988). The team organization, working, tools used and the process of design and development is explained in detail in the following sections.

Team organization: Most engineering organizations can be classified into several types of structures:

- Functional organization: Management organizes the employees according to the functions that they serve in the organization. The functional departments for

example may be human resource development, marketing, design, R&D, manufacturing, purchasing, tool design, reliability and quality assurance, customer support etc. There is a hierarchical structure in each of the functional departments and people reside within their functions and serve the different products of the firm. Such a structure has many advantages, such as functional expertise and clear channels of authority, communication and accountability. But this structure encourages 'over the wall approach' for NPD. In the over the wall approach one function will carries out designing activities without considering implications the design will have on downstream activities. An example of this is a styling engineer designing the body without considering the manufacturing implications. Communication barriers can be high with this organizational structure due to strong distinctions between departments, and often cross-functional expertise is limited. Figure 2.2 illustrates a functional organization.

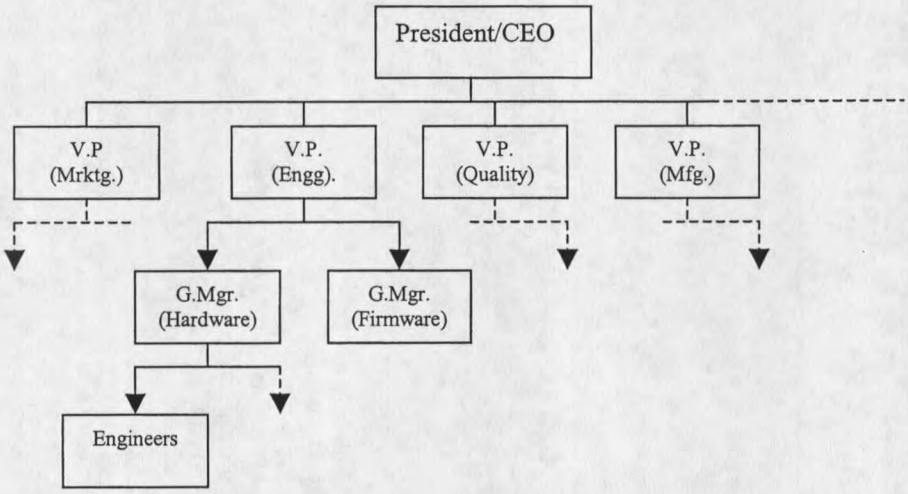


Figure 2.2 Typical functional organization.

- Product Organization: Often management chooses to organize employees based on the different products that the firm makes. A person at the level of vice-president or director heads each product family and there are dedicated functions under this person responsible only for that product. Functions like marketing, purchasing, manufacturing, design etc that are wholly responsible for that product range only. The advantages of such a setup include increased dedication and focus on the product, better problem solving and communication. But the engineers commonly get too focused on developing one product for an extended period of time. As a result there is there is little learning beyond the scope of that particular product and therefore limited expertise. Figure 2.3 illustrates a typical product organization.

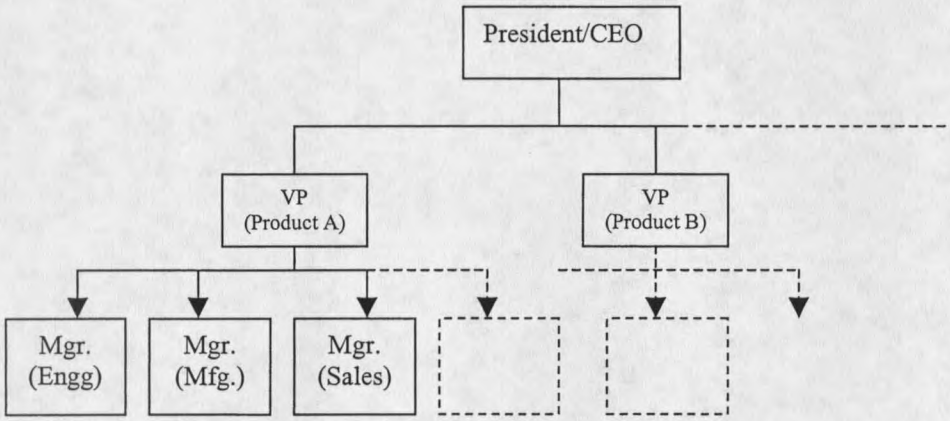


Figure 2.3 Typical product organization.

- Matrix organization: The matrix organization shown in Figure 2.4 combines the advantages of both the functional and product organizations. Dual authority exists in this structure; the engineers are responsible to the product managers for

development activities and also to the line managers for functional duties, and professional guidance (Scott, 1998). The development programs run by the product line managers are numerous and have a short life cycle, therefore the structure of this organization changes quite often. The program managers are responsible for designing the work, assigning it, setting targets and coordinating activities of engineers with help of the functional heads. The functional heads assign engineers to the different projects, provide technical guidance, evaluate performance and provide incentives based on recommendations of the project managers.

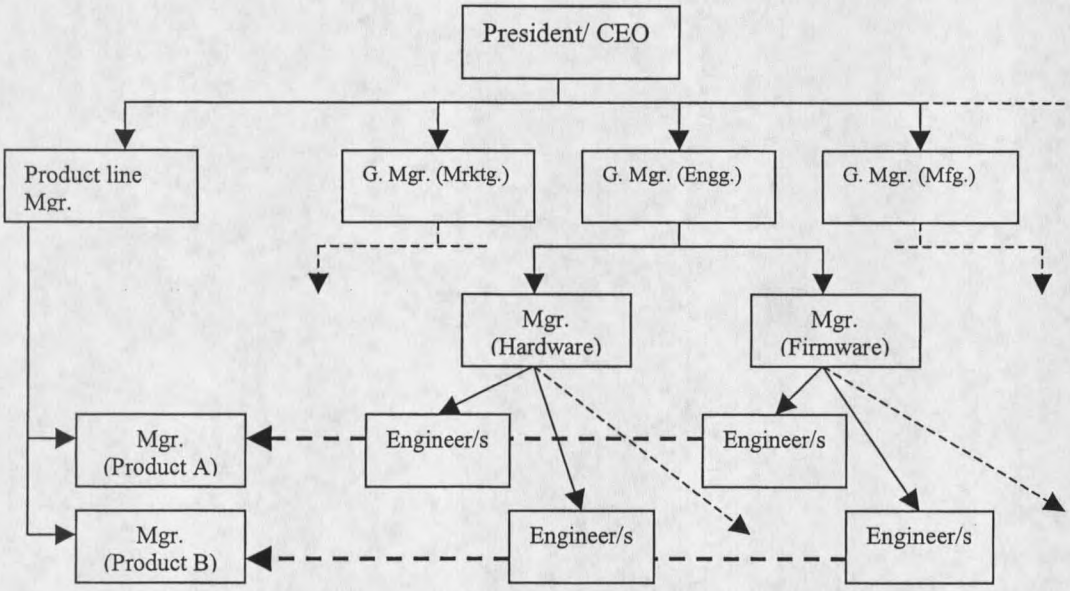


Figure 2.4 Typical matrix organization.

Cross-functional PD teams: Described above are some of the common types of organizational structures, but responsibility for completing PD projects and meeting CQT goals lies with PD teams. Such PD teams commonly consist of people drawn from different functions for the period of the project and headed by a project manager / team leader who is responsible for the final outcome of the project. The team members use their individual expertise to aid development of the product and dedicate their time to single or multiple projects. The rationale for cross-functional teams is explained below (Nonaka, 1990):

- A cross-functional group can produce more product design ideas than a single person.
- Common goals can be set, with collective responsibility for product success.
- Functional expertise brought together paves way for better coordination and appreciation for other functions.
- Problem solving, which is key to product development becomes easier because functional barriers are broken down easily resulting in better relationships and compromise rather than confrontation.
- Performance evaluation is simpler because it can be linked easily to the performance of the project.
- Activities can be run in parallel rather than sequentially and this supports the principles of concurrent engineering. (The relevance of concurrent engineering (CE) has been addresses later in this chapter).

Two of the most distinct structures commonly observed in NPD are heavyweight and lightweight team structures.

- Heavy weight team structure: A senior manager who has expertise and experience beyond that of functional managers heads a heavy weight PD team. The team consists of people drawn from functional groups, dedicated full-time to the project and co-located for the duration of the project (see Figure 2.5). Such a team identifies itself with the product and a we-spirit exists that drives them to do what it takes to ensure the success of the project. This structure represents a system solution to product development wherein the team members try to ensure that support activities are made available, schedules are adhered to and quality standards are met. The effect of such teams is not always positive on the organization. Sometimes the members tend to get over involved in their own project and do not look at the broader causing possible priorities clashes. Functional expertise usually suffers because very little time is spent within their functional departments and there is little knowledge amplification beyond the scope of the project.

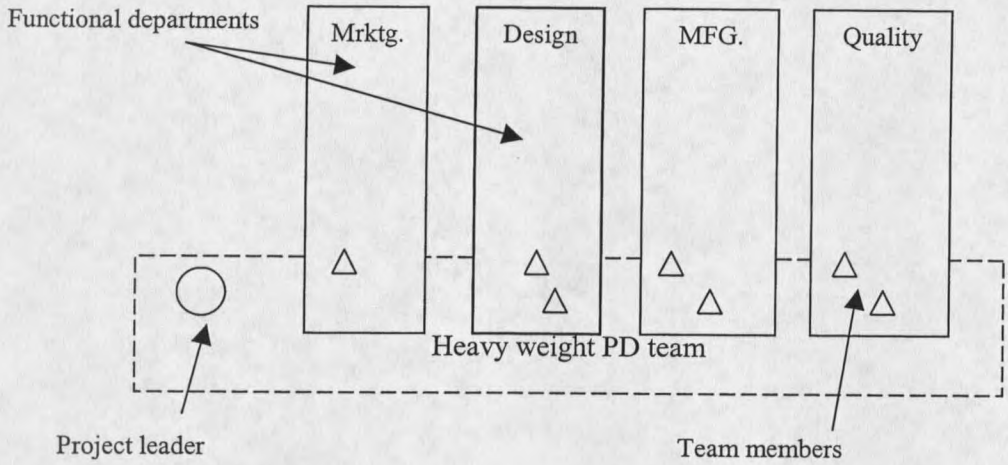


Figure 2.5 Heavyweight team structure

- Lightweight team structure: A middle-level manager is commonly assigned a task of developing a new product or improving an existing one. The manager then, with the help of a liaison and the functional heads forms a team of engineers who often work part-time on that particular project. (see Figure 2.6). Unlike the heavyweight structure the team members reside within their functions and work on the project part-time based on the project schedules. The task of the manager is to direct and coordinate the activities of the individuals and try to maintain project schedules. This structure is better than the heavyweight structure in ensuring that no one project gets priority but rather a balance exists between both the projects and the overall goals of the functional groups and the organization. Adopting this structure could possibly ensure that functional expertise is maintained while the project is completed. Such projects however commonly lack integrated efforts.

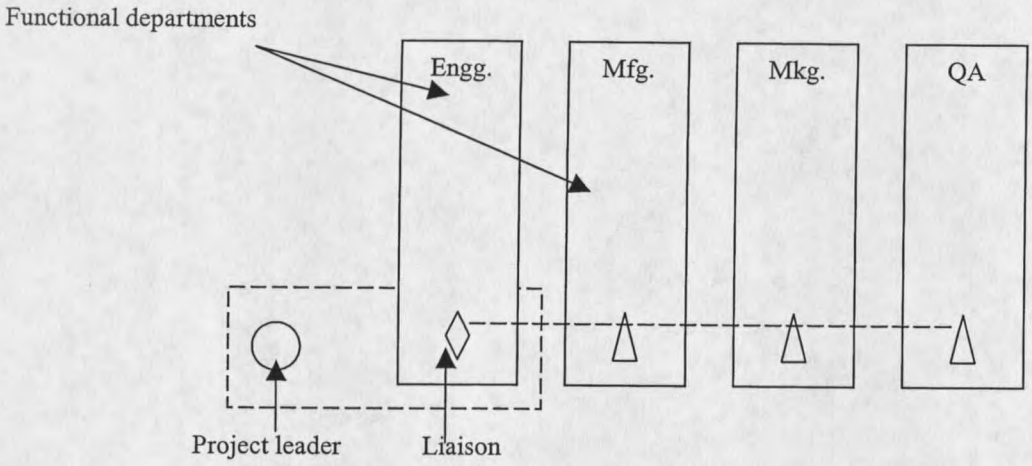


Figure 2.6 Lightweight team structure

Organization theory: Organization theory is a mature field and has developed since the industrial revolution. In the 1930's to the 1950's (Taylor, 1911; Fayol, 1919; Weber, 1947 as quoted in Sobek, 1997) organizations were viewed as rational systems, which worked effectively only when formal structures and strict hierarchies were in place. However the human relations school (Mayo, 1933; Dickinson 1936 as quoted in Sobek, 1997) argued that organizations are social systems and work best when there is less control and more participation and focus on human relations. However studies in the 1950's and 1960's found that no one management approach worked the best (Burns and Stalker, 1961; Lawrence and Lorsch, 1967 as quoted in Sobek, 1997). Rather effectiveness is based on how well the organizational structure fits the needs of the environment in which it operates. This theory is called Contingency theory and it makes two claims, 1) there is no one best way to organize and 2) different ways of organizing

are not equally effective (Galbraith, 1973 as quoted in Sobek, 1997). In other words contingency theory says that organizing is based on a number of contingency factors such as uncertainty and diversity of the environment, task characteristics and organization site.

Contingency theory is relevant to PD because it considers organizations as system consisting of many parts and these parts must fit well for the system to work effectively. In the same way product development systems may also have many interrelated parts and care must be taken to ensure that the parts fit well together. On such means of integrating is effective communication.

Communication: Communication, both within the team and with management is important to the success of the project. Perhaps the most common mode of communication in PD is a meeting. Meetings range from executive briefings to team meetings aimed at cost, schedules, technology issues resolution.

Some of the other forms of communication found to be highly effective through numerous studies are personal face-to-face communication and written communication (Court, 1997; Lynn, et al., 2000)

- Face to face communication: In the experiences of many leading firms face-to-face interaction is the richest and most effective form of communication (Court, Culley and Mcmohan, 1997). This form of communication is appropriate for PD and one of the main reasons for collocating team members is to ensure greater ease and frequency of this form of communication. Face-to-face communication

allows for good interaction between team members and does away with ambiguity.

- Written communication: Scheduling a meeting to hammer out each and every issue is neither feasible nor practical. Written communication therefore is equally essential and complimentary to face-to-face communication. Whenever an issue requires cross-functional coordination an alternative strategy to face-to face communication is to write a report presenting the diagnosis of the problem, key information and recommendations that is then distributed to all concerned (Sobek, Ward and Liker, 1998). The recipients can then offer feedback on the report via another report and any disagreements can then be then hammered out in a meeting. For written communication to work effectively the system needs to be designed such that key information is transmitted efficiently. Standardization the format of written communication can help ensure efficiency. Such methods can be taught and mastered over time.

For any PD system to be effective it must emphasize both face-to-face and written communication. IT offers new avenues for communication such as e-mail and networking and both of these have proven to be very convenient (Court, et al., 1997). Communication is also an integral part of information management and is dealt in detail in following sections.

Suppliers

Suppliers play an important role in ensuring an efficient PD process. The supplier's role can extend from supplying raw material to designing and developing sub-systems of the product. Literature suggests suppliers are extensions of the PD team since firms who have formulated such strategies have benefited immensely in terms of NPD performance (Brown and Eisenhardt, 1995). So any strategy for the team should include one for the suppliers also. Some issues related to supplier management are highlighted below:

- Long-term commitment: If the firm has to demand a bigger role from the suppliers then it has to ensure that suppliers are also satisfied. This involves ensuring long-term business based on performance. Commitment should be visible, i.e., the engineers from the firm should help the supplier in improving its systems, which may involve giving technical help or educating them about the latest tools and techniques. This helps to bring the level of the suppliers closer to the customer firm in terms of technology, knowledge and quality.
- Early involvement in NPD process: Active supplier involvement in the PD process has been stressed in all recent NPD literature. To benefit from the supplier capabilities the supplier should be involved in the NPD process right from concept development (Clark and Fujimoto, 1991 as quoted in Liker, Kamat, Wasti and Nagamachi, 1995). Involvement should include educating the supplier about the NPD process, defining his role clearly and spelling out the performance parameters. A policy of 'target costing' could then be adopted, i.e.,

working back from the cost of the vehicle and what the cost of the sub-system can be (Liker et. al., 1995). This is the target cost given to the supplier and the purchasing engineer and the supplier therefore knows the cost restrictions. Any cost savings on behalf of the supplier are then treated as a bonus and are shared by both.

- Black box sourcing: First tier suppliers should be given total responsibility for the supplying the sub-systems and meeting the C-Q-T targets for that sub-system. The parent firm should enhance design and development capability so that the supplier can design the sub-system from the overall system requirement given to him. This is known as 'black-box' sourcing wherein the system requirement, space, performance measures, and interface requirements are defined and the supplier is responsible to design, develop and test the sub-system to meet those requirements (Liker et. al, 1995). The design requirements are articulated precisely but the design is left up to the supplier. The supplier is also responsible for the second tier suppliers and all the procurement and quality issues. The PD team should also ensure that the supplier knows the NPD process and the deadlines for the project, which helps the supplier understand his role more clearly.
- Information management: Information sharing is encouraged in such close firm –supplier partnerships. Relevant information is passed onto the supplier during development, the supplier is encouraged to share the unique findings during development, and document lessons learned. Real time electronic information

sharing is stressed and found beneficial from success stories of many firms (Court, et al., 1997). The supplier should grow with the firm in terms of design and development capability and this can help to improve the relationship between the two even more.

Manufacturing capability

The ability to make things rapidly and efficiently and transform materials into components and assemblies is a major source of competitive advantage. It has been highlighted in numerous studies that manufacturing remains an integral part of the PD process (Clark and Fujimoto, 1991; Cusumano, 88). Manufacturing plays two major roles in the NPD process. First, it is responsible for the prototyping and secondly for ramping up for pilot and final production. Traditionally firms follow 'serial engineering' in which manufacturing is not considered integral part of PD, and the PD team hands over documentation and brings them up to speed once the development activities have ceded and the design is frozen. This 'over the wall' approach leads to numerous problems, two such common problems are:

- Waste of time and effort in handing over the design and bringing manufacturing up to speed.
- Design For Manufacturing (DFM) principles are not applied during design and development and consequently manufacturing problem get highlighted during pilot production.

Consequently the costs and effort involved in design changes at this late hour are considerable.

Serial engineering is a now considered the old way of developing products, while concurrent engineering (C.E.) is the dominant model. To cut development time and cost, CE prescribes manufacturing activities to run in parallel with design activities rather than sequentially. Phasing of the manufacturing activities should be such that they run in parallel with the activities of designers. This helps early problem solving and knowledge sharing and learning while the development is in progress. (CE and overlapping of activities will be dealt in-depth in the next section). Communication both downstream and upstream is important to the development process. The designer should actively communicate to manufacturing while the design activity is progressing to help manufacturing gain an early start on developing tools and processes. Communication between manufacturing and designers is important during prototype building and testing, so that manufacturing can also start developing test systems for testing pilot and production parts.

Recent literature (Thomke and Bell, 2001; Thomke, Loch and Terwiesch, 2001) also recommends using early prototypes as learning and problem-solving tools. The earlier the prototypes are built and tested, earlier the problems in the design will be highlighted and consequently lesser will be the problems downstream in the PD process.

Since manufacturing has to finally manufacture the product they should take the lead along with design engineers in developing processes that enable early prototyping. Manufacturing working in parallel with design and test engineers could also make use of

finite element analysis and simulation tools to judge design performance and highlight manufacturing issues early on. Learning from the prototypes and using then to solve manufacturing problems could help shorten the pilot product stage and lessen time to market.

Manufacturing capabilities are crucial to the entire PD process. The success of product development is affected by how fast prototypes are built and how fast the final product is manufactures and shipped out. Therefore the PD process should focus on faster prototype development, integrated problem solving with manufacturing and faster learning. This can be achieved by adopting the following strategies:

- Early and active involvement in the designing process.
- Stress continual manufacturing process improvements rather than radical changes in manufacturing technology. Continuous process improvements should be aimed at making manufacturing processes more efficient and with lesser variability. This runs in parallel with the teachings of JIT and TQM.
- Since suppliers also play a critical role in prototyping and production, developing stronger supplier relations and involving them in the process helps shorten development time. Direct and early interaction between manufacturing and suppliers to ensure common understanding of the product and also to ensure that problems pertaining to both the product and logistics are solved sooner rather than later.

Technology

Technology is the fifth and one of most important inputs to the development process. Technology is a generic term to describe the tools, software and information technology systems used by the PD team to carry out their engineering activities. Information and knowledge management are important considerations because they have been highlighted in many studies as key factors contributing to competitive advantage in NPD.

Data, information and knowledge and their management: These terms tend to be used rather synonymously, but they are different. Data are raw numbers or facts that have not been organized or interpreted (Court, 1997). Information is data with meaning attached to it so that it can be interpreted. Knowledge is the state of knowing. Knowledge is connected to the mental activity of recoding and understanding data and information and applying it to useful tasks (Court, 1997).

Knowledge as an organizational capability has been recognized only recently (Quinn, Anderson, and Finkelstien, 1997; Nonaka, 1990). This organizational capability is firm specific and grows within the firm through the process of learning that takes place through everyday engineering activities. Knowledge has the potential to become a major source of competitive advantage if harnessed properly. This implies that knowledge needs to be developed and applied effectively in NPD to effectively meet the QCT goals.

To be able to apply knowledge the first thing to do is to understand conceptually how knowledge is an organizational capability. Figure 2.7 displays knowledge as an

organizational capability consisting of multiple layers (Kusunoki, Nonaka and Nagata, 1998). These three layers are:

- Knowledge base: This layer consists of functional knowledge, which lies in individuals, groups, technologies, databases etc. This is the local knowledge residing within all the elements of the firm.
- Knowledge frame: This layer captures the structures and frameworks that bind the individual knowledge bases together. It consists of stable organizational structures and patterns in within which knowledge is transmitted and received. e.g., the project team. It is related to the formal and informal links existing within the organization e.g. technician reporting to an engineer.
- Knowledge dynamics: This layer captures the dynamics of the interaction that takes place both between individual knowledge bases and frames. It involves the coordination and communication and so is related to the process of design and development.

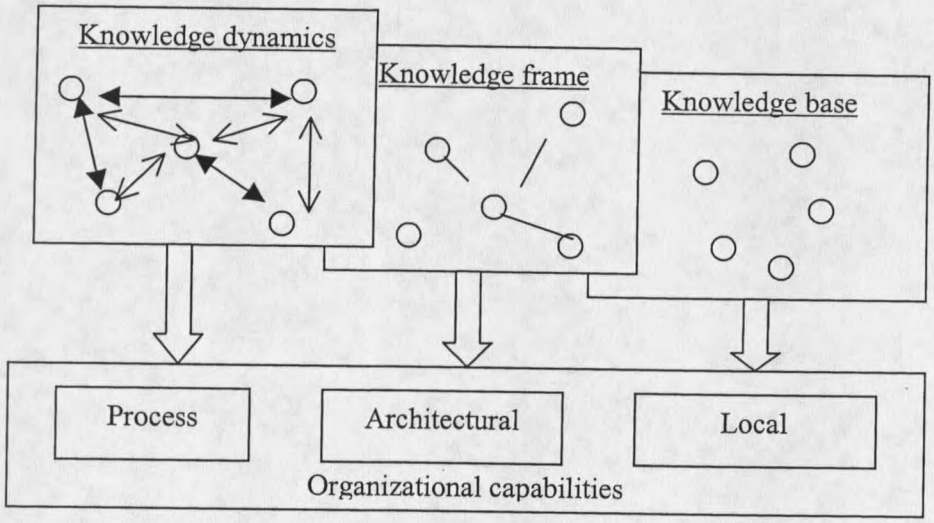


Figure 2.7 Organization capabilities as multi-layered knowledge base

There are numerous managerial implications that emerge from this model. Research in this field has demonstrated that all three layers affect the performance of the product. The affect of each layer varies from firm to firm but all three can be enhanced for better PD performance. The knowledge base is designable, i.e., it can enhance by direct managerial actions, such as hiring better professionals and adopting new technology. Learning within the firm can be enhanced to a lesser degree but management can provide the right atmosphere wherein learning is encouraged. The knowledge frame can also be designed to a certain degree by putting the right people together and formulating a stable organizational structure and development process. The knowledge dynamics are designable to a very small degree though it is affected by the knowledge frame and knowledge base. Knowledge dynamics spontaneously emerge from the structure as a result of many factors such as good communication and interaction between

members, understanding of others function etc. These knowledge dynamics have the greatest effect on the performance of PD. Removing barriers to communication and having a system for communication and coordination can potentially enhance these capabilities.

Information management and information technology: Two aspects of information are important to PD, the access of information and transmission of information. The ease and effectiveness of this information flow determines the performance of the development activities in the design team. Flow of information takes place within the team and to the external environment. Information is also generated thru the interaction with the different design and development tools that are commonly used in the PD environment. The most commonly used tools are:

- CAD/CAM/CAE: computer aided design/ manufacturing/ engineering.
- CIM: computer aided manufacturing.
- MRP: Material requirements planning.
- EDM/PDM: electronic data management / Product data management.
- FEA: finite element analysis.

These systems are designed with the purpose of helping the PD engineers to do their jobs more efficiently and improve the use, flow and quality of information. These systems are all linked via the network to PC's on workstations; this helps access, storage and retrieval of information. These tools linked to the system are supposed to reduce lead times, help get designs right the first time, reduce overall cost of design and development,

better use of information and aid communication. Information technology (IT) is one means of effectively combining these systems so that they effectively help engineers do their jobs better and faster. IT helps integrate some of these tools to facilitate day-to-day activities and ensure availability of relevant information.

Though these systems do achieve what they are designed to do as recent studies prove that they are not completely effective in aiding information management (McDermott, 1999). Many issues need to be addressed before information technology (IT) systems can be designed to manage information. These issues are briefly explained below:

- Capture soft information: A good information management tool should be capable of capturing soft information which consists of data and knowledge that lies in the minds of engineers and on notes, comments etc that are never formally put on paper. This information is related to problem solving and decision-making that is built through experience and interpersonal interaction during design and development. This type of information should be channeled into the PD system; otherwise it resides with the person and will never enrich the organization (Court, 1997).
- Aid interpersonal communication: Interpersonal communication has been identified as one driver of knowledge dynamics (Kusunoki, et al., 1998) and should therefore be encouraged by the information management system. Both face–to-face and written communication is important to PD and any information

management tool or system should aid the interplay between these two types of communication and lessen ambiguity (Court, 1997).

- Accuracy and completeness of information: Information is most important for decision-making that occurs repeatedly during NPD. Studies have shown that structured decisions are taken based on experience, knowledge and information (Court, Culley and Mcmohan, 1997). Most importantly good decisions are taken when the information provided is accurate and complete in all aspects. When the search for information decreases then decisions are made faster and better. The IT system should therefore be capable of providing accurate and complete information.
- Timeliness of information: Engineers are always under pressure to complete tasks on schedule; therefore engineering hours should be utilized wisely. Studies have shown that engineers spend majority of their time either waiting for or searching for information (Court, et al., 1997). If information can be made easily accessible and available in a timely fashion then most engineering activities will become efficient (Court, et al., 1997). Databases are good means of providing information, but for them to be effective, the latest updated information must be made available easily.
- Presentation media and format of information: Information gets processed during each engineering activity and so engineers must be provided with a wide range of presentation media. Engineers should also be trained about the appropriateness of each media and how best to use it. Studies have shown that

use of multiple media helps communication but only if people use them effectively (Court, et. al., 1997).

Model of an information management system: Very few firms have tried to model an information system that takes into account all of the issues described above. A model of such a next generation information system for knowledge management in NPD is shown below (Numata, 1998). It is an ideal model and illustrates many key characteristics that an information technology system should have to be able to effectively manage information and knowledge. As shown in the Figure 2.8, there are three functional levels: symbiotic network, knowledge bases and communication base.

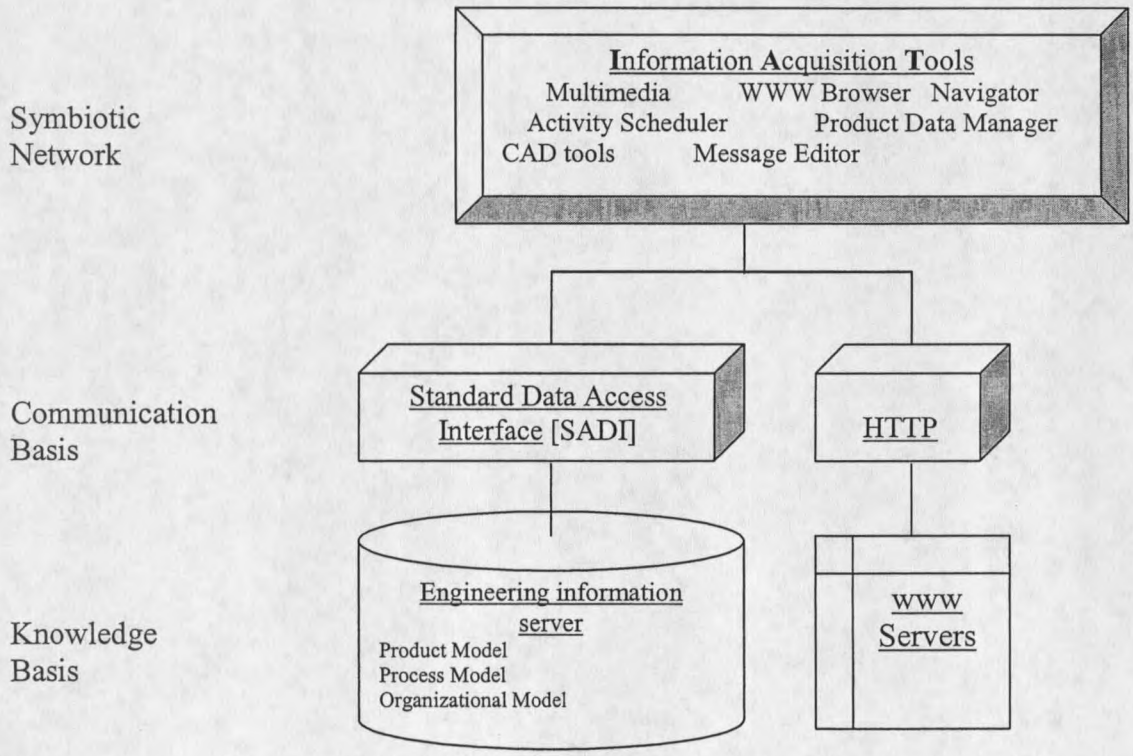


Figure 2.8 Model of an information management system

The symbiotic network is a tailored cooperative working environment, which supports the members in sharing information, exchanging ideas, and presenting and solving problems. How this interpretation is to be done is important and the interpreter can show his/ her interest directly to the expresser. The information created during real time could then be refined by the initiator and stored in the Knowledge base. Since knowledge is difficult to formalize and interpret by a third person, the people with knowledge are the direct integrators in the system. Middle management helps tailor this working environment to suit the needs of the people involved to meet the goals set by top management.

Expressible knowledge is stored in the knowledge base. This knowledge base is composed of engineering information server, a database server and a WWW server. These are linked to the symbiotic server. The database server helps manage the product data, process data and organizational data. The WWW server enables the users to access the web for external data.

The communication basis is the internet based communication channel, which provides communication services for all the information flow. The Internet has a big role to play in this model and remains the base for the entire network. Its role is both internal as well as external in this model and is one of the enabling technologies for this model.

Once such a system is put into place it will potentially make information and knowledge management more effective and the top management will be able to communicate to engineers using the middle managers as agents. Thus the system could

enable various forms of communication and also use of multi-agents such as middle levels managers and engineers. The fundamentals of this system are to serve the communication and information needs of the organization both effectively and efficiently.

This model of an information management system addresses some of the issues that are typically lacking in current information management systems. It is designed to aid the effective execution of the PD process.

PD Processes

New product development is commonly carried out using a stage-gate process, in which the concept is transformed into a design and then into a prototype and finally to a finished product. The NPD process adopted is different across industries, but Figure 2.9 captures the general form of this process, a generic model that describes the PD process adopted by many firms. (Ulrich and Eppinger, 2000).

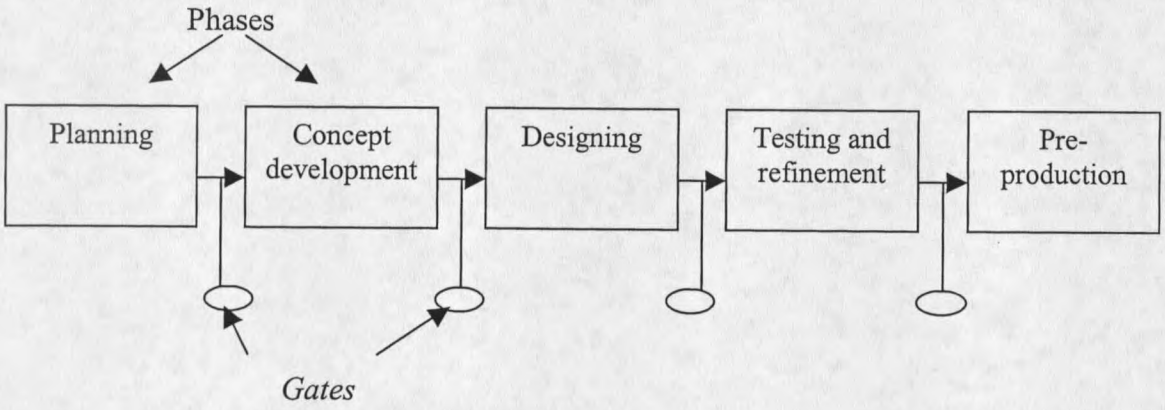


Figure 2.9 Phase–gate PD process

A typical PD process has a number of phases consisting of specific development activities.

- Planning: In this phase management identifies a certain need from marketing or other sources and proposes development of a new product. Management then assigns a project manager/leader to the product who is then responsible for the project from concept development to product launch. They commonly decide the budget and launch dates.
- Concept development: The project manager puts cross-functional team together and outlines the project plans and schedules. The PD team then develops a concept of the new product and test it for economic and technical feasibility. Some preliminary designing and definition of product architecture may also take place. Once the concept is proved, detail work plans made.
- Designing: The designers in the team start designing the product and make blueprints and bills of materials. The prototyping and testing activities are also initiated and the design is reviewed and finalized. The design files are then sent out to a vendor or to in-house manufacturing for prototyping.
- Testing and refinement: The prototype is then tested for functionality and performance and the design is refined based on the results. Many such design-build and test cycles take place until the design is proven for all the performance parameters. Then the design is frozen and all the designs, activities and results are documented.

- Pre-production: The development organization then hands over the documentation over to manufacturing who then start developing their tools and processes for pilot production. The development team helps manufacturing in problem solving, while the pilot product is planned. The product is tested and refined if necessary for aiding manufacturing. The development activities are then signed off and the product is ready for launch.

Gates are management reviews after every phase where the findings and results of that phase are presented to management. Management reevaluates the feasibility of the project and decides whether to proceed into the next phase or not.

New strategies for PD process

There are however several inherent problems in the phase-gate PD process. The phase –gate process consists of gates that serially follow the previous and the process is somewhat similar to serial engineering. It also propagates structured development activities with little flexibility. The current markets however are volatile and dynamic as explained in chapter1. This requires a PD process that is flexible, fast and more effective than the phase-gate PD process. Researchers have therefore investigated newer strategies, such as:

- Overlapping stages and flexible NPD process
- Frequent and early experimentation
- Quick turnaround on prototypes
- Testing strategy consisting of mix of sequential and parallel testing.
- Use of set-based C.E.

- Design standards and engineering checklists.
- Flexible work standards

The new strategies have varying effects on PD performance and have been discussed in-depth in PD literature. The following discussion focuses on the aspects of these strategies with strong relevance to the research questions.

Overlapping of stages and flexible PD process: The traditional model of development, which consists of structured development stages and sequential phases, is obsolete in a turbulent market environment. The traditional phase-gate process was sequential, in which the concept would be decided, drawings made and the concept frozen, before it went into prototyping and testing (See part (a) of Figure 2.10). But this sequential process is inadequate in a turbulent environment where markets change rapidly and new technology cycles are emerging rapidly. If the process is frigid and structured then it will not be able to respond to the new information and will lead to obsolete product (Iansiti and McCormack, 1997).

The PD teams can no longer focus just on trying to finish every stage as fast as possible to ensure speed of implementation (Iansiti, 1995). Time To Market (TTM) still remains the top priority of the development process and efforts need to be made to reduce total lead-time, but speed becomes a subtler concept. This is because total lead-time consists of two elements: concept lead-time and development lead-time. The concept lead-time is the window of opportunity within which new ideas, concepts can be incorporated, and so this window of opportunity must be left open as far as possible to absorb emerging information (Iansiti, 1995). The development lead-time is the time in

which the concept is prototyped, tested and ready for production, shorter this lead-time the greater the ability of the firm to respond to change. Figure 2.10, part (b) illustrates the flexible PD process. Efforts should therefore be directed towards reducing the development lead-time to ensure speeding up TTM.

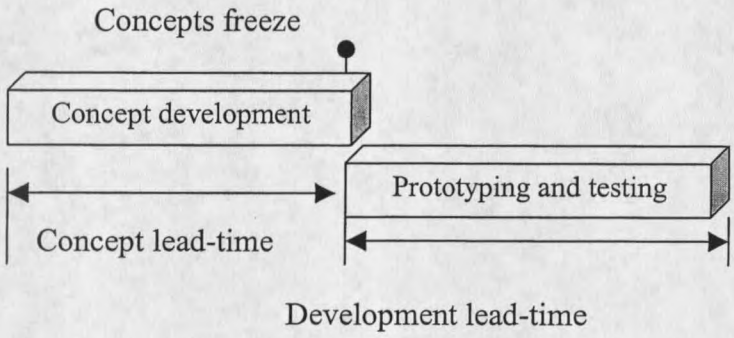


Figure 2.10 (a) Traditional PD model

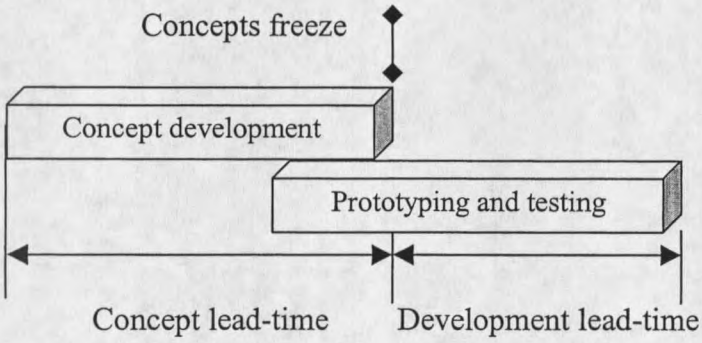


Figure 2.10 (b) Flexible PD model

Concurrent Engineering (C.E.) and flexible PD process: Concurrent engineering calls for joint participation of all the functions simultaneously in the development process. In CE, functions such as design, test engineering, manufacturing, purchasing, and reliability begin the process together and coordinate their activities such that the

overall TTM is reduced. The flexible process accepts the cross-functional team approach but goes beyond this and suggests the simultaneous implementation of conceptualization and development. Concurrent engineering also prescribes a phase gate PD process in which the phases are separated distinctly (Iansiti, 1995), the flexible process goes one step ahead and calls for overlapping of the phases. A flexible PD process requires better managerial skills, frequent design iterations, information absorption and a system-focused approach to the development process.

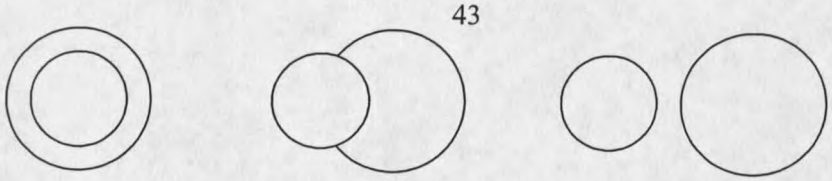
But overlapping of phases is not suited to all PD project and management needs to decide first whether to overlap PD stages at all. If they do decide to adopt a flexible PD process then they need to determine the amount of overlap before the project can progress. Overlapping is justified if the surrounding system consisting of the development team, design-build-test (D-B-T) strategies and information management system support it. Another factor to be resolved is design uncertainty and if the PD process does not have a strategy for uncertainty resolution then the cost and effort of rework may outweigh the benefits of overlap. Also overlapping works best if the system supports early experimentation and information assimilation that allows for designs to be changed earlier in the process and less frequently later on. If uncertainty can be reduced faster then more overlap can occur and the product can be developed even faster.

Frequent and early experimentation: Recent studies have also highlighted that frequent and early experimentation and subsequent learning could contribute significantly to effectively meeting the QCT targets set for NPD. Experimentation involves building

the prototypes, developing the test system, testing the prototype and analyzing the results of the test data. If all these activities can be reorganized and redesigned so that they are accomplished faster the process of experimentation could occur faster, thereby reducing development time.

Prototyping: Using a combination of new technology and proven technology, new prototypes can be made faster (Thomke, 2001). New technology includes the use of rapid prototyping and unconventional manufacturing techniques. Sub-system prototypes should be made early on in the process so that they can be used as learning tools. Prototypes must not be made for killer[3] tests but for a gradual process of learning and redesigning. Frequent in-house prototyping also enables manufacturing problems to be highlighted early on in the process rather than have to bear the cost of expensive design changes later on (Loch, Terwiesch and Thomke, 2001). One study showed that early prototyping and testing increased PD performance up to 40 %.

Testing: Testing involves two major activities, testing the prototypes or controlled experimentation and analysis of the test data. Thomke and Bell (2000) have defined three types of tests, completely overlapping, partially overlapping and independent tests, as seen in Figure 2.11.



Fully overlapping Partially overlapping Independent

Figure 2.11 Types of tests

In the fully overlapping tests all previous parameters are tested along with the new design parameters that can be tested as the design progresses and becomes more complete. In the partially overlapping tests, only critical, dependent and problematic parameters are tested with the new parameters. In the independent tests the previously tested parameters are not tested at all rather they are assumed frozen and only the new parameters are tested. The kind of strategy to be adopted depends on the complexity and nature of design and cost of testing. This test strategy should also define whether tests would be carried out either sequentially or in parallel.

Sequential testing enables information to be generated that can be used for design reviews or for supporting decisions before the second test is planned. Sequential testing takes time and not all resources are completely utilized (Loch et al. 2001). When some critical resource is used for the testing and its utilization increases then the waiting time for that resource increases exponentially. This means that dependence on one resource will mean that engineering will have to wait a longer time for feedback (Thomke, 2001). So the tests also need to be scheduled such that the low fidelity tests are conducted before hand and data utilized before conducting a minimal of high fidelity tests.

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[3] Tests in which prototype is tested for all functions and design specifications.

Parallel testing on the other hand speeds up the development process and also allows for multiple solutions to be tried out for solving the same design problem. Parallel testing more closely supports the flexible PD process by allowing more opportunity to test different solutions and learn more before a certain design is selected and frozen (Loch et al., 2001). Uncertainty resolution early on is important to maintain a flexible PD process and parallel testing helps reduce uncertainty to a great degree.

Parallel testing increases complexity in the design process because it requires design activities to be carried out in parallel and is best applied when the design is modular. Costs associated with parallel testing are also considerably more as compared to sequential testing and parallel testing also puts a greater strain on human and testing resources for its successful implementation.

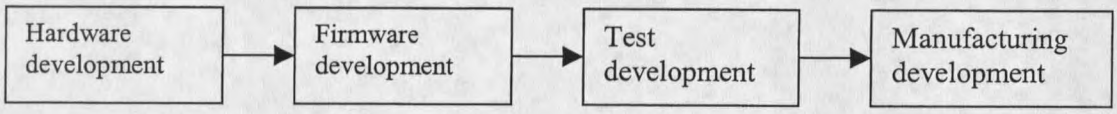
So the best strategy for management is to balance the costs of the test with the value of the new and early information. Cost of building a prototype depends on the technology and resources available, degree of accuracy of the prototype needed and the fidelity of the test. Learning incorporated after every test depends on the skill and knowledge of the designer, quality and timing of feedback, and solution landscape (Bell and Thomke, 2001). Considering these and other factors certain guidelines have emerged regarding the choice of strategy:

- When design is modular then conduct parallel testing, if not modular then test sequentially.
- If development lead-time needs to be reduced, test in parallel.
- When tests are expensive, test sequentially.

- When the design space is fairly well understood, test in parallel, but if the design space has not been explored before, test sequentially.

Point-based C.E. and SBCE: Even though most companies now adopt C.E. and form cross-functional teams and follow a phase–gate PD process the process they actually follow is only a refinement of the point based approach shown in Figure 2.12.

Point-based Serial engineering



Point-based C.E.

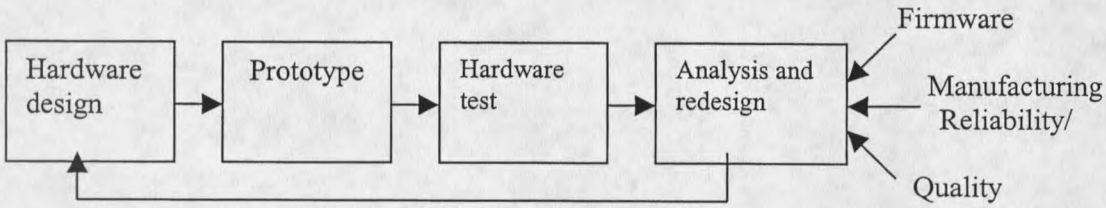


Figure 2.12 Point-based serial and concurrent engineering

In a purely point based serial design (also called sequential engineering) approach one function would design the product and then communicate it to the other function and then onto manufacturing and so forth in an 'over the wall' approach. There are numerous disadvantages to sequential process (Fleischer and Liker, 1999), some of which are shown below:

- Sequential design takes too long: Carrying out engineering activities that are not dependent on each other in parallel is obviously faster than doing them serially. Engineers don't have to wait for a task to be completed before starting his/her own. Shorter feedback loops allow tasks to be adjusted rather than having to wait till the task is completed before adjusting your own.
- Product design cannot be finalized until its manufacturing is defined: If manufacturing engineers are not part of the PD team then manufacturing issues will not get highlighted before detail design or design completion. Consequently changes in the design late in the development process will incur considerable cost and effort.
- Sequential process commonly results in poor design: In a sequential process the design will undergo numerous changes when problems are identified when the design moves from one function to the other. When the formal deadline for release is reached the design will still be flawed and customers will therefore be left unsatisfied.

These are other disadvantages of serial engineering are well understood by all the firms and so they choose to adopt C.E. But the C.E. adopted by these firms was just a refinement of the point-based approach (illustrated in Figure 2.12).

Point-based concurrent engineering: Sobek, et al., have pointed out that at most American firms one function designs the product (e.g. styling engineering) (1999: 69). They decide and freeze the concept early on from their perspective, which meant that the

entire design space was never mapped. They then test the design and seek input from other functions on the team during data analysis. Even though a team jointly designs the product, in reality only one function creates the conceptual design. This process therefore does not differ very much from the point-based approach for two reasons. First, the team is focusing on one solution and iterating on one design only. Secondly, each function is offering inputs, which may or may not be compatible to each other or even detrimental to system performance and so there is no theoretical guarantee that the process will ever converge on an optimal design. Rather the PD team has set timelines for the development activities even before the first D-B-T cycle takes place and therefore chooses a quick solution that satisfies everybody, which may not be the optimal solution. In contrast Toyota's SBCE system in follows C.E. in the truest sense. At Toyota different functions create and test different concepts concurrently, continuously interact with each other so that they gradually converge onto one optimal design.

But the process of point-based C.E. is not completely detrimental to firms developing new products. A recent study in this area (a study conducted by Terwiesch et al. as quoted in Sobek, Ward and Liker, 1999) has shown that iterative strategies are well suited when the design iterations are fast, the cost of rework is low and the quality of the initial starting point (i.e., how close they are to the solution at the first try) is high.

Toyota's Set-Based Concurrent Engineering process: In Toyota's SBCE process the design participants reason about, develop and communicate sets of solutions in parallel and relatively independently (Sobek, Ward and Liker, 1999). As the PD process

progresses the different functions then narrow their respective solutions based on the information communicated with each other and other participants like customers and suppliers. As the solutions slowly converge the different functions then commit to one optimal design.

Figure 2.13 illustrates the 3 main process steps or principles of SBCE, which are mapping the design, integrating by intersection and establishing feasibility before commitment. These principles are explained in the following discussion.

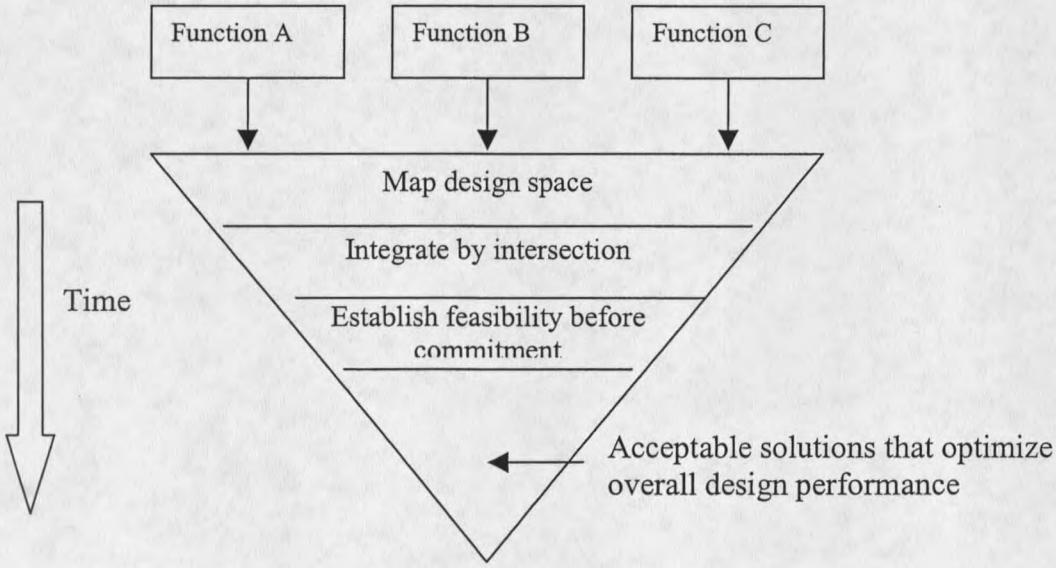


Figure 2.13 Process of Set-Based Concurrent Engineering

Principle 1: Map the design space: The functions involved in the PD effort simultaneously define broad sets of feasible solutions from their areas of expertise. They

determine the primary constraints on their system, what can or cannot be achieved or what should or shouldn't be achieved based on experience, experimentation; testing and analysis or through external sources like lead users (customers) or suppliers. To help decide among these alternatives they explore tradeoffs by designing, prototyping, or simulating alternative systems. Then these sets of ideas are communicated to the other functions. This process emphasizes on learning rather than on arriving on a design solution

Principle 2: Integrate by intersection: As these functions begin to understand and appreciate the consideration from their own and others perspective they attempt to integrate systems by identifying solutions workable for all. Teams try to look for intersections where the feasible region of their solution sets overlap. But then, rather than taking key decisions that most American companies do to simplify the interactions, Toyota imposes just the minimum constraints needed at that time. This sustains flexibility in the process for further exploration of ideas, improvements and adjustments as and when they are needed. This reflects the different approaches taken by American firms and Toyota. Most American firms believe in making decision early on so that confusion is avoided, on the contrary Toyota believes in making decisions in its time, thus leaving the design open to changes and tradeoffs from the new information generated via continuous experimentation and interaction between team members or from external sources. (e.g., the market or technology might change over the period of development and so if some level of change can be incorporated in the design then market risk is reduced). Pioneer researchers in the field of SBCE have also argued that PD teams have less chance of

getting locked into a sub optimal solution if they impose just enough constraint to function properly while allowing enough room to adjust and optimize (Sobek, et al., 1999)

Principle 3: Establish feasibility before commitment: Sobek, et al., also view Toyota's entire SBCE as a system to fulfill this third principle, i.e., to ensure that designs are feasible before committing to them (1999: 74). Some of the ways in which Toyota ensures feasibility are by gradually narrowing the sets of solutions while increasing detail. The process not only involves generation and communication of ideas but also a decision process that gradually eliminates possibilities until the final solution remains. As these sets of solutions become narrower the ideas within the sets grow sharper and detailed designing and prototyping is undertaken. This process of narrowing solution sets through experimentation runs in parallel and communication goes back and forth until each function converges on a solution that integrates with the overall system.

But this process cannot go on forever because every project has a time constraint. So the PD team stays within this narrowing funnel and attempts to make the design more robust. To any outsider the PD system at Toyota will be viewed as a system that has uncertainty and ambiguity. But Toyota adopts a unique technique to control the process by managing this uncertainty at the process gates. Rather than viewing the PD process as a network of tasks and timing the information flow between tasks, Toyota views it as a continuous process where structured information is transferred as and when needed. The PD gates are not merely used for review of the project progress but rather for integrating

the ideas from the different groups, reducing uncertainty and converging on a detail design.

Even though SBCE is not a recipe to overcome the shortcomings of current C.E. practices it does contribute to effective PD practice. The discussion of point based C.E. and the improvement offered by SBCE is discussed further in chapter 5.

Engineering checklists and design standards: Information is the output of all these tests and information needs to be leveraged in order to support decision-making and problem solving. Data generated from these tests needs to be analyzed and not only stored but also converted into useful information to be used later or for other subsequent projects. One major gain is that if this information is modeled properly can become a living design standard. These design standards can then be used as checklists for all products and also a good focal point for design reviews.

Detailed checklists guide design engineers throughout the designing process and most importantly are useful for design reviews. If these standards are updated and well put together then if the new part meets these standards then its functionality, manufacturability, quality and reliability are assured to a certain degree. These checklists also facilitate organizational learning across different NPD teams within the firm. When new knowledge is encountered it is absorbed into the checklist and applied across the firm and becomes the new design standard (Liker, Sobek and Ward, 1998). To make this system work effectively, the responsibility of maintaining the checklists is the responsibility of the NPD team and the information is only ironed out by the central

organization. This takes care of the bureaucratic procedures that always hamper information flow.

Flexible work standards: Another important factor that contributes to the flexible PD process is flexible work standards (Sobek, et al., 1998). Traditionally work standards were specified and detail work processes defined in the project plan. Every activity was decided before hand and coordination was defined. But this process designed was designed by the central organization and was to be followed by all development teams. This means that the processes were never representative of the actual work that happened in every project that was unique to it. Rigid processes and systems also curtail innovation and creativity within the team and the ownership lies with the central organization and not the team, which is more important.

A more suitable approach to aiding the flexible development process is to define the system requirements and design guidelines and leave it to the development team to adopt their own procedures that best suit the project. The development team is provided with a broad understanding of the requirements and deadlines through simple plans that encourage flexibility in the actual development process. The engineers and project manager then devise their own plans and strive for continuous improvement. Team members should define and redefine their own processes until they arrive on an optimal strategy for the project at hand. These strategies should then become standard operating procedures for the team throughout the development process until something better is proven and adopted. These strategies are not adopted based on people's whims but rather

need to be proven by scientific methods to be significant in shortening the development time and effort.

Also since the team makes their own standards they are more likely to follow them and improve them for the teams benefit. Thus developing the product and also the development processes remain the forte of the development team.

Current PD literature and research questions

The product development literature presented above covers a broad range of issues such as PD processes, management and technology issues. But most of this literature has been born from studying automotive, aerospace and software industries. Few researchers have documented PD practice at electronic industries, even though electronic industries are one of the major drivers of the US economy (Industry Week, 1998). Studying electronic industries is strategically important because this sector consumes 18 % of total US R&D expenditure (Science and engineering indicators, 1998) (see Figure 2.14). They are also the fastest growing industries (barring the recent downturn in hi-tech) and most components in consumer electronics, airplanes and even automobiles are electro-mechanical parts.

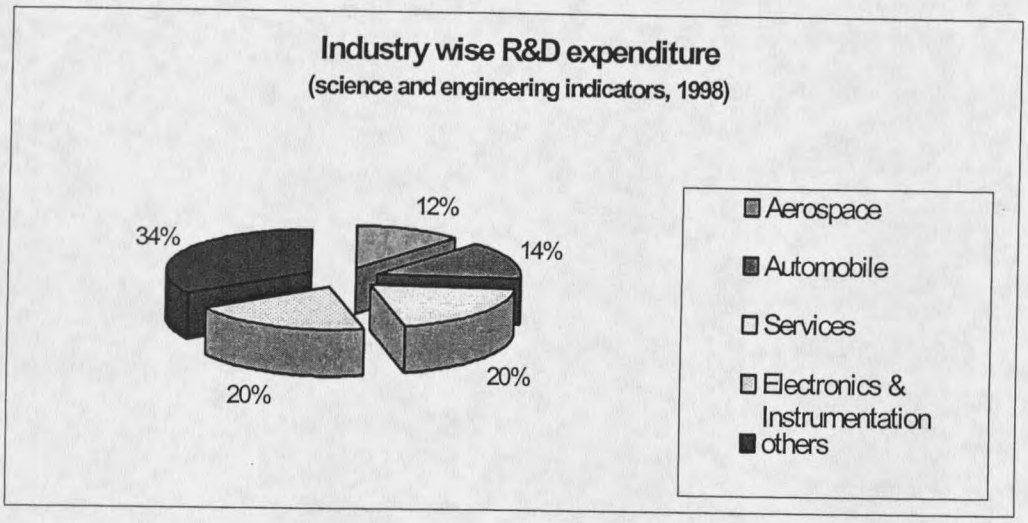


Figure 2.14 Industry wise R&D expenditure

The electronics industry is also volatile with rapidly changing technology and intense international competition (see Figure 2.15) all competing on their ability to introduce new products into the market. Enhancing NPD capabilities by adopting world-class NPD practices holds huge potential for these firms and it is in this area that we hope to contribute through this research.

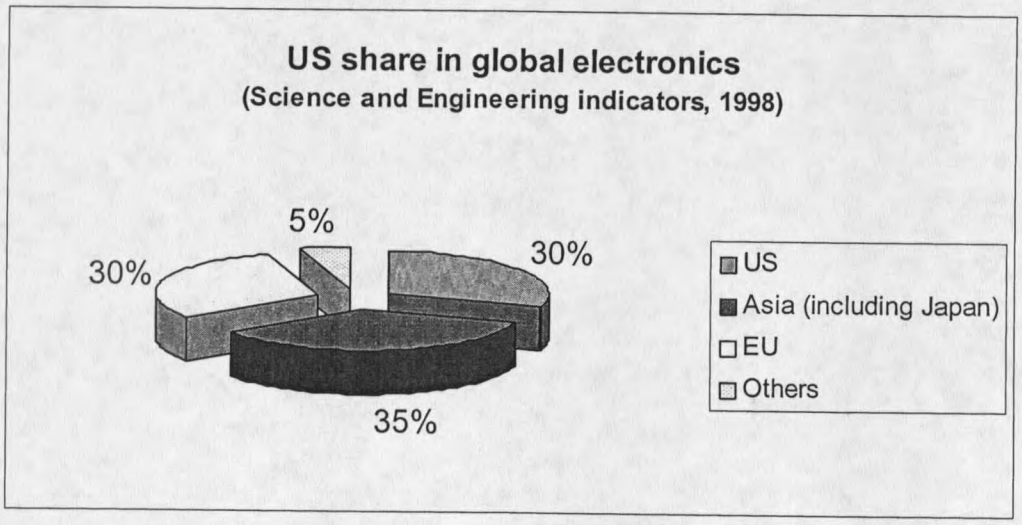


Figure 2.15 U.S. market share in global electronics

A second reason is that; while many studies have highlighted PD issues and prescribed good practices (IT, supply chain management, CAE, FEA etc), few studies have looked at PD from a detailed process standpoint. We hope to study PD as a system and through this research hopefully contribute towards improving the system performance as a whole rather than prescribing a way to improve any one aspect of PD.

During the course of this research we studied PD systems at 4 diverse electronic firms and found that their overall PD practices were similar to the ones followed by aerospace or automobile industries. But closer inspection of the PD systems revealed that the issues within PD were unique to this industry type and so world-class PD practices prescribed primarily for automobile/aerospace industries may or may not work here. PD issues relevant to this industry need further investigation to make any such determination.

Recent PD literature has acknowledged that D-B-T cycles are important but no one has investigated the role of test equipment in these D-B-T cycles. On careful investigation of the role of test equipment, we found that just making these tools faster cannot enhance their role. In this research we will also show that these tools (EMS) play a key role in the information transformation process and to improve PD performance the information transformation needs to be made faster and more effective.

Numerous researchers have talked about data and information and how best to manage it, but few have investigated the process by which, data gets transformed into useful information. This study will reveal the interaction between engineer, EMS and information and the role each element has to play in the information transformation process. This could potentially help companies redefine the role of the tools (such as

EMS) and make them better so that they support a world class PD process. But this study does not attempt to investigate everything about the information transformation process but rather open avenues for further research.

Organization theory prescribes many ways and means of integrating different functions to effectively carry out NPD. During the course of this research however, we unearthed a complex integration problem inherent to PD in electronic industries. This integration problem was a result of the fundamentally different hardware and firmware development cycles that these firms adopted. In the course of this thesis we call this integration problem as the hardware-firmware-test triad (H-F-T triad). The fact that the firms choose to adopt point based C.E. precipitates this H-F-T triad. We have investigated the possibility of adopting set-based C.E instead of point-based C.E and opened new avenues for further research.

By studying PD systems at diverse electronics industries we hope not only to answer the research questions but also contribute to better overall understanding of PD practice.

Summary

In this chapter a strong case has been established for understanding NPD systems and processes and need to highlight major aspects related to it. Different types of organizational and team structures were explored and their relative advantages and disadvantages were also discussed. In this chapter it was established that effective communication, both face-to-face and written was necessary to ensure effective working

of PD teams. A new more active role for suppliers and manufacturing engineers in the PD process was also stressed along with more direct interaction between the two. This chapter also highlighted the importance of information and knowledge and need to manage them better. To accomplishing this a new model of information management system was also presented.

In a later section it was explained how most firms commonly adopt sequential engineering and use a phase-gate PD process as opposed to SBCE and a flexible PD process. The last section of this chapter showed how this research potentially contributes to current stream of world-class PD practice.

CHAPTER 3

RESEARCH METHODOLGY

The major goal of this project was to investigate the role of EMS in NPD and attempt to understand the role it has to play in D-B-T cycles and managing engineering information. This research was carried out using qualitative research methods instead of the more conventional quantitative methods. The purpose of this chapter is to justify the choice qualitative methods and to explain the principles and methodology adopted to carry out this project.

The chapter is divided into three sections. The first section explains the qualitative research approach and its suitability for this research. The second section explores grounded theory and explains why it was adopted. The third section explains the research design.

Quantitative vs. qualitative research

Research is systematic inquiry, objective analysis and recording of observations which lead to the development of generalizations, principles or theories finally leading to the prediction and possible control of events (Best and Kahn, 1998). The two broad approaches to research are quantitative and qualitative methods. These two methods are defined and contrasted in Table 3.1.

Figure 3.1: Differences between quantitative and qualitative research (Borland, 2001; Creswell, 1998.

	Quantitative	*Qualitative*
Purpose	To explain, predict or control phenomenon.	To explain gain insight and understand phenomenon.
Approach	Deductive, focused and outcome oriented.	Inductive, holistic and process oriented.
Hypothesis	Specific, testable and stated prior to conducting study.	Tentative, evolving and established at the end of the study.
Research environment	Controlled	Naturalistic
Design of study	Structure defined from the start and use of controlled parameters.	Flexible, specified only in general terms initially and the structure evolves, nonintervention.
Data collection	Observations, structured interviews and questionnaires. Raw data is numbers	Document study, open-ended interviews, and extensive field observation. Raw data is words.
Data analysis	Prescribed procedures, mathematical and statistical analysis.	General guidelines for data coding, analysis methods evolve continuously.
Strengths	∘ Larger sample size ∘ More generalization ∘ Objective	∘ Causal relationships can be established ∘ More context ∘ Inferences can be made
Weaknesses	∘ Difficult to establish causal relationship ∘ Less context ∘ Difficult to draw inferences	∘ Smaller sample size ∘ Subjective and less generalization

Quantitative research is the more commonly adopted method for researching in the engineering domain. The purpose of quantitative research is to explain, predict and or control phenomena by collecting and analyzing numerical data. Quantitative research is most applicable when the problem or phenomenon is fairly well-understood and a

hypothesis or hypotheses can be stated with some certainty. The hypothesis can then be tested by collecting and analyzing numerical data.

Quantitative research follows the scientific method that involves the following steps: state a testable hypothesis, collect data from controlled variables, analyze the data using widely accepted mathematical methods, then accept or reject the hypothesis. Data collection typically occurs in a controlled environment with measures stated prior to the study. Conclusions are strictly based on the outcomes of the statistical or mathematical analysis. This method of conducting research is effective and commonly used for many reasons. Quantitative studies commonly involve large and statistically significant samples, which aid mathematical analysis. The mathematical or statistical analysis then in turn enables generalizations to the larger population.

But quantitative methods have their limitations. They are most commonly used when the phenomenon has been fairly well-understood. A testable hypothesis must be clearly stated at the beginning of the study and the measures must be quantifiable. The data collection is restricted to controlled variables and so typically little contextual information is collected in the process (Creswell, 1998). Statistics can attach significance levels to correlations among data, but establishing causality is difficult without sufficient contextual information. Qualitative studies on the other hand involve collecting contextual information and therefore help add interpretative value to the numerical data.

Qualitative research methods are usually employed when the problem or phenomenon itself is not understood well enough to state propositions or hypotheses with well-defined variables and measurables. Qualitative research is a method of gaining

insights and understanding phenomenon by collecting and analyzing narrative data. Since the phenomenon is being studied for the first time, prior assumptions and specific hypotheses are avoided before the problem study is under way. It is only after probing the problem through careful and systematic data collection and analysis that some preliminary hypotheses are stated. These hypotheses are then tested conceptually as the study progresses and more data is collected.

The research design, unlike the serial process in quantitative methods, follows a more iterative process. A qualitative study starts with a few preliminary propositions based on a relevant and extensive literature review, and then narrative data is collected and analyzed. As themes emerge from the data the preliminary propositions are refined and some hypotheses stated. More data collection and analysis again is carried out to test these hypotheses. This cycle is continued using a systematic, consistent research design until a state of saturation is reached. Saturation is a stage where all new data substantiates the propositions and no new significant themes emerge from the data (Denzin and Lincoln, 1998).

Qualitative studies help investigate phenomena is their natural environments, and holistically, i.e., an attempt is made to capture all relevant contextual information. Contextual information lends credibility and interpretative value to the data and helps establish concrete causal relationships.

The qualitative approach however, suffers from two major drawbacks, a smaller sample size and greater subjectivity as compared to quantitative research. These drawbacks are reduced by more intensive data collection, being consistent with the

research design and adopting a rigorous and systematic data collection and analysis methods.

If applied systematically and rigorously both quantitative and qualitative methods are effective in increasing knowledge and understanding, but are suitable for different situations and for answering very different research questions. The next section explains the suitability of qualitative methods for investigating the research questions.

Suitability of qualitative research to current problem

In researching the role of EMS[4] in NPD[5] our understanding of the problem is limited because there is little evidence that suggest that similar research has been carried out. This author has found no other study that has investigated the role EMS plays in the experimental strategies of NPD and the related data management, communication and interaction within functions. The currently available PD literature offers little guidance into the question at hand, little data available that could be built upon or tested, and there is little basis for developing testable hypotheses. Thus, an in-depth qualitative study would be useful to develop a better understanding of the issues and relationships regarding relationship between EMS and NPD processes. Doing so will lay the groundwork for quantitative studies that will further develop and strengthen our understanding of this important element of electronics design.

[4] Electronic measurement systems
[5] New product development

Research approach selection

Qualitative studies can be conducted in a number of ways. Some of the options available for data collection are questionnaires, observations and interviews.

Questionnaires could potentially be sent out a large number of participants and this would aid in establishing concrete conclusions. But this method suffers from two major drawbacks. First, it is difficult to determine the right questions to be asked, since there is no means of trying and testing out questions first. Secondly there is little interaction between the informant and the researcher, this lack of direct interaction means that contextual information may be lost and no follow-up questions can be directed interactively based on the response of the informants.

Directly observing engineers involved in their daily work is a second approach. The researcher would shadow the engineer for an extended period of time as he or she went about their daily tasks. This could ensure that detailed observations were made but could not guarantee that all the necessary information could be made, i.e., not all aspects of their work could be captured in a short time. It is also logistically difficult to observe every aspect of their job in the given time restrictions. Observing engineers would also require relocation to the customer site for extended periods of time, which would be costly and would also involve confidentiality issues.

Given the severe drawbacks of questionnaires and direct observations, interviews seemed the best method to collect data. In this approach the researcher interviews participants in their work environments by asking them questions that would probe the role of EMS in new product development. The one-on-one interaction would work

favorably in collecting contextually rich data and also facilitate follow-up questions based on the responses. Interviews could enable a balance between eliciting the right kind of information and maintaining flexibility (Hunkins, 1972). A similar set of questions could be used for all the informants to maintain comparability, but the questions could be open-ended giving the informant some latitude for response. Follow up questions could be used to probe for more information or attempt to understand some new information that emerged in the response.

The next step is to choose a methodology that guides data analysis and validation of the data collected through semi-structured interviews. A widely accepted and commonly used methodology is 'Grounded theory'.

Grounded theory

Grounded theory is a systematic, rigorous and widely accepted methodology within qualitative research. The intent of grounded theory is to extract and develop a theory or an abstract analytical schema from the phenomenon (Creswell, 1998). It is applicable to situations where individuals interact, take actions, or engage in a process in response to a phenomenon. Grounded theory is 'grounded' in that no presumptions or hypothesis are made before the study is conducted and that only through careful data collection and analysis does theory emerge. The theory must have direct correlation to the raw data and is only true in the context of phenomenon.

Development of theory is crucial to the current research since current understanding is very limited. "Theory" in this context means developing a picture or

schema of all that is happening in relation to the phenomenon in that particular environment considering all the elements that are involved. Grounded theory uses a systematic research design called the constant comparative method. The constant comparative method consists of an iterative cycle. Data is first collected, analyzed and preliminary hypotheses are stated. Then more data is collected, analyzed and compared to the first data. Hypotheses are then either accepted, built upon or refuted and newer ones stated. Then more data is collected, analyzed and so on. This process runs in a cycle until such a time that concrete theory has been generated and any further replications serve to substantiate the same theory.

Grounded theory also has systematic procedures that guide theoretical sampling, data collection and analyses. Theoretical sampling, as opposed to random sampling, is choosing sites and informants based on requirements of the research and certain principles of grounded theory. Grounded theory also has procedures to guide analyses strategies. Data coding is the most commonly used technique for analyzing the data. The research design for this project is based on grounded theory approach and is explained in the next section.

Research Design

After careful study of relevant literature on grounded theory and qualitative research, a conceptual framework was made for the research design for this project. Figure 3.2 depicts this framework.

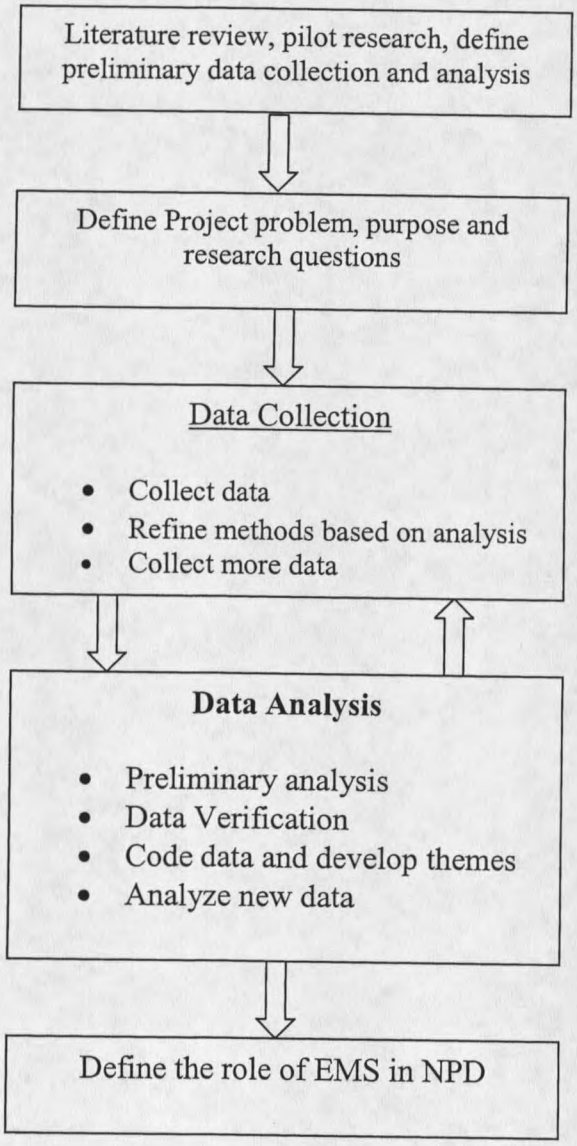


Figure 3.2 Conceptual framework for current research design

Extensive literature review was carried out to build a strong theoretical background for the study. Chapter 2 highlights the results, explaining relevant issues such as documented PD practices, knowledge management, and organizational theory in detail. Next, based on discussions with Tektronix and study of current issues, the problem purpose and research questions were formulated and later refined as new data came to light. These are explained in Chapter 1.

Grounded theory suggests collecting data from small samples spread across many categories within the scope of the project. Therefore data was collected through multiple sets of interviews and observations at 4 companies that develop and manufacture electronic products and using EMS extensively in their PD process. The various activities involved in collecting data are explained below:

Site selection: Grounded theory calls for studying multiple informants who are part of the central phenomenon or problem under investigation. Following this principle several criteria were adopted to choose the sites for our study.

- Established in the market place and growing steadily.
- Reputation for a sound technological base and good R&D and frequently introducing new products in the market.
- Having project teams of 5-15 people.
- Having midrange projects of duration of 12-24 months.

Formal channels were used to gain access to the sites and interviews with project teams and lab visits were planned.

Theoretical sampling: The selection of the informants is a key decision in qualitative study and clear criteria are needed to determine the nature and number of informants. Grounded theory calls for 'theoretical sampling', i.e. choosing a homogenous group of individuals who have experienced collectively or individually experienced some aspect of the phenomenon. Using this and current understanding of the makeup of project teams as a guideline the following criteria were finalized.

- At least 5–6 informants from each project team.
- Informants should represent different functions project management, design engineering, hardware and software engineering and test engineering.
- They should experienced engineers with at least 5 to 10 years in similar capacities.

Collecting data: Two sets of interview questions were formulated for two levels of inquiry within NPD. The first sets of questions were directed towards the senior managers and project leaders to understand the overall organization, the PD process, team makeup and functioning and some understanding of D-B-T cycles. The second set of questions was directed towards hardware, test, firmware and manufacturing engineers to understand design, testing and data management activities. These questions sought in depth information about how EMS were designed and used, how tests were carried out, data collected and analyzed in context of the PD process. (See Appendix for list of questions).

The interviews were of 1 hour each held in natural setting at the customer site, either in a conference room on at the workplace of the informant. The list of questions was given to the respondents prior to the interview for their review. Questions were asked and the responses written down with also some contextual comments. Depending on the response to a certain question follow-up questions were asked if the responses were incomplete or unclear.

Field notes were taken by hand during the interview and interviews were also audiotaped with the permission of the informant. Interviews were scheduled such that there was some time in between interviews to review the field notes and fill in the gaps of information.

Follow-up interviews: After conducting the first set of interviews detailed notes were made from the field notes and the audiotapes. This data was then organized in a way that reflected the flow of the PD process and use of EMS in it. Reviewing the results of the preliminary analysis of the data and related literature a list of desired outcomes for the interviews was made (see Appendix). This working document would serve as a benchmark against which the data from the interviews would be compared and follow-up questions formulated based on the gaps in the data. This step is also a part of analysis since grounded theory calls for member checks, i.e., taking the collected information to the informants and checking for its authenticity and factual error. Presenting this document to the informants during the follow-up interview so that they could review the information and correct any errors or add new information helped reduce factual errors.

At the end of data collection, our sample consisted of 6 project managers, 10 hardware and firmware engineers and 3 lab managers adding up to 35 hours of interviews.

Data Analysis

Data analysis immediately follows data collection. It consists of preliminary analysis, followed by formulation of follow up questions and then carrying out in-depth analysis. The steps followed for analyzing the data are explained below:

- Organize the data: The transcripts from the initial interviews and the follow-up interviews were coupled for the same respondent. All the transcripts from one case were studied at one time.
- Read through the notes and summarize every important response: The notes were read at least twice and then common responses were understood and notes made and also some rough figures drawn. Some preliminary categories were identified made and also sub-categories found. This was a part of the open coding process.
- Peer review: Grounded theory recommends reducing the interpretation error; this was accomplished by a peer review of these transcripts and notes.
- Engage in data coding
    - Open coding: Open coding helps organize the data and facilitate the emergence of theory. Some preliminary categories that best represented

the research questions were identified, and then codes were assigned to them. Reading through the notes and assigning the codes to the raw data accomplished open coding. The codes were then refined so that there was minimum overlap in the data assigned to a certain code. (See Appendix A for the list of open codes)

- Axial coding: In this coding method, a few important phenomenon were identified and all relevant information about these phenomenon was assembled together and fixed categories formed. Relationships were explored with the conditions present and also the outcomes were studied and documented.
- Selective coding / conditional matrix: The coding done before was streamlined with respect to either a time line or chronology of events and a summary was made. Various visual representations such as matrices and flow charts were used to represent the results of the analysis (some of the flowcharts and matrices are seen in chapters 4,5 and 6).

- Discuss findings: Two main themes, H-F-T triad and Information transformation, emerged after axial coding of the data and are discussed at length in chapter 5 and 6 respectively.

Summary

Adopting qualitative research methods proved to be extremely beneficial because we were able to collect in-depth data about PD systems and processes at four electronic industries. Through about 35 hours of semi-structured interviews and observations we were able to collect substantial data that was then analyzed using grounded theory. Two major themes emerged after multiple attempts of open and axial coding that are discussed in chapter 5 and 6. We were also able to gain a broad understanding of the NPD practices carried out at electronic industries, which is explained in chapter 4.

CHAPTER 4

CASE DESCRIPTIONS

In an attempt to address the issues set at the onset on this research, PD[6] practices at four firms[7] were studied. Understanding PD practices meant studying PD organizations, processes, experimental strategies and information management at these four firms, which was done through semi-structured interviews and onsite observations. The purpose of this chapter is two-fold. First it provides the reader with a comparative description of the product development organization and processes adopted at these four firms. Secondly it lays the groundwork for discussions to follow in chapters 5 and 6.

Though all four firms design and develop of electro-mechanical devices, they are diverse with respect to size and product line. Figure 4.1 is a comparative chart showing the profile of these four firms. The names used in Figure 4.1 are however fictitious to preserve confidentiality.

[6] Product development (also used interchangeably with new product development)
[7] Testtek, Techcon, Unolaser and DC systems

	TESTEK	*TECHCON*	*UNOLASER*	*DC Systems*[8]
Products	Oscilloscopes, logic analyzers, optical test equipment and signal sources	Develops hybrid and multi-chip modules and encapsulation.	Fiber optic test systems, laser current sources and temperature controllers	Automotive, motorcycle dynamometers, power commanders[9].
Business($)	1.2 Billion ('2000)	3.5 Million ('2000)	2.5 Million ('2000)	1 Million
Employees	4500 worldwide	250-300	175	100-150
Customers	Provides products to large electronics/PC mfg. firms and the open market.	Custom builds products for other electronics mfg. firms.	Provides products to large electronic / laser device manufacturers.	Provides products to the open market.
Prototype and test labs	Prototyping subcontracted and also done in-house. Test labs shared by all projects.	Prototyping sub-contracted, manufactured in-house. Test labs shared by all projects.	Prototyping sub-contracted, manufacturing in-house.	Prototyping and manufacturing done mostly in-house

Figure 4.1 Comparison of company profiles

Testtek

Founded in 1946, Testtek is one of the world's leading companies that provides measurement solutions to customers in many industries including computers, communications, and semiconductor industries. It designs, develops and markets a range of products including, oscilloscopes; logic analyzers; communications test equipment, including products for network monitoring and protocol test, optical transmission test and mobile production test; video test equipment; services and accessories. Its headquarters are in Beaverton, Oregon, and has operations in 25 countries worldwide. Testtek's large workforce and in-house test labs and manufacturing facilities enable them to provide

[8] The names provided to all four firms are fictitious to preserve confidentiality.

innovative products and new technologies. Figure 4.2 shows an oscilloscope manufactured by Testtek.

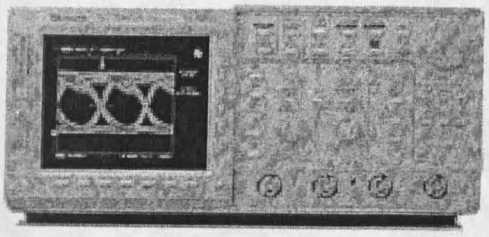


Figure 4.2 Oscilloscope made by Testtek

Techcon

Compared to Testtek, Techcon is smaller company that provides semiconductor manufacturing and packaging solutions. It has one site in Beaverton, Oregon that houses its engineering, testing and manufacturing operations. Techcon custom builds electronic products complete with packaging (e.g. metal encapsulation for a PCB) for its customers, which are usually larger corporations. Designs for new products come directly from the customers, then Techcon designs the circuit boards and packaging, carries out all functional, heat mitigation and reliability tests and volume manufactures the product. For this purpose, it has state of the art design, test and manufacturing facilities all in-house. Figure 4.3 shows an integrated circuit manufactured and packaged at Techcon.

[9] Electronic instrument attached to the fuel system of motorcycles that improves fuel efficiency.

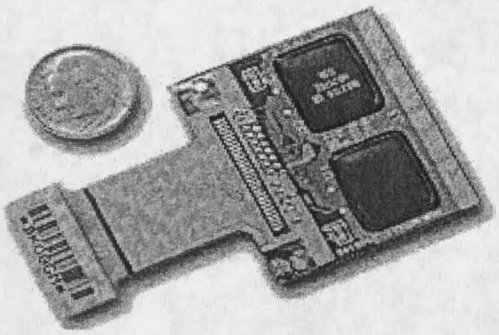


Figure 4.3 Product manufactured at Techcon.

Unolaser

Unolaser, established in 1986, is almost the same size as Techcon and provides test and measurement systems for fiber optic telecommunications. Based in Bozeman, Montana, its products include fiber optic instruments and test systems, laser current sources and controllers and multimeters. Product ideas come from lead customers but all engineering activities from designing, prototyping, testing and manufacturing are done in-house. To develop innovative products, Unolaser has advanced R&D labs; JIT based manufacturing line along with another facility in Boulder, Colorado and remote offices in Japan and UK. Figure 4.4 shows laser current source manufactured at Unolaser.

Figure 4.4 Laser source made by Unolaser

DC Systems

DC Systems makes mainly two products, Dynamometers and power commanders for automobiles, motorcycles and snowmobiles. Its engineering is much smaller in comparison with the other three companies and focuses on making variants of the two products for the open market. Most of the prototyping and some component manufacturing is subcontracted and but major manufacturing and assembly is done in-house. Figure 4.5 shows a dynamometer manufactured by DC systems

Figure 4.5 Dynamometer made by DC systems

Choice of diverse firms: It is evident from the description of these four firms that they are diverse in terms of their products, size and competencies. Consequently the PD organization and processes they have in place to design, test and manufacture new

products are slightly different. But this diversity works in our favor because we are able to generalize across the firms and investigate PD issues that were common across all four firms. The themes that emerged and discussed in chapter 5 and 6 are grounded in PD issues common across all four firms.

PD organization

The PD organizational structure provides the backbone for the PD, because people make things work. We documented the overall organization structure of these four firms but focused more on understanding the structure, composition, strength and functioning of the cross functional teams that constituted the PD organization.

The PD organization structures at Testtek, Techcon and Unolaser are consistent with current practices of adopting cross-functional teams for the product development effort. (The lack of cross-functional effort of the 4th sample can be attributed to its size; engineering consists of only 10 -12 engineers). Figure 4.6 illustrates the PD organization structures adopted at the four firms.

The PD structure at Testtek consists of a core team of 5-8 functional managers and a program manager. The core team leads the overall PD effort and their main functions include concept planning, coordinating team members and reporting status to top management. The program manager heads a cross functional team consisting of 10-20 engineers who carry out the design and development activities. While the core team manages more than one project at a time the PD team members are dedicated full time to one project and mostly collocated. The PD team structure at Testtek resembles a heavy

weight team structure (Clark and Wheelwright, 1992) and advantages offered by this structure such as focused development activities and a sense of 'espirit de corps' towards the team and product are visible at Testtek.

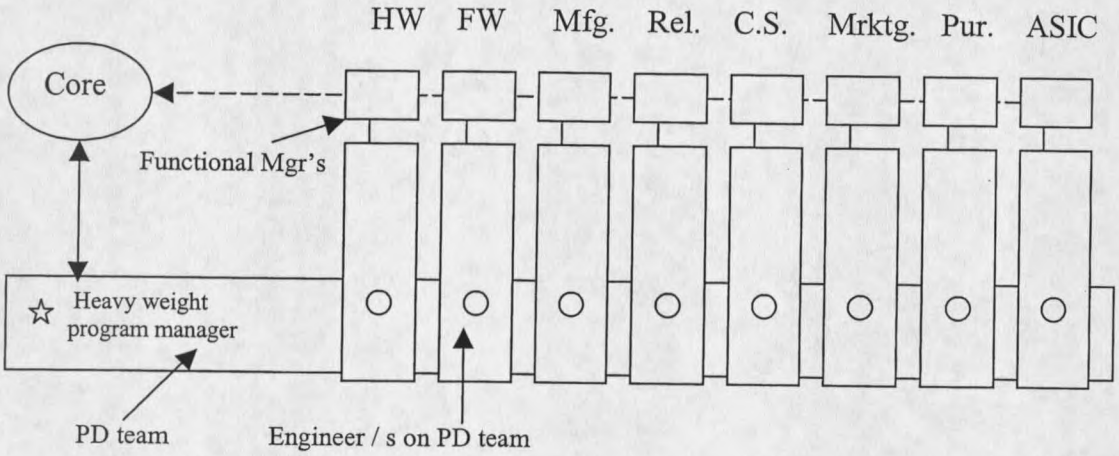


Figure 4.6.1 PD organization at Testtek

The team members are more or less involved right from the start and set their own design targets and schedules and are collectively responsible with the program manager to meet aggressive QCT targets. At Testtek marketing and manufacturing engineers are integral to the PD team, the implications of which are discussed later in this chapter.

In contrast, the team strength at Techcon and Unolaser ranges from 5-8 engineers and the structures resemble the lightweight team structure. In the lightweight structure the program manager leads the PD effort and functional managers assign engineers for the period of the project (Clark and Wheelwright, 1992). At both these firms the program manager sets the QCT goals for the team and directs and coordinates their activities (seen by the dotted line in Figure 4.6.2). An example of this was seen when a program manager

at Techcon and a hardware engineer at Unolaser were asked about the role of the program manager in the PD process, the responses were "I am responsible for the customer technical interface and I develop schedules, cost estimates and manage the process of development from start to end" and "usually it is the program manager who interfaces with the customer and gets the idea formulated into tangible terms and decides the costs and schedules" respectively. The effort of the engineers is also spread over multiple projects (2 to 3) depending on directions of the functional manager, so the program managers also coordinate with the functional heads.

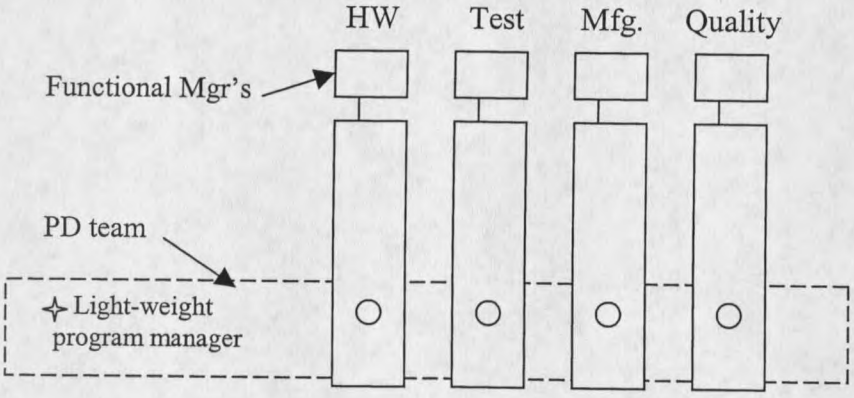


Figure 4.6.2 PD organization structures at Techcon

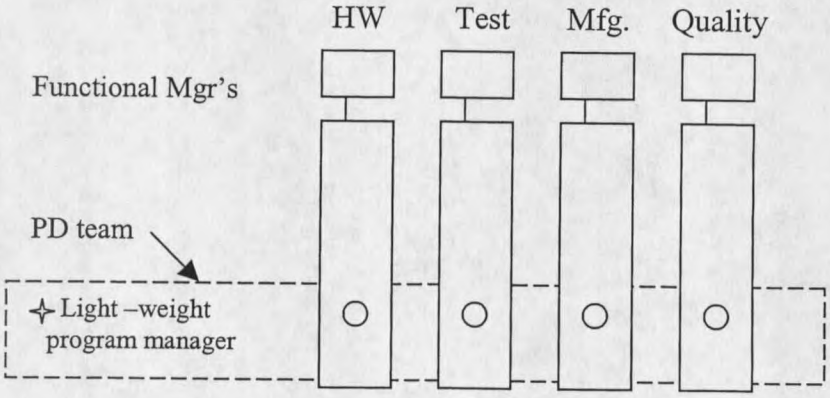


Figure 4.6.2 PD organization structures at Unolaser

DC Systems follows a traditional approach to PD where the engineering manager is in charge of all the development activities and there are no cross functional teams. Whenever need arises for new product or improvement on an existing one, either driven by top management or customers the engineering manager initiates the development activities. Concept development is done with the functional heads, (hardware, firmware or manufacturing) and then further development activities are assigned to the engineers. The engineering manager interfaces with top management and marketing, and plans and schedules development activities and status reviews.

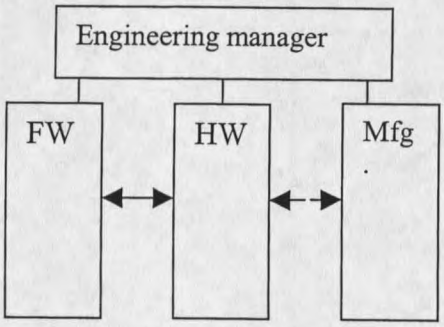


Figure 4.6.3 PD organization at DC systems.

Role of Program manager/project leader: PD literature has given considerable importance to the program manager since he/she has to play multiple roles during product development. Data collected on PD organizations from these four firms revealed two major roles of the program manager. The first role of the program manager was to serve as a link between the customers and the PD team and be a multi-linguist translator. What was commonly observed at all four firms was that the PM would continually interact directly with customers or through marketing. The program manager would then convert customer requirements to product specifications and relay them to the PD team. Even

though at Testtek the PM had the support of the core team to carry out this task, it was primarily the PM's responsibility to carry relay this information and act as a customer's representative through the development process. One possible reason for this was that most program managers that were interviewed during this research had engineering backgrounds (mostly EE) and also previous experience as hardware engineers/technicians (10-24 years).

The second role of the program manager is related to project management, which involves directing and coordinating engineering activities and ensure that QCT targets are met. The program manager at all these firms continually interacts with the team members and sets schedules, reviews progress through meetings and helps resolve integration problems.

Both these roles of the program manager were consistent to the ones commonly defined in PD literature but there was no evidence from the data that the program managers extended their role to that of concept champions. Concept champions are engineering managers who are the focal point of the new concept being developed and also ensure that decisions are taken consistent to the concept goals. Having a concept champion also helps to focus development activities of different team members towards a common goal. This aspect of program managers was found lacking at all four firms.

Product development process

Three of the four firms, Testtek, Techcon and Unolaser, have a formalized PD process that closely resembles a conventional phase-gate process (See Figure 4.7) as described in the literature (Ulrich and Eppinger, 2000). A phase consists of specific PD activities, which is followed by a gate, i.e., management review of the progress and evaluation of the project. The gate is also a go/no go for the next phase, top management decides based on progress and technical and economic feasibility if the next phase of the project should be pursued. The number of phases and work content varies across the sample but for sake of simplicity the development activities could easily be couched into four major phases as illustrated in Figure 4.7. The PD process followed at these three firms consisted of 2 to 3 planning and concept development phases, 1 to 2 design and test phases and 1 to 2 pilot and pre-production stages. Even though DC systems did not have a formalized and documented process their practices also resembled the ones observed at the other three minus the formal phases and gates. Figure 4.8 describes the activities unique to the different phases at the four firms.

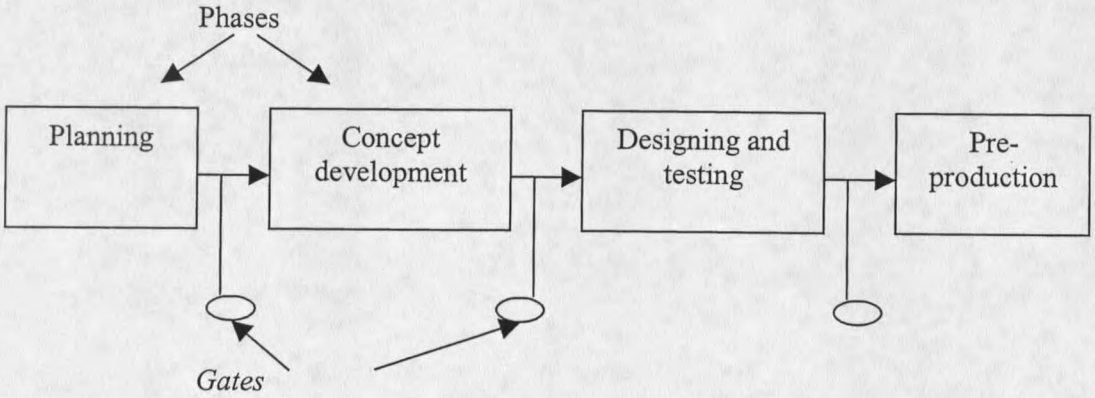
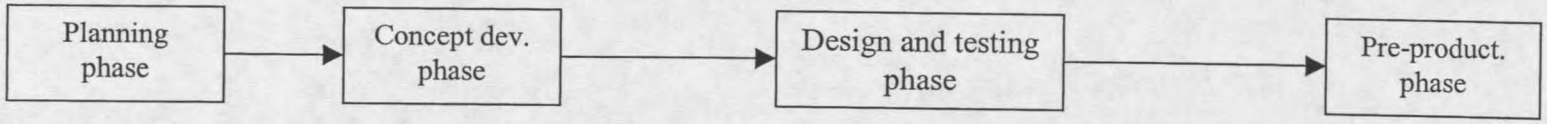


Figure 4.7 Phase–gate PD process



Testtek	Product ideas converted into product specs. PM assigned and PD team formed. Feasibility studies started and risks identified.	Product specifications finalized, functional plans formalized, Engineers assigned tasks, preliminary design and testing started.	Detail electrical and mechanical design started. Prototyping outsourced, EMS planned. Preliminary tests conducted and design iteration occurs.3-5 such D-B-T cycles for engineering prototypes, firmware released to match each hardware prototype. Design evaluated for performance and EMS design finalized.	Final firmware released. Pilot production and testing on automated EMS. Design of product and EMS optimized and documentation completed.
Techcon	Product specs converted into designs. Feasibility studies carried out electronic design and materials.	BOM finalized, parts count done, development plans finalized and preliminary design started	Board design, thermal and mechanical design completed. Board prototyped and EMS planned. Testing completed and data analyzed jointly. 2-3 such D-B-T cycles conducted and tests systems evaluated before design is frozen. Active and passive reliability tests carried out.	Design reviewed for yields and documentation given to Mfg. Pilot production tested on automated EMS and design frozen.
Unolaser	Market research and development of product specs. Risks identified and feasibility studies conducted on design.	Product specifications finalized, schedules and functional plans and engineering starts preliminary design	Detail design completed and prototyping is outsourced. Firmware tests code and releases for prototyping testing. EMS designed and prototype tested for all parameters. Test data analyzed and 2-3 such D-B-T cycles completed before design is frozen. Design optimized and integrated tests carried out, mfg. brought up to speed.	All functions coordinate to optimize design and EMS. Pilot production tested on automated EMS and data analyzed jointly.
DC	Market research and development of product specifications	Product specifications finalized. Preliminary design started	Detail design completed, prototyped outside and completed firmware downloaded. EMS designed and prototype tested for all parameters. 1to 2 D-B-T cycles and design optimized.	Design handed over to mfg. Pre-production started and tested on EMS.

Figure 4.8 PD process at the four firms

Project phases and milestones

Though the project phases and milestones at these four firms are different the PD activities can be explained by using the 4-phase model seen in Figure 4.7 as a framework.

Planning phase: During this phase management identifies a need and then plans for new product and assigns a program manager or a core group to the project. The ideas for a new product often come from customers through marketing or are generated from within the organization.

Testtek has a multifold strategy to generate product ideas. It attempts to balance a market pull, technology push and platform development kind of strategy. In market pull the ideas come primarily from lead users and new customers through marketing. Being a forerunner in the developing test systems, it generates new technologies and then finds the appropriate market for them thus effectively undertaking a technology push. Once Testtek establishes this new technology platform it leverages it and provides new products built around this technological sub-system. Techcon, Unolaser and DC systems primarily adopt a market pull and customized development kind of approach. New product ideas flow primarily from marketing and then the firms develop appropriate technologies to meet customer needs. Following a major development project, smaller projects are undertaken to provide variants of existing configurations.

In this phase top management assigns a program manager to initiate the project except in the case of Testtek where there is core group to support the program manger. The program manager plays a lead role in understanding the customer/market data and

then converting it into overall product goals or concepts. The program manager then develops a timeline and cost targets and starts putting together a team with the help of the functional managers or the core team. Once top management assigns money to the project the PM and team members can attempt to conduct further feasibility studies on the new product idea.

Concept development: At all four firms the PD teams are primarily in place is during the concept development phase. As described in Figure 4.8 at the beginning of the concept development phase the PD teams begin transforming the overall product goals into product concepts and then into technical specifications. Since product designs at all four firms are fairly complex, they are commonly broken down into smaller design problems. The way the design problem is decomposed has a major effect on the following design and development activities. Problem decomposition takes place in various schemes, most common of which is functional decomposition (Ulrich and Eppinger, 200). Functional decomposition either encompasses user functions or component functions.

For almost all of the products developed at these four firms the fundamental decomposition was into electronic and mechanical design. Another aspect of design that was commonly observed at all these firms was that the electronic design constituted the biggest component of the development effort and the major partition within electronic design came in terms of hardware and firmware design. The PD teams were organized

along the partitions, for example a program manager at Techcon commented "We have two major groups in NPD, the hardware and embedded software groups".

During concept development these hardware and firmware groups break down the overall product concepts into separate goals that hardware and firmware has to accomplish. These goals are further broken down into functional plans that take the shape of the hardware and firmware system requirements. This breakdown was evident from a statement of a hardware engineer from Testtek "We have HRS[10] and SRS[11] that are the backbone of the information needed for development". All the design and development activities in the following stages then revolve around the hardware and firmware development. This form of decomposition further leads to integration issues explained as the hardware-firmware-test triad in chapter 5.

The concept development also involves modeling the ideas via analytical or physical prototypes so that early learning can be affected. Prototyping is integral to PD because it helps the designer to visualize the design problem, detect unanticipated phenomena and helps expedite the development process (Ulrich and Eppinger, 2000). Prototypes can be either analytical or physical, and they can either be specific to test one function/parameter, or comprehensive system-level testing (see Figure 4.8).

[10] Hardware system requirements

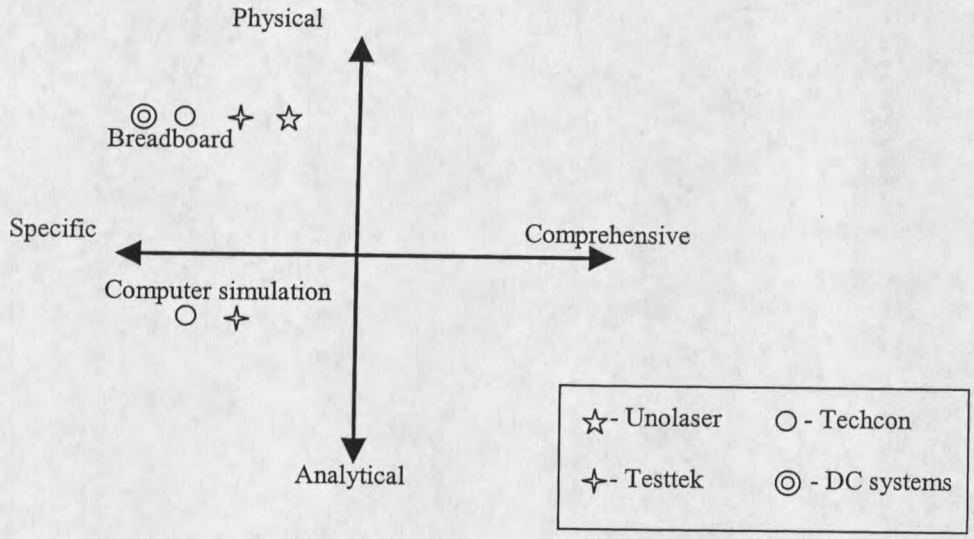


Figure 4.9 Types of prototypes during concept development phase

Analytical prototyping involves simulation, for example, and is done early in the development process. Some of these firms do some level of computer simulation during this phase, for example Techcon simulates the components on the PCB to anticipate time to failure.

All these firms commonly do a breadboard of the design to either visualize the design or to test a few critical parameters when the designers have little experience with the design space. For example when an engineer from Unolaser was asked about early prototyping he replied, "We may sometimes breadboard part of the PCB just to see what the design looks like". This was well in line with the single design, sequential testing strategy adopted by all these firms. The design concepts are frozen early on and the prototype is used to prove a concept rather than using the prototype to generate new information or to test multiple concepts. These firms therefore belie the opportunity to generate early information about the design space by use of early prototyping. Most

[11] Software system requirements

commonly at all four firms the major physical prototyping occurs in the design and testing phase and comprehensive prototypes are made closer to pilot production.

Design and testing stage: This phase consumes the maximum engineering effort and commonly stretches from 3 months to a year. A number of design, build and test (D-B-T) cycles occur during this phase at the end of which the design is proven and ready for production. At Testtek and Techcon there are two internal milestones within this phase, the first indicates that the hardware design is completed, while the second indicates that the firmware and test system design is completed and the whole product is tested.

The first D-B-T cycle is critical at all four firms and consists of the hardware designer or engineer taking the conceptual design (schematics, specifications etc) and making a detail design using CAD tools (PCAD, HCAD etc). The detail design is usually a layout with all the components and the transmission lines on it. At Techcon, Unolaser and DC systems this design is close to what the final product will look like in fit, form and function. But at Testtek the first detail design is still far from resembling the final product. The design is made to test some major functions and the communication between components.

Once this design is completed the design files are sent to a sub-contractor or to manufacturing for prototyping. While the design is being prototyped the hardware engineer puts together instrumentation for testing the prototype. But at Techcon test

engineers carry out the testing so the hardware engineer coordinates with them to set up the test equipment and finalize the test protocol.

Designing the test systems (EMS) involves putting together the instrumentation (e.g. oscilloscopes, voltmeters etc.) and then writing a test program to run the test using Labview, C++ or Borland's Pascal. Once the prototype is ready it is connected to the EMS using a socket and then the test program is run from the PC and the output is collected via the instrument screen or recorded on the PC. The design complexity of the EMS also changes with the product design; at Testtek for example the EMS to test the first prototype consists of a signal source at one end and voltmeters or oscilloscopes at the other. But as the design progresses the EMS will consist of PC from where the test program is run, connected to the prototype, signal sources and instrumentation to test different output values. Figure 4.10 illustrates configuration of a typical EMS. (Testing, data collection and analysis is explained in-depth in chapter 6)

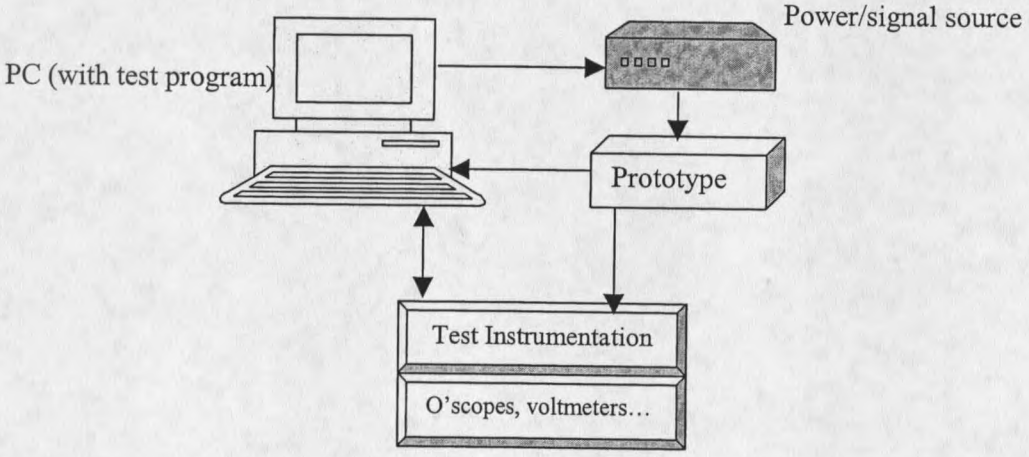


Figure 4.10 Configuration of a typical EMS

The prototype is then tested for all the different functions and the test data is commonly logged onto the network (server). The hardware engineer then pulls this test data onto a PC and analyses it using different software such as Excel, Mat lab etc. The tests data or the analysis is also shared with the other engineers on the team so that they can analyze it from their perspective and critique the design. For example the data is sent to the firmware engineer who then tries to analyze the problems and find out whether it was a firmware or hardware problem and how it can be solved. A complex interaction occurs between these two functions because at the time that the hardware engineer is designing and testing the hardware the firmware engineer is also designing and testing the firmware. This gives rise to an integration issue, namely the hardware-firmware test triad, which is tackled in-depth in chapter 5.

Once the test data is analyzed and the design is reviewed jointly, the hardware engineer refines both the hardware and test system design. The prototype made during the second D-B-T cycle is most commonly tested for all parameters including the ones that were proven in the previous test. Most of the testing done on engineering prototypes by these firms during the design and test phase is either partially or fully overlapping type. In a partially overlapping test, the critical parameters tested during the first D-B-T cycle are tested again and in fully overlapping tests all parameters are tested again along with the new parameters incorporated in the design. The test data generated by the EMS is again analyzed jointly and the product and EMS design is refined again. Typically Testtek goes through 4 –5 and the other three firms go through 2 –3 such D-B-T cycles before the prototype resembles the final product and can be tested for all the design

parameters. At the end of the design and test cycle the EMS is also complete so that the product can be tested and for the functions and the hardware design is frozen.

The test data from this final test is used for statistical analysis to check for consistency and variation of the outputs. This test data is also used by the other functions such as reliability and manufacturing engineering to carry out reliability and yield calculations respectively. The bugs in the firmware are also fixed and a major firmware release takes place before the design is frozen and passed onto pre-production. Minor changes are made in the design based on the suggestions of the team members and all the product documentation is compiled so that the design can be handed over to manufacturing engineering for pre-production.

Pre-production phase: Towards the end of the design and test phase and the beginning of the pre-production phase the development team bring manufacturing up to speed with the development activities. Product documentation including the test system (EMS) design is handed over and manufacturing starts setting up production processes for a pilot batch.

Manufacturing takes the lead from the development team and manufactures the prototype using production processes and tests it using automated EMS. All team members analyze the test data jointly and fix any glitches and also try to improve the yields. All related development activities such as firmware releases; reliability experiments and environmental testing are also completed before the design is frozen and ready for launch.

Manufacturing is a potential source of competitive advantage because it manufactures the final product and its capabilities are reflected in the performance of the product, i.e. how fast can it be made, how well it performs and how much it costs to be made. Manufacturing involvement in the PD process across the four firms as illustrated in Figure 4.11.

	Planning and concept development phase	*Design and test phase*	*Pilot and Pre-production phase*
Testtek	Manufacturing engineer integral part of PD team and helps in concept development and preliminary designing.	Helps designing of product and test systems. Helps team with test data analysis and evaluation of EMS.	Takes over EMS development from hardware engineer, designs mfg. and EMS for pilot production and coordinates with PD team to resolve issue.
Techcon	Mfg. engineer part-time member of PD team. Little involvement in concept development or designing	Helps develop test protocol and interacts with PD team during testing and data analysis	Interacts with PD team to understand product and EMS design. Then designs Mfg. and EMS for pilot production.
Unolaser	Mfg. engineer not a part of PD team. Almost no involvement during concept development.	Minimal involvement during designing and testing. Some interaction with PD team during test data analysis.	Interacts with PD team to understand product and EMS design. Then designs Mfg. and EMS for pilot production.
DC systems	Mfg. engineer not a part of PD team.	Minimal involvement during designing and testing.	Interacts with PD team to understand product and EMS design. Then designs Mfg. and EMS for pilot production.

Figure 4.11 Manufacturing involvement in the PD process

As seen in the figure manufacturing involvement in the PD process is different across the four firms. At Testtek manufacturing engineering is integral to the PD process, while at Techcon and Unolaser manufacturing involvement come late in the process.

Testtek therefore comes closest in adopting concurrent engineering, which prescribes early and active manufacturing involvement in the PD process. Manufacturing engineering at Testtek not only builds prototypes in-house but also develops test systems concurrently with engineering. Like for example when a Testtek hardware engineer was asked about the nature of the prototypes, he replied, "We have 1-3 engineering builds and the next time builds are done they are done completely in manufacturing to try out subcomponents". The PD process at Testtek also prescribes a joint design review before every major board turn, (i.e. before every major design iteration) and consequently encourages integrated problem solving, learning and continuous process improvement.

Even though Techcon and Unolaser encourage manufacturing involvement during design and development, they are unable to completely exploit the advantages offered by early and active manufacturing involvement in the PD process. Though a manufacturing engineer is a part–time member of PD team at Techcon, he is not actively involved in the designing and testing activities but restricted to reviewing and understanding the product designs and evaluating the test systems. Closer to product release the manufacturing engineer is trying to improve product yields and develop manufacturing test systems with help of the PD team. This involvement does help the transition of the product for development to manufacturing to be a little smoother but it does not offer the benefits of DFM[12] for example. Manufacturing at Unolaser is treated completely independent of the PD team. For example when a program manager at Unolaser was asked about the role of manufacturing involvement, he replied "they do help us at times but we do not consider

[12] Design for manufacturing

manufacturing as part of PD". Same is the case at DC systems, manufacturing has no active involvement until the design is frozen and the product is ready for pilot production. At all three firms the PD team brings manufacturing up to speed with the product design (close to transition from engineering release to pilot production) and then hands over the complete product documentation to manufacturing after engineering release. When a hardware engineer at Unolaser was asked about his job description he said "One of my major jobs is to put all the documentation together so that we can hand it over to manufacturing". This 'over the wall' approach has two major drawbacks; manufacturing problems are highlighted late and lead to delays and extra costs, for example in one instance a hardware engineer commented "sometimes manufacturing comes back to us because the yields are very poor". Thus manufacturing capabilities cannot be enhanced and leveraged as a potential source of competitive advantage.

Communication in the PD process

Communication is very critical to the PD process because it is necessary to ensure that ideas and problems are communicated to team member effectively and at the right time. Critical aspects of PD such as generation of ideas and problem-solving are based on how effectively information is transferred between team members. Figure 4.12 is a chart showing the common modes and means of communication at the four firms.

Testtek	*Techcon*	*Unolaser*	*DC systems*
Weekly core team meetings, technical meetings and schedule meetings. Engineers communicate with e-mails and face-to face communication. Design reviews held at every major hardware board turn.	Engineers communicate with e-mails and face-to face communication. Team meetings every fortnight. Joint design reviews are held with input from all team members.	Engineers communicate with e-mails and face-to face communication. Continues interaction and knowledge sharing between hardware–firmware engineers.	Engineers communicate with e-mails and face-to face communication. Continues interaction and knowledge sharing between hardware–firmware engineers.

Figure 4.12 Modes and means of communication

As seen from the figure face to face communication is most evident mode of communication across these firms. By collocation of team members these firms encourage face-to-face communication, which is the richest and most effective mode of communication (Court, Culley and McMohan, 1997). Program managers at these four firms also stressed on problem solving at the lowest level and consequently required team members to communicate within themselves before any issue was taken to a top management meeting.

Written communication is also important because almost half the time the team members communicated through e-mails and reports. For example when engineers at Testtek and Techcon were asked how they communicated, their most common responses were; "If we can meet the other guy across the hall we talk to him, otherwise I send him an e-mail", "We usually use face-to face or e-mail and reports, say 50-50 %"

Discussion of test reports is of importance to this research because most of the learning and information transfer takes place after a test is conducted and reports are

complied. Issues that require cross-functional coordination are highlighted as a result of the tests are communicated to all team members through this test report. It is a regular practice to compile a test report and send it to other functions through e-mail or a hardcopy. But there is no formalized system, which governs what this report, should contain and what format it should have. Recipients of these reports then use this repot for their own analysis or wait till a design review meeting or a top management meeting to discuss issues and problems.

Toyota on the other hand has a very formalized method by which engineers follow a standardized method of report writing and it is also written to elicit a response from the recipient. The recipients are also required to offer feedback on this report and send their responses via another report (Liker, Ward and Sobek, 1998). This activity of responding to one report with another is not a one-time activity but rather an iterative process so this integrated mechanism of written communication greatly helps hammering out issues sooner rather than later. The meetings that are then subsequently held are more focused since engineers are on the same level of understanding and come prepared with issues that have not been solved and focus their energies on few things rather than trying to accomplish everything. The logic adopted by Toyota is very simple; they try to eat the pie in small pieces rather than trying to eat it all at once. The firms that were studied on the other hand tried to get everyone into a war room and solve all the problems all at once.

Adopting a strategy similar to Toyota's holds substantial gains for all these firms but it would require two major changes in the PD system. First of all this strategy would

require support from a information management system that helps the engineer to access all the information and data that is needed for decision support. Issues related to information management are tackled in Chapter 6, which focus mainly on the information transformation process and information management system. Secondly the PD process itself should define procedures that require engineers to interact via written communication and prescribe standardization in report writing, which would make the task more systematic and less ambiguous.

From the discussion provided above about the PD organization and processes followed at all these four firms, it is evident that even though they have a development team and a similar PD process, the way they go about design and development activities is different. In this research we utilized this diversity to gain a better understanding of the issues that we sought to investigate and were also able to generalize across the samples and present our analysis and findings. Chapters 5 and 6 discuss two major themes, the Hardware–Firmware–Test triad and Information transformation that emerged when we generalized across our sample.

CHAPTER 5

HARDWARE-FIRMWARE-TEST TRIAD

At all four firms the electronic design and testing constitutes the biggest component of the development effort. At the heart of electronic design is the PCB[13], which consists of hardware and firmware. The physical components constitute the hardware and firmware is the embedded software that drives this hardware. These two are so completely dependent on each other that hardware design cannot progress without firmware and vice-versa. The design and testing of the hardware and firmware is however, fundamentally different and no one engineer is capable of doing both.

Faced with this problem of having these different design and test cycles, management at these four firms breaks the development organization into hardware and firmware development groups, which form the largest contingent of the PD team. The hardware and firmware engineers for a particular PD project break the overall product concepts into separate hardware and firmware goals. These goals are further developed into functional plans that outline separate system requirements for hardware and firmware. As hardware engineer from Testtek said, "We have HRS[14] and SRS[15] that are the backbone of the information needed for development." All the design and test activities involving the EMS in the following stages then revolve around the hardware and firmware development.

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[13] Printed circuit board
[14] Hardware system requirements
[15] Software system requirements

As explained in Chapter 4, three of the four firms in our sample follow a stage gate PD process. The design and test phases consume major engineering effort; and also involve the use of EMS, and therefore the major data collection during this project was focused on these phases.

The decomposition of the PD team into hardware and firmware groups was observed in three of the four firms. This decomposition into hardware and firmware coupled with the design and development of the EMS leads to the integration issue we termed as Hardware-Firmware-Test (H-F-T) triad. The H-F-T triad emerged as a main theme after qualitative analysis of the data and was observed at Testtek, Unolaser and DC systems but not at Techcon since its products do not contain embedded firmware.

This chapter first describes in-depth the Hardware-Firmware-Test triad theme, then shows point-based concurrent engineering precipitates this integration issue and how following set based concurrent engineering offers a probable solution.

Design and development phase and H-F-T triad

The H-F-T triad is embedded in the D-B-T cycles that are integral to the design and development phase. Figure 5.1 shows a typical D-B-T cycle consisting of board design, prototyping and testing with electronic measurement systems (EMS). Then design is iterated on based on the results of the test and the next D-B-T cycle is initiated.

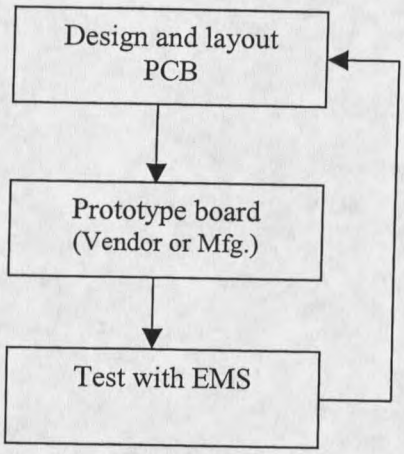

Figure 5.1 Typical D-B-T cycles from PD literature.

But the D-B-T cycles observed at the four firms were not so simplistic due to two factors:

- The PCB design consists of two distinct entities, hardware and firmware that have separate D-B-T cycles.
- The design and development of EMS, which was the primary testing tool, runs parallel to the design and development of the product.

Data collected during the course of this project showed that the hardware and firmware development cycles at these firms were different and complex. But management needs to have some integrative mechanisms between the two cycles so that these two groups can finally converge onto one product design. The following sections describe the hardware and firmware cycles and how these firms choose to integrate them.

Hardware development cycle

Prior to the first hardware D-B-T cycle, the hardware engineer/s conduct some feasibility tests on the conceptual design. They then iterate on the conceptual design and make schematics of the different modules of the design. The key ASIC in the design is also designed, tested and proven.

Typically in the design and development phase the engineer/s takes the schematics and layout the board using CAD tools. If the board has high-speed lines they use auto routing capabilities and try to optimize the design. At Testtek and Techcon, peers review this design before final blueprints are made and shipped over to a subcontractors/ manufacturing for prototyping. (see Figure 5.2 for the hardware development cycle).

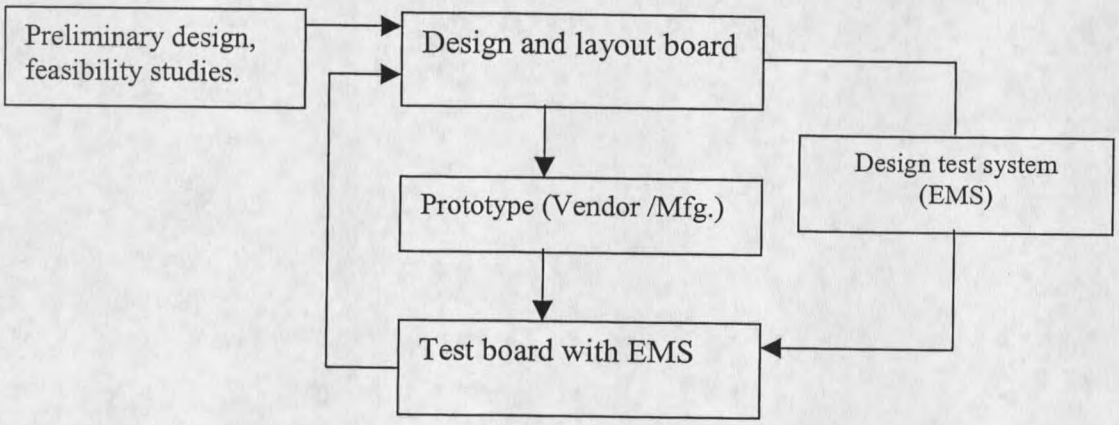

Figure 5.2 Hardware development cycle

While it is being prototyped the hardware engineer/s plan the test protocol based on the test requirements decided in the planning phase. The engineer puts together the

instrumentation and plans the tests. The development of this test depends on the state of the prototype, how close it is to the final product.

For complex designs the initial testing typically consists of testing the prototype for preliminary functional requirements and communication between the different components. The design is then iterated on, and as it progresses the testing, too, becomes refined and increasingly complex. The prototype slowly begins to resemble the final product. At the end of the first D-B-T cycle the hardware engineer will have typically used an EMS to test the prototype for all the functional outputs, communication and consistency.

Figure 5.3 shows a typical EMS used for testing a range of design parameters. It consists of a user interface, which is usually a PC from where the signals are sent and data recorded, the instrumentation that carries out the test, and the interface (sockets) that plug into the board.

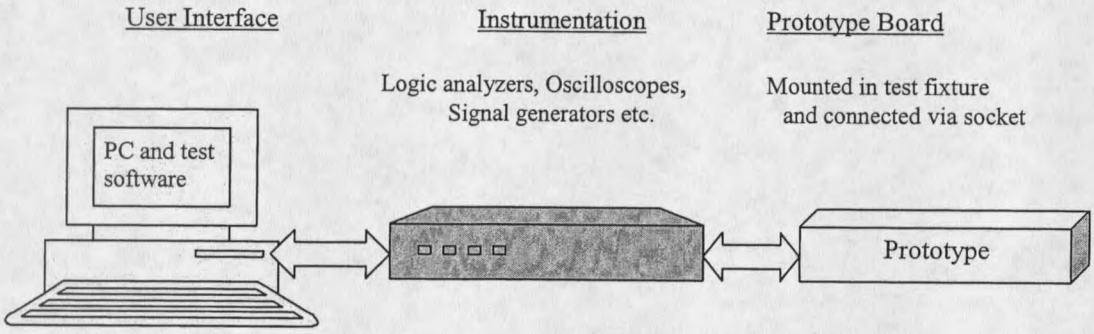

Figure 5.3 Block diagram of an EMS.

Designing the EMS: The design of the EMS is usually the domain of the hardware engineer. The hardware engineer/s assembles the instrumentation needed for testing the

prototype. The instrumentation is mostly rack mounted and connected to the prototype through a custom designed socket. The engineer has then to write the test code in C++, PASCAL or Labview. The power PC then drives the instrumentation and sends out commands that are converted into signals sent to the prototype. The output signals are received and converted into data saved and processed by the PC. Labview, which is the most commonly used test software, performs two functions. It runs the test protocol and compensates for the lack of firmware in the hardware. The design of the EMS depends on the state of the prototype; i.e., what needs to be or can be tested and the amount of firmware available for the test. The design of the EMS is also evaluated at the end of every test to determine if it was capable of testing everything in the test protocol and to fix any bugs. Evaluation of the EMS is also necessary because manufacturing engineering most commonly bases the design of the manufacturing test systems (EMS also) on the design of this engineering EMS.

Testing the hardware: Once the prototype is manufactured it is visually tested for proper assembly of components before it is tested for basic functions. Firmware is downloaded unto the prototype before it is mounted on the test fixture and connected to the EMS using a socket. This EMS has all the needed instrumentation already connected to it along with the test program in the PC that drives the EMS. The test is then run via the PC and data is collected and stored on the PC. The PC is programmed to log the data and also cleanse it so that it can be downloaded onto a spreadsheet for analysis. The hardware engineer then downloads this data into a windows interface and uses Excel or

other generic programs to analyze the data. The results of this data are made available to firmware so that they can evaluate the performance of the firmware. The results of the test are also used to evaluate the performance of the EMS so that its design can be improved. This test data forms the basis of the next hardware design iteration. Analysis of the test data ends a typical D-B-T cycle, known commonly as a board turn.

Firmware development cycle

Prior to the firmware development cycle both hardware and firmware engineers break down the conceptual PCB design into modules and formulate hardware and firmware development plans. These plans contain the breakdown of the design into the functions that hardware and firmware will have to fulfill.

Firmware engineering then takes these specifications and starts writing code for the hardware. Preliminary testing of this code is done using an emulator or a simulator. This emulator, which is typically commercially available, helps to simulate the hardware and test the firmware for bugs. This emulator however is not perfect and therefore the firmware cannot be completely tested with it. This preliminary tested firmware is then released to hardware engineering to test on the hardware prototype. (The firmware development cycle is illustrated in Figure 5.4). The firmware D-B-T cycle runs parallel to the hardware cycle but lags a bit because firmware engineering needs a proven prototype to test the firmware on. Therefore the firmware engineer obtains a hardware prototype after it has been tested for hardware functionalities for its own testing. Firmware engineering then runs their own test protocol using the hardware provided to them and an EMS, which may or may not be the same as the one used by hardware. Once the

firmware test is completed, the results of the tests are reported to hardware. The firmware engineer then evaluates the firmware based on their own test results and the test results provided by hardware engineering.

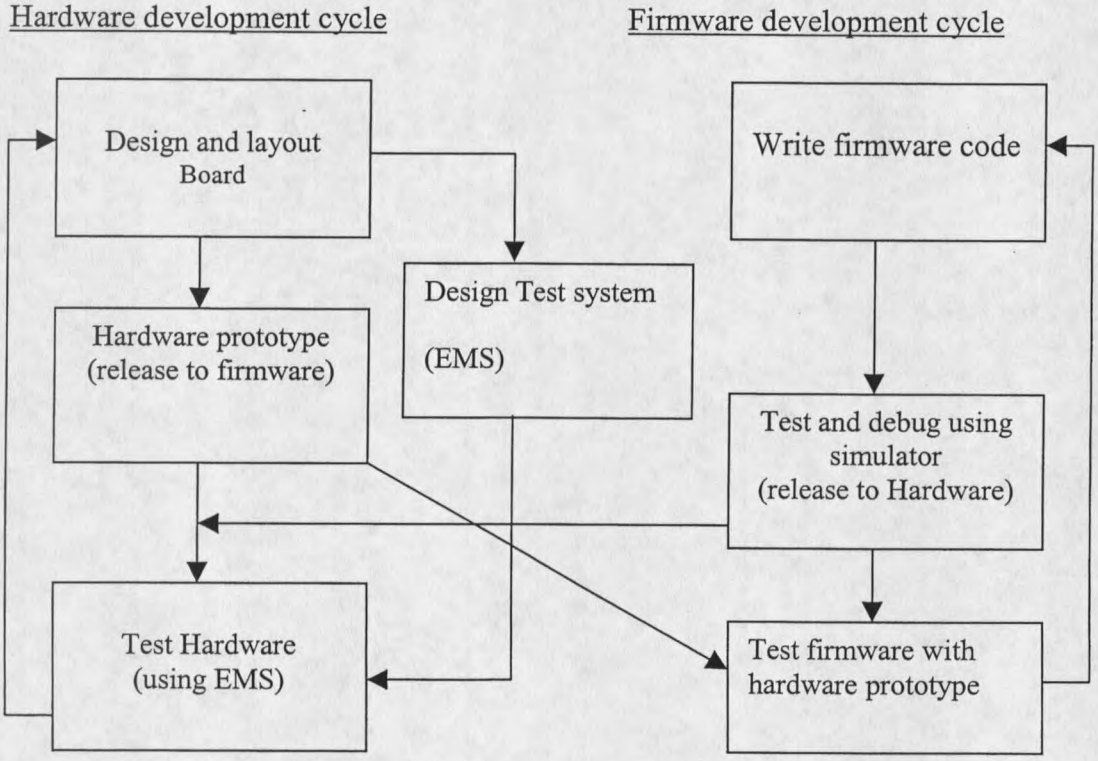

Figure 5.4 Hardware and firmware development cycles

Testing and learning

If testing is viewed as a learning activity then major learning in these firms occurs after the hardware and firmware tests are completed. The hardware engineer/s at these firms typically analyze the test data and then compile a report and send it to firmware engineering. Firmware engineering also prepares their own report after the firmware tests and uses both to evaluate the firmware. A major design review, typically formal but

sometimes an informal meeting, takes place before the next design iteration where the hardware and firmware problems are discussed and probable solutions are finalized. (e.g. a hardware engineer at Testtek commented on these joint discussions, "Hardware engineers go to the software guys or sometime they come to us when we feel that either software or hardware is not doing what is supposed to and effecting some performance parameter"). A similar kind of activities and interaction after a test was observed at the three firms.

The solutions suggested as a result of these discussions may consist of firmware solutions to hardware problems or vice versa. Hardware also uses the information to evaluate the design of the EMS and plan improvements and additions for the next design iteration. Figure 5.5 depicts this joint analysis and consensus activity.

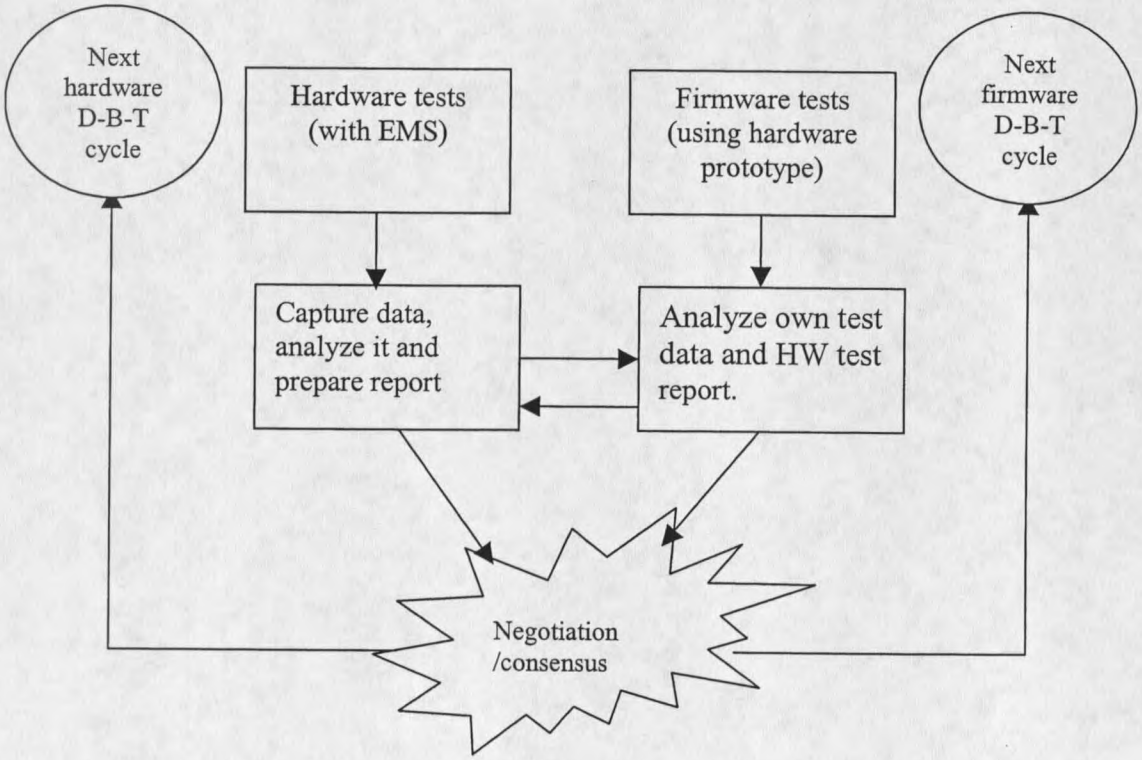

Figure 5.5 Test data analysis and post analysis activities

Integrating hardware and firmware development

Hardware engineering depends on firmware engineering to provide them with sufficient firmware to drive the hardware so that the prototype can be tested. Firmware engineering cannot realistically evaluate the code without a hardware prototype to test it on. They also need a test report from hardware engineering to evaluate the firmware completely. These interdependencies are inherent to the triad and PD team converges on an acceptable design that meets requirements as a result of a number of such hardware-firmware D-B-T cycles.

Hardware engineering also designs and evaluates the test systems. The design and development processes are designed such that major activities occur with respect to a hardware board turn. So hardware tends to dominate the process and remains on the critical path even though firmware often causes major delays in the development. The bugs in the firmware are not fixed even when the hardware is ready for engineering release.

Communication, information transfer and learning during designing and testing is very minimal and takes place mostly at the end of a hardware and firmware D-B-T cycles. This interaction is also driven to finding quick solutions to the problems that have been uncovered during testing (see Figure 5.5). But the problems of finding solutions to the design issues that get highlighted after the test are compounded by that fact that the test data is often confusing. The information management system is designed such that it helps the storage and retrieval of the test data but the interpretation of the results is still the task of the design engineers. The hardware engineer generates the test reports from a

hardware perspective and therefore the firmware engineer has to put in considerable effort to interpret them in the firmware domain. When the test engineering is a separate entity both hardware and firmware face this problem. These reports often lead to confusion and waste of development time and effort.

As the hardware and firmware development cycles progress in parallel trying to optimize the product design the hardware engineer/ test engineer has also to optimize the test system (see Figure 5.6). Manufacturing takes the lead from the design of this EMS so that the automated EMS can be designed and developed to test the pilot prototypes and eventually the final products.

In short, hardware and firmware engineers are working in parallel with separate D-B-T cycles trying to converge on one design that best fulfills the product requirements. Doing so they are also trying to also design and develop the EMS to test the design, while always being under pressure to meet CQT targets. All these factors coupled together leads to a rather significant integration problem that we have termed as the H-F-T triad. This H-F-T triad is seen in Figure 5.7 depicts the complex integration between the hardware and firmware development cycles. This figure is similar to Figure 5.6 except it adds the EMS development cycle, and integrates it with the hardware firmware development cycles.

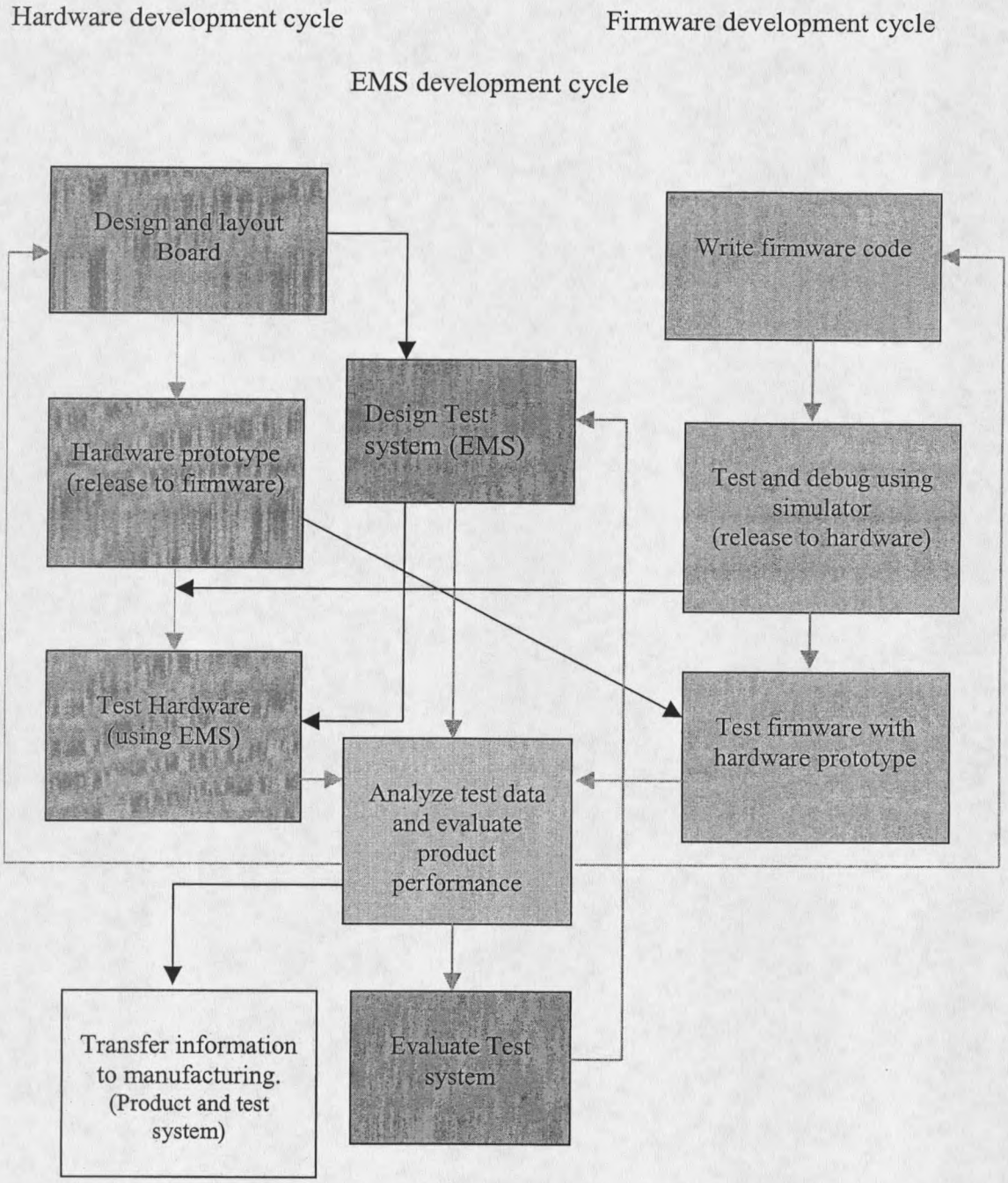

Figure 5.6 Hardware-firmware-test triad

Current approaches to the HFT integration problem

Faced with the integration problem due to the H-F-T triad three of the four firms in our sample consciously adopt certain practices to facilitate seamless integration between hardware and firmware development.

They try to define the hardware/firmware requirements precisely early on and make them standard operating procedures (SOP's), i.e. all succeeding development activities tend to follow them. The hardware system requirements /firmware system requirements (HRS/SRS) would then be the basis of all-further discussions and interactions between the two development groups. These firms adopt conventional organizational solutions by forming cross-functional project teams and collocating. In addition, they try to define design requirement very early on and try to carry out development activities a structured way so that further conflicts can be avoided.

This structured way of development requires firmware to plan its development based on the hardware development plan and release firmware to match a hardware prototype. Hardware engineering is also typically required to offer immediate feedback after testing the prototype. This is followed by a major design review, where the two functions come together and try to arrive on a consensus about the design changes. Program managers typically stress on decision-making at the lowest possible level to avoid conflicts and major disputes during design reviews.

The common rationale behind these organizational solutions is that by putting people together in a common space, giving them common target, and set of rules to meet it, people will be able to resolve all kinds of conflicts and come up with an optimal

solution. This however does not resolve all the issues related to the H-F-T triad. Having a common target and a structured way of going about their activities does help engineer go about their tasks in a systematic fashion and does provide a framework for resolving conflicts related to the design and development activities. But these organizational solutions do not necessarily guarantee design optimization. Typically, one dominant function overpowers the rest of the team and all decisions tend to favor that function. Secondly since the focus is on resolving cross-functional issues as soon as possible, the designers tend to finalize a design concept early on and then spend the rest of the development time testing this concept, making it compatible to the other designs and resolving problems. Thus the entire design space is typically never mapped and there is no guarantee that the final product design will be optimal.

An alternative approach

Though the organizational solution adopted by these firms is one way of dealing with the H-F-T integration triad, we attempted to reexamine the process by which the development takes place. Adopting a systems approach, and studying the process by which any system works (PD process in this case) is a common Industrial Engineering approach. Investigating the H-F-T triad from the nature of the PD process adopted at all these four firms not only provides some insights into why this problem occurs but also aids in prescribing an alternative solution to the integration issue.

Concurrent Engineering (C.E.) and H-F-T triad

The firms that we studied principally adopted Concurrent Engineering (C.E.) by formulating cross-functional teams and encouraging all functions to work concurrently during development. But their process in reality is just a refinement of the point based serial engineering approach. (Figure 5.6 is an illustration of the point based serial approach and point based concurrent engineering approaches, which are discussed in chapter 2). The H-F-T integration problem is exacerbated by the fact that these firms used point-based C.E.

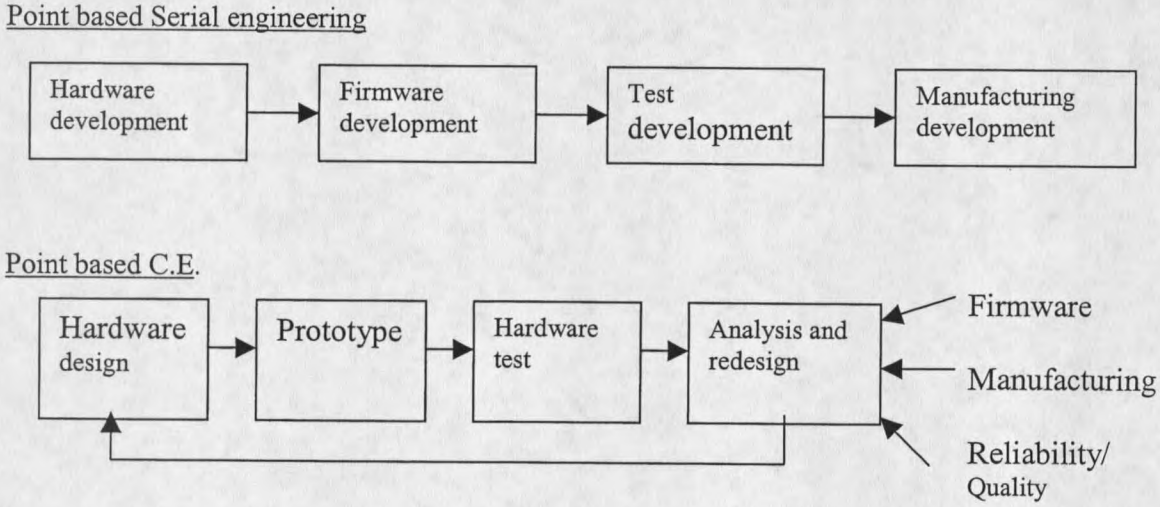

Figure 5.7 Point based serial and concurrent engineering

Point based concurrent engineering

During the discussion of the H-F-T triad it has already been established that the process is hardware centric (i.e., hardware is always put on the critical path). Hardware

engineering decides on a concept early and comes up with a design from their perspective to what they felt would satisfy the product requirements. Because hardware comes up with a design and then firmware tries to design the firmware so that it makes this hardware work, the entire design space is never completely mapped. Hardware engineering then prototypes and tests the design and seeks input from other functions on the team during analysis (This point based C.E. process observed at all three firms is illustrated in Figure 5.7). An example of this is when the test data is sent to other functions like firmware, reliability, manufacturing who then offer suggestions from their perspective and review the design jointly before every major board turn. The next design iteration is result of this information transfer and joint analysis.

This process therefore does not differ very much from the point-based approach for two reasons. The first reason is that the team is focusing on one solution and iterating on one design only. Secondly each function is offering inputs, which may or may not be compatible to each other or even detrimental to system performance and so there is no theoretical guarantee that the process will ever converge on an optimal design. Firmware often ends up just satisfying the hardware design requirement rather that actually offering a solution to the design problem. Typically firmware engineering hardly ever comes up with a conceptual design to fulfill product requirements, it only develops firmware to run the hardware.

Since the PD team sets timelines for the development activities even before the first D-B-T cycle takes place, they choose a quick solution that satisfies everybody and

try to freeze the design so that it can be manufactured. But this design may or may not be the optimal solution to the product requirements.

The firms that were studied were also involved in developing new innovative products, where the design space is not well known, tools for testing and analysis are not in place and therefore the feedback loops are longer and consequently the integration issue like the H-F-T triad and other issues become more apparent. This can be explained by the fact that hardware engineering will not be able to arrive on a solution without considerable design iteration and testing and so will be the case with firmware. Developing the test system will also be a complex task due to the inexperience in the design of the product. This will lead to complex H-F-T triad and major integration problems. If issues related to the H-F-T triad are coupled with the ones related to manufacturing and reliability/quality then tremendous communication and cross-functional integration is needed in the process to arrive on an optimal design.

Adopting set based concurrent engineering (SBCE) rather than a traditional C.E. process offers a probable solution.

Toyota's Set Based Concurrent Engineering process

In Toyota's SBCE process the design participants reason about, develop and communicate sets of solutions in parallel and relatively independently (Sobek, Ward and Liker, 1999). As the PD process progresses the different functions then narrow their respective solutions based on the information communicated with each other and other

participants like customers and suppliers. As the solutions slowly converge the different functions then commit to one optimal design (refer to chapter 2, pp: 37-41).

Figure 5.8 illustrates the 3 main process steps or principles of SBCE, which are mapping the design, integrating by intersection and establishing feasibility before commitment. The following sections discuss the possibilities of applying the principles of SBCE in current situation.

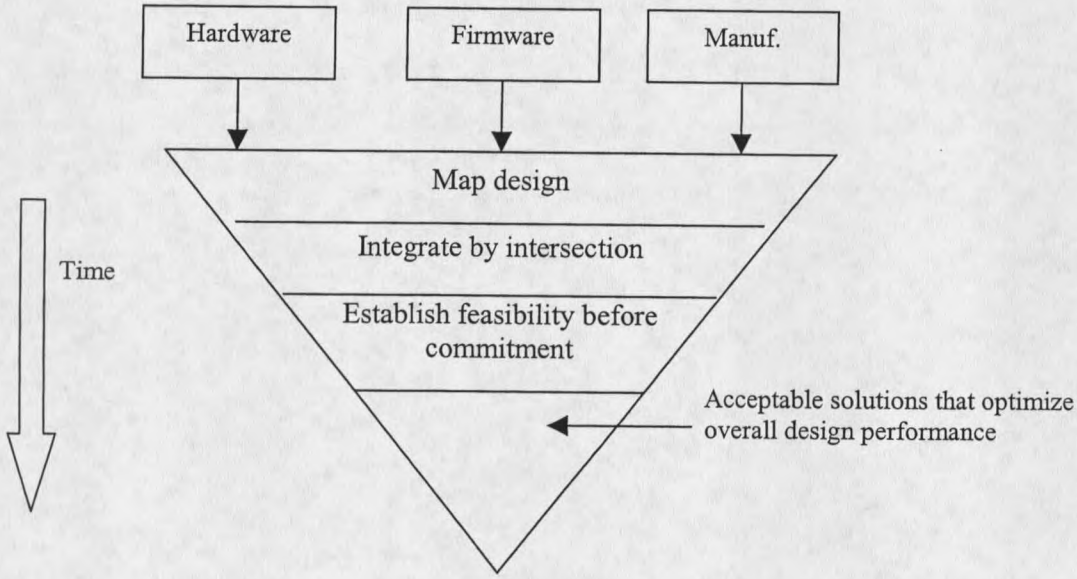

Figure 5.8 Process of Set Based Concurrent Engineering

Principle 1: Map the design space

The functions involved in the PD effort could simultaneously define broad sets of feasible solutions from their areas of expertise (hardware, firmware and manufacturing in our case). Rather than making the PD process hardware centric, these three main functions could jointly undertake the task of encrypting the customer requirements. They

could jointly decide product requirements that will serve to guide further design and development activities rather than strict specifications that will restrict creativity. Using product requirements as a guiding framework will enable the three functions to develop multiple concepts that still fulfill the same product requirements.

During concept development the three functions could make use computer simulation, partial prototypes and previous knowledge to generate multiple designs and test them. For example hardware could make 3-5 different designs, breadboard them, test them using EMS and prepare a comparative evaluation. While hardware is doing this firmware engineers can write different sets of codes, test them within the software or by using an emulator/simulator and do a similar comparative evaluation. Thomke (2001) has also stressed developing physical prototypes (either partial[16] or preliminary[17]) and testing them during concept developing. The purpose of these activities should not be on arriving on a solution but rather on learning more about the design space from a hardware, firmware or manufacturing perspective.

EMS has a very important role to play in this process, since it is critical for engineers to come up with multiple concepts, build partial prototypes and test them. The EMS therefore must be capable of providing a comparative evaluation of the performance of these designs. The same EMS should be capable of testing all the prototypes, aid the engineer in analyzing the data and also provide a comparative evaluation of one design against the other. Another capability of the EMS that could prove to be advantageous would be the ability to store test data and analysis and learn about the design space as

[16] Prototype representing only a part of the whole product
[17] Prototype in its infancy stage, i.e. not resembling the final product in neither fit nor form

further tests are carried out. This capability would potentially help the engineers learn about the design space even more and aid development of further designs.

Team meetings that are commonly held for evaluating project progress should be used rather for communicating ideas to each other. Communications should not only be restricted to meetings and should occur on a daily basis through written or face-to-face communication by exploiting the fact that the PD team is collocated.

Principle 2: Integrate by intersection

This second principle is critical to ensure that the multiple conceptual designs made by hardware, firmware and manufacturing are not converging too rapidly. This principle could be applied in the following manner.

Once hardware, firmware and manufacturing have made multiple designs and tested them they should focus their efforts on understanding and appreciating the designs and solutions offered by the other functions and also determine the feasibility of their own designs. Once hardware, firmware and manufacturing are satisfied that they have a fairly good understanding of the design space they can attempt to integrate some of these designs by identifying workable solutions. These solutions are the intersections where the feasible regions of these different design sets overlap. If hardware, firmware and manufacturing engineers have done a good job of communicating their ideas to each other then the conceptual designs will already reflect some level of commonality and the intersections of the feasible design sets will be wide.

Once feasible regions have been identified, the teams should not be hasty and quickly freeze the solutions, but rather should impose only minimal constraints. This is

important because the firms studied typically froze design concepts and sub-system interactions early as possible, sometimes even during the planning phase. The practice of freezing hardware and a firmware system requirement well before design and testing begins is a sure way of getting locked into a sub-optimal solution early on. Instead applying minimal constraints enables new information or technology to be incorporated in the design. Pioneer researchers in the field of SBCE have captured the essentials of this principle by arguing that PD teams have less chance of getting locked into a sub optimal solution if they impose just enough constraint to function properly while allowing enough room to adjust and optimize (Sobek, et al., 1999).

Modular design: One way of fulfilling principles one and two of SBCE is to pursue a modular design. In a modular design typically the overall product requirements and sub-system interactions are defined. Decomposing the overall design into sub-systems not only helps making the task of designing more manageable, it also allows latitude for pursuing multiple designs for the sub-systems and finally helps in integrating the modules together since the sub-system interactions are fixed.

In our case it could to the discretion of the PD team to decide how best to decompose the product design. The decomposition of the overall product design could be done based on either the product's main functions or physical parts. Say, for example, the PD team is designing an oscilloscope and chooses functional decomposition, then the modules could be (a) data acquisition system, (b) signal conditioning system, and (c) communication system, as shown in Figure 5.9.

Rather than dividing the PD team into hardware and firmware development groups, the team could organize into sub-groups for each module comprised of hardware, firmware and manufacturing engineers. Even though the PD team retains the collective responsibility for meeting the QCT targets, the sub-groups are responsible for the design and development of the modules.

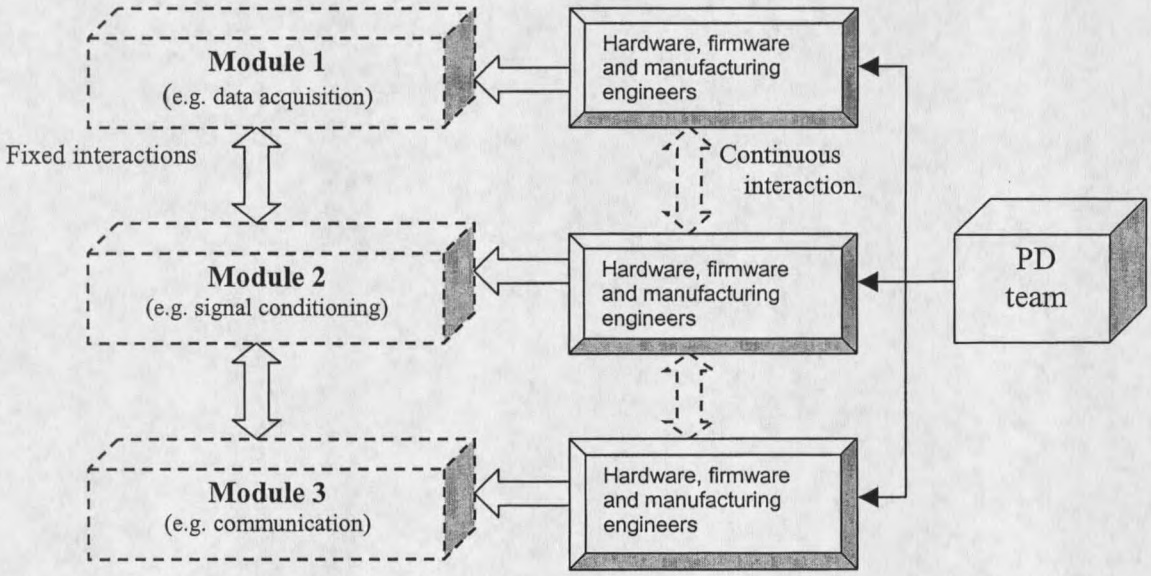

Figure 5.9 Example of a modular decomposition of PD effort

But for this kind of PD team decomposition to work the interactions between the modules need to be defined well and the design of the module is left to the discretion of the engineers responsible for the module. Clear definition of these interactions is necessary so that finally the designs of the different modules can be integrated fairly easily. Also by fixing the interactions between the modules but leaving the design of the

modules open to new information and further experimentation only minimal constraints are imposed as prescribed by the second SBCE principle.

The engineering group responsible for that module then can begin to try out the different concepts and develop designs from the feasible solutions chosen earlier. Designing should also be followed by prototyping and testing. Once the testing is completed and test data is analyzed the findings should be communicated to the other groups so that each group can then review their own designs while continually attempting to converge onto a handful of solutions (2-4 final designs).

EMS has a major role to play during testing and evaluating the different designs. While communicating design ideas the different subgroups should also plan and communicate the test protocol for designs. This will help them jointly develop a single or somewhat similar EMS that can be used across the different subgroups. To aid in evaluating design performance and also help engineers converge onto a few feasible designs the EMS should have two major capabilities. Firstly it should be capable of proving a comparative analysis of the different designs within the module. Secondly it should also be capable of integrating the test data from different modules and projecting the system level performance of the product when the modules are put together. This system level evaluation will help engineers in deciding the feasibility of their designs in terms of product performance.

This lays greater stress on active and continuous communication and interaction during experimentation so that feasible zones are understood even better. The model of

the new information management system explained in chapter 6 supports SBCE by facilitating continual communication and information transfer.

Principle 3: Establish feasibility before commitment

Sobek, et al., 1999, also view Toyota's entire SBCE as a system to fulfill this third principle, i.e. to ensure that designs are feasible before committing to them. Some of the ways in which Toyota ensures feasibility are by gradually narrowing the sets of solutions while increasing detail. The process not only involves generation and communication of ideas but also a decision process that gradually eliminates possibilities until the final solution remains.

In adopting SBCE once the development sub-groups have tried and tested a number of designs and communicated them to the other groups, they should narrow their ideas, integrate the designs and finalize 2 –3 designs that offer optimal solutions to the customer requirements. Then they should make detailed designs, prototype them and test them for all the functional requirements. At this point it is still not necessary to choose among the designs, 1 or 2 of these designs may still be integrated so that it offers a more optimal solution. But this process cannot go on forever because every project has time constraints, so the team should concentrate on staying within this narrowing funnel and attempt to make designs more robust.

As the product design converges and becomes more detailed the EMS design should also reevaluated and finalized so that a single EMS can be used for the final testing of the 1 or 2 final designs that have emerged. Manufacturing engineers can also

then directly or indirectly use the same EMS for pre-production testing purposes since they already had the opportunity to provide input to the EMS design.

At the outset the SBCE process seems laden with uncertainty and ambiguity, but on the contrary if the gates are used for integrating ideas, reducing uncertainty and converging on a detail design and not merely for review of progress then the process can be controlled better. Also rather than viewing the PD process as a network of tasks and timing the information flow between tasks the information transfer should be continuous process wherein structured[18] information is transferred as and when needed.

The design and development that goes on at all four companies is unique and so the three principles of SBCE described above are not recipes to resolve the integration and related PD issues faced by these companies but they offer a new perspective to C.E. SBCE also offers a better way of decomposing the design effort because integrating the development effort becomes easier. It not only lessens the effect of the hardware-firmware integration problem but also promises an optimal product design.

Managerial implications and downside of SBCE

Adopting SBCE has pretty significant implications on management styles and the PD process. On the surface adopting SBCE seems laden with uncertainty and ambiguity, but it is through this chaos that new meaning can be created (Nonaka, 1998). Managerial styles have to accommodate uncertainty by stressing continuous communication and

[18] Structured refers to standardized system of interactive written communication (explained in chapter 4).

coordination of engineering tasks. The PD manager has also to ensure that the development groups are not moving in divergent directions with their designs. The PD manager therefore needs to be a concept champion and ensure that ideas are continuously converging and decisions taken by the engineering groups are true to the product goals.

The PD gates, which are conventionally used for reviewing project progress, should be used for integrating ideas, reducing uncertainty and converging on a detail design and controlling the converging process. Also rather than viewing the PD process as a network of tasks and timing the information flow between tasks the information transfer should be continuous process wherein structured[19] information is transferred as and when needed.

SBCE requires a different mindset and engineers need to break from the conventional thinking of testing and proving one 'best' design. Uncertainty in the development process and extended periods of time spent in concept development also defies logic that hardware, firmware and manufacturing engineers are commonly accustomed to. Hardware and firmware engineers are also used to being divided functionally and breaking them off into hardware-firmware pairs will also require considerable adjustment on part of the engineers. The hardware and firmware engineers will also lack support from peers and interaction between hardware-hardware or firmware-firmware engineers will potentially decrease and as a result functional expertise may suffer unless additional measures are taken.

[19] Structured refers to standardized system of interactive written communication (explained in chapter 4).

Another crucial consideration is that if the convergence of designs is not managed well then the ideas may not converge and as a result the PD team will not meet its goals on time and the product will not be shipped. The problems in ensuring convergence also get compounded by the fact that more the number of modules in the design the tougher it becomes to converge the different designs.

But the most important consideration for management would be the cost involved in adopting SBCE. Radically changing the development process and having multiple development groups will definitely involve more engineering hours, more managerial control and thereby greater costs. Testing multiple prototypes will also strain testing resources and may require dedicated test equipment which is currently shared by many PD groups. Since SBCE also gives importance to continual communication and interaction, it might necessitate collocation of team members and effective channels for communication, such as web-based communication. This may require some investment in infrastructure also.

One strategy that might help management understand the cost implications completely would involve adopting SBCE initially for higher end projects only. The high-end projects are those that involve either major change in technology, development of new platform, or a 3-4 year project with major investment. The benefits from adopting SBCE for such a project may offset the costs involved and also help change the mindset of the engineers slowly.

Conclusion

Instead of making the PD process hardware centric these firms should encourage hardware, firmware and manufacturing groups to explore multiple design concepts independently, prototype and test them. Rather than dividing the development effort as hardware and firmware development they should stress on modularity and pair up hardware, firmware and manufacturing engineers for each module. These groups should then design and experiment on multiple concepts while attempting to converge onto a few feasible designs. Then through continuous communication and interaction converge on to one optimal design while always being cognizant of the constraint of time to market.

Adopting SBCE not only diffuses the complex integration problem that these firms face but also enables concurrent engineering in its true sense and therefore helps the PD team to develop an optimal design. Adopting SBCE and a modular design is not possible without an effort to develop a EMS that is capable of both testing and evaluating multiple designs and also providing evaluation of the system level performance of the product design as a whole. SBCE is also not completely possible without a flexible PD process and efficient and effective information management system. Issues related to information transformation were also investigated and theme that emerged (information transformation) as a result of qualitative data analysis is discussed in the next chapter.

CHAPTER 6

INFORMATION TRANSFORMATION

Analysis of the data revealed that the EMS is used for testing and data analysis prominently during the test phase of a D-B-T cycle (commonly known as board-turn in electronics manufacturing). The test phase was therefore examined more closely. The data revealed that the test phase involves two major activities, testing the prototype using primarily the EMS, followed by analysis of the test data using EMS and other analysis software. Recent research has also given considerable important to the 'analysis' aspect of the D-B-T cycle and researchers have gone to extent of expressing the D-B-T cycle as a D-B-T-A cycle (Thomke and Bell, 2001).

Analysis of the test data is crucial for numerous reasons, some of which are highlighted below.

- Analyzing the test data uncovers design performance information helping the designer understand the design space better.
- Analysis of the test data also helps reveal problems in the design and pinpoint the root cause.
- Analysis of the test data helps the designer compare design performance to product requirements and initiate the next design iteration.

Another reason why test data analysis is important is because it consumes considerable amount of development time. One of the premises of a world class PD

process is to reduce development time and introduce the product as fast as possible into the market (Iansiti, 1995). Therefore finding alternative ways of reducing the time required for test data analysis could help in reducing overall development time. The following section gives an indication of the proportion of PD time spent in test data analysis.

A typical D-B-T cycle in the four cases studied takes 6-12 weeks, of which the test phase consumes approximately 1/3 of the time, i.e., 2-4 weeks. Within the test phase time spent on actual testing was small, (approximately 1/5 of time of the test phase) as compared time spent in capturing, processing, interpreting, analyzing and transferring test data. Over the course of several D-B-T cycles in a typical development project, the time spent for test data analysis can amount to as much as 6 to 8 weeks, which is a considerable amount of time. Thomke also carried out a similar exploration and found that typically engineers spend 70% of their time either looking for or managing data and information. (Bell and Thomke, 2002).

During the course of this research we focused our attention on the activities that constituted the test and analysis cycles over the period of the entire project and also documented the chronological flow of activities and information during each D-B-T cycle. The data revealed that test and analysis activities at the four cases could be classified into five categories (see Figure 6.1).

1. Data generation: Setting up the test system, writing the test code and running the test.

2. Data capture: Using multiple means to gather the different forms of the data generated by the EMS.
3. Information creation: Conducting preliminary analysis using the EMS and detail analysis using other software tools. Analysis involves converting signals, outputs, and waveforms into design performance information.
4. Information capture: Storing the test data and results of the data analysis in engineering files or PC's and then transferring it via electronic data transfer or a report.
5. Knowledge creation: Creating knowledge about design performance by communication the results of the test and then conducting joint data analysis with team members.

Further analysis of the test and analysis cycles helped uncover the information transformation process, by which data is transformed into information and then into knowledge about the design performance. This chapter first explains information transformation, it's importance in NPD, especially D-B-T cycles and the role EMS plays in it. Secondly, this chapter also presents a new model of an information management system that potentially facilitates information transformation and expounds on the possible implications the new model has on the design of EMS.

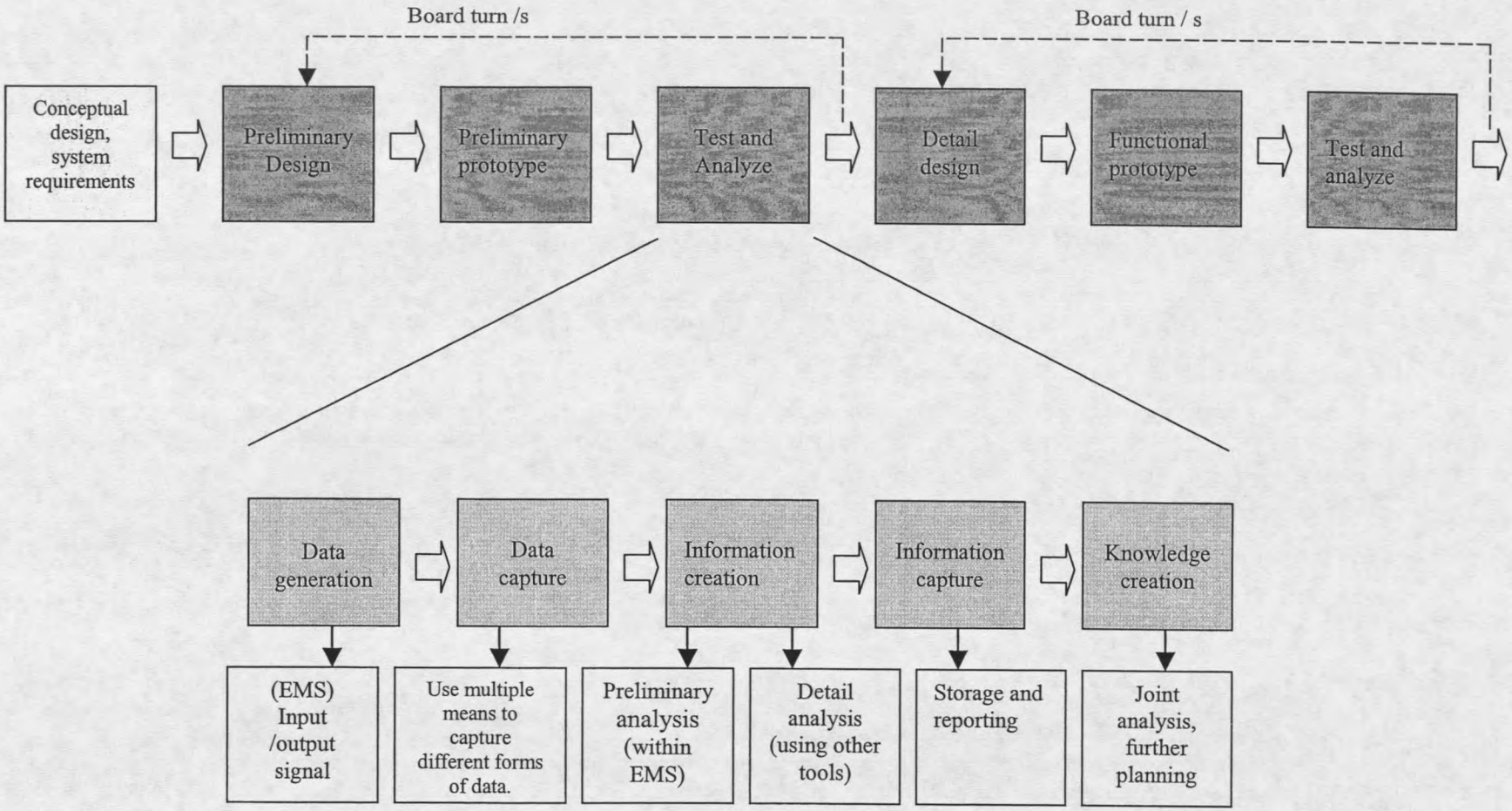

Figure 6.1 Information transformation process

Information transformation process

Information transformation is a crucial aspect of every D-B-T cycle because only after design performance is evaluated can the design be improved. In the information transformation process, test 'data' is processed and converted into useful 'information' that is then applied to create knowledge about the design performance.

Data are raw numbers or facts that have not been organized or interpreted and therefore has little use (Court, 1997). When data is revealed in a certain context and meaning is attached then it becomes 'information' and is useful for learning about the performance of the design, for instance (Court, 1997). Knowledge is the state of knowing. Knowledge is connected to the mental activity of recoding and understanding data and information and applying it useful tasks (Court, 1997).

The transformation from data to information occurs as a result of the complex interactions between the different elements in the information transformation system. The elements in the system include the test engineer (typically hardware engineer), PD team, EMS, and data capture and analysis tools. Typically the hardware engineer directly interacts with the other elements to generate tests data and convert it into information and then into knowledge about design performance.

The following sections reveal the information transformation process in depth with respect to preliminary and detail design.

Information transformation during preliminary design

The number of D-B-T cycles (or board turns as they are known in this industry type) per project varied across the four firms, based on the complexity of the product and the experimental strategy adopted by these firms. Another distinction between D-B-T cycles was observed during preliminary design and detail design.

Typically preliminary design consists of converting the concepts into a design that does not represent the final product either in fit or form. A preliminary design is commonly made to test the main modules or components of the PCB.[20] The design engineer may need one to three D-B-T cycles (or board turns) to reach a satisfactory preliminary design. Detail design on the other hand consists of converting the tested and proven preliminary design and converting it into the final design. This design typically resembles the product design in fit, form and function. The EMS used for testing this design is usually also used for testing the final product. Detail design may also require 1-3 D-B-T cycles based on how well the preliminary design was carried out and how complex the final product is.

The following sections describe the information transformation during a typical D-B-T cycle within preliminary and detail design.

Typical D-B-T cycle during preliminary design

The engineers at the different firms use CAD tools such as HCAD or PCAD to convert schematics into a preliminary layout of the PCB. These design files are then sent to a vendor or to manufacturing to build a partial prototype and then preliminary

[20] Printed circuit board

firmware is downloaded into it. This prototype does not resemble the final product in either fit or form but consists of main components assembled together even by crude means if necessary.

Testing this preliminary design typically consists of checking whether the different components on the PCB are communicating with each other, functioning properly and capable of generating signals it was designed to produce. To accomplish this, the engineer typically writes a test program using Lab view, C++ or Pascal and also designs the EMS. The hardware engineer then downloads this test program into the EMS, which commonly consists of instrumentation such as oscilloscopes, voltmeters and signal generators connected to power sources and a PC, as illustrated in Figure 6.2.

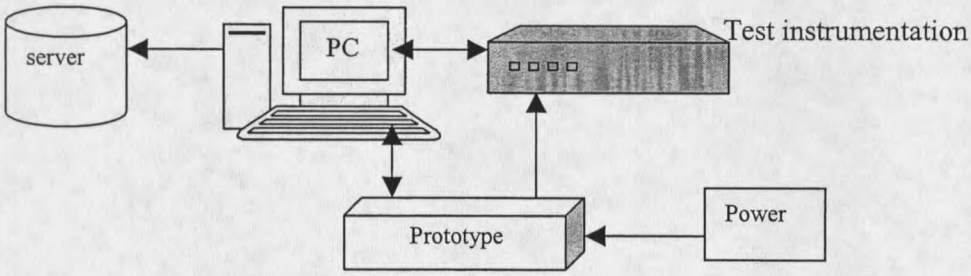

Figure 6.2 Typical EMS to test preliminary design

Information transformation

The hardware engineer then runs the test program, and the EMS sends different inputs such as signals and waveforms to the prototype to test the all the design parameters. The common forms of outputs from the prototype are waveforms, digital signals and other numerical values, which are monitored and captured by the EMS.

If the outputs are waveforms then the engineer records the means and amplitudes of these waveforms or freezes the instrument screen, captures the waveforms and prints it on paper. If the outputs are signals, (e.g. volts and amps) then the engineer either records these values in engineering notebooks or saves the values in a computer file. Often the EMS is programmed to send the tests data directly to the server for temporary storage.

The engineer can then download the test data onto his/her desk PC and compile data from previous tests to compare it to the theoretical or design values. The test values or waveforms are usually plotted against theoretical values for comparison and deviations are recorded. Typically the test data along with the analysis carried out on it is either recorded in engineering notebooks or saved on a computer file which is then sent to the central server. Other functions on the team such as software, quality or manufacturing engineers can access this information if the need arises.

The engineer then reviews the design; records all the firmware problems then typically compiles a test report. This test report outlines the test carried out and presents the results of the test and recommendations. This report is commonly sent to firmware, manufacturing and also goes into the product data file. The product data file a document that tracks the progress of the project. This file usually contains all engineering information regarding the development of that product including marketing data and product specifications, CAD drawings, test data and results of analysis, minutes of meetings and related technical information.

By carrying out activities starting from writing the test program to compiling the test report the engineer effectively converts test data into information useful for

evaluating the performance of the preliminary design and deciding the changes or improvements needed.

While the hardware engineer is reviewing the design the other functions on the PD team, mainly firmware, quality and manufacturing engineers are either carrying out their own tests on the prototype or reviewing the test data provided by the hardware engineer. For example, firmware engineers run their own tests based on the firmware system requirements and then compare the results of their data to the one provided by the hardware engineer.

This is typically followed by a joint review session during which the different functions inputs to the preliminary design from their perspective. For example, manufacturing engineers attempt to highlight design for manufacturability (DFM) issues, and firmware engineers highlight hardware-firmware interface problems. The team tries to reach some consensus on how best to meet the hardware and firmware system requirements while incorporating recommendations from quality, reliability and manufacturing engineers. These dynamics between the team members helps increase knowledge about the current design performance and also paves the way for the next design iteration. Figure 6.3 illustrates the information transformation for a typical board turn during the preliminary design phase. The next design iteration is either another D-B-T cycle (board turn) within preliminary design or the engineers might progress to detail design.

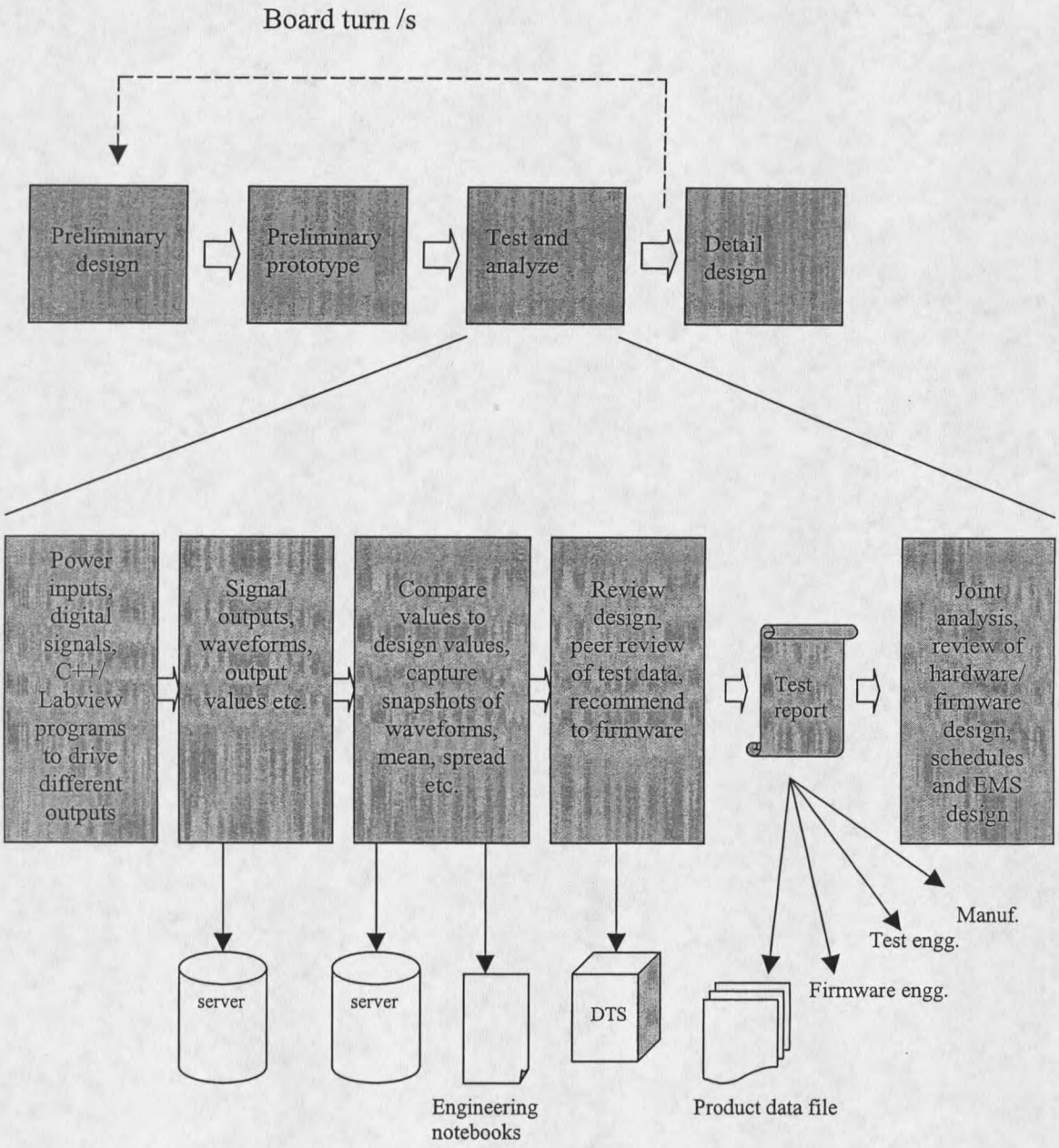

Figure 6.3 Information transformation during preliminary design.

Information transformation during detail design

After completing 1 to 3 D-B-T cycles of preliminary design, if the engineer is satisfied that the components are working and that the different sub-modules are communicating with each other, then detail design starts. Detail design incorporates all the components and closely resembles the final product in fit, form and function. A final layout of the board is made and then sent out to a vendor or to manufacturing for prototyping.

To test this prototype the engineer writes the final test program and also designs the EMS, which typically involves adding new instrumentation to the EMS designed for testing the preliminary design. Depending on the nature of the design (i.e., how close it resembles the final product) the EMS maybe an automated test system. An automated test system typically consists of a standard set of instruments commonly needed to test all design parameters connected to the prototype and driven by a PC. The design of this EMS is critical because manufacturing usually bases the design of their test system on this EMS and often uses the same test code. Figure 6.4 is a schematic of such an EMS.

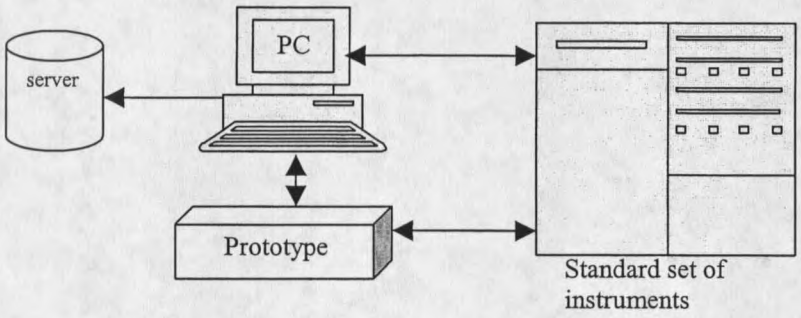

Figure 6.4 EMS for evaluating detail design performance

The design engineer programs the test software to send multiple signals that will test all the functions that the product is supposed to fulfill, including communication and waveforms. The outputs are most commonly seen on the instrument screen or recorded by the EMS. Most common outputs include digital values, waveforms and time domain plots for all critical outputs. The EMS is typically programmed to collect the test data, save it as an ASCII file, and upload it onto the server. Figure 6.5 illustrates a typical D-B-T cycle process and information transformation during detail design.

As compared to preliminary design the EMS also plays a slightly bigger role in transforming this test data into information by plotting time domain plots, generating documents that show outputs vs. inputs, deviation and remarks on whether the test was passed or not. The tests data analysis provided by the EMS is also uploaded onto the network and saved in the product data file.

The design engineer then analyses this test data for consistency of outputs, compares it to previous test data and design values. Statistical analysis is commonly carried out which includes determining Cp, CpK, S.D. values for the various outputs and times series data. Some graphical analysis is also done such as plotting histograms and line graphs for time series data using commercial software like Excel. Other forms of analysis include mathematical analysis like Fourier transforms using software such as Mat lab. The hardware engineer also attempts to make a distinction between hardware and firmware defects based on the tests data and previous experience. This test data and analysis is saved onto the server so that the other functions can easily access it for their own analysis. The engineer then typically compiles a report of test data analysis and also

comments on the performance of the This report is sent to the other functions on the team including firmware, quality and manufacturing engineers for their own analysis. By carrying out all the above activities the hardware engineer acts as the chief agent in facilitating information transformation.

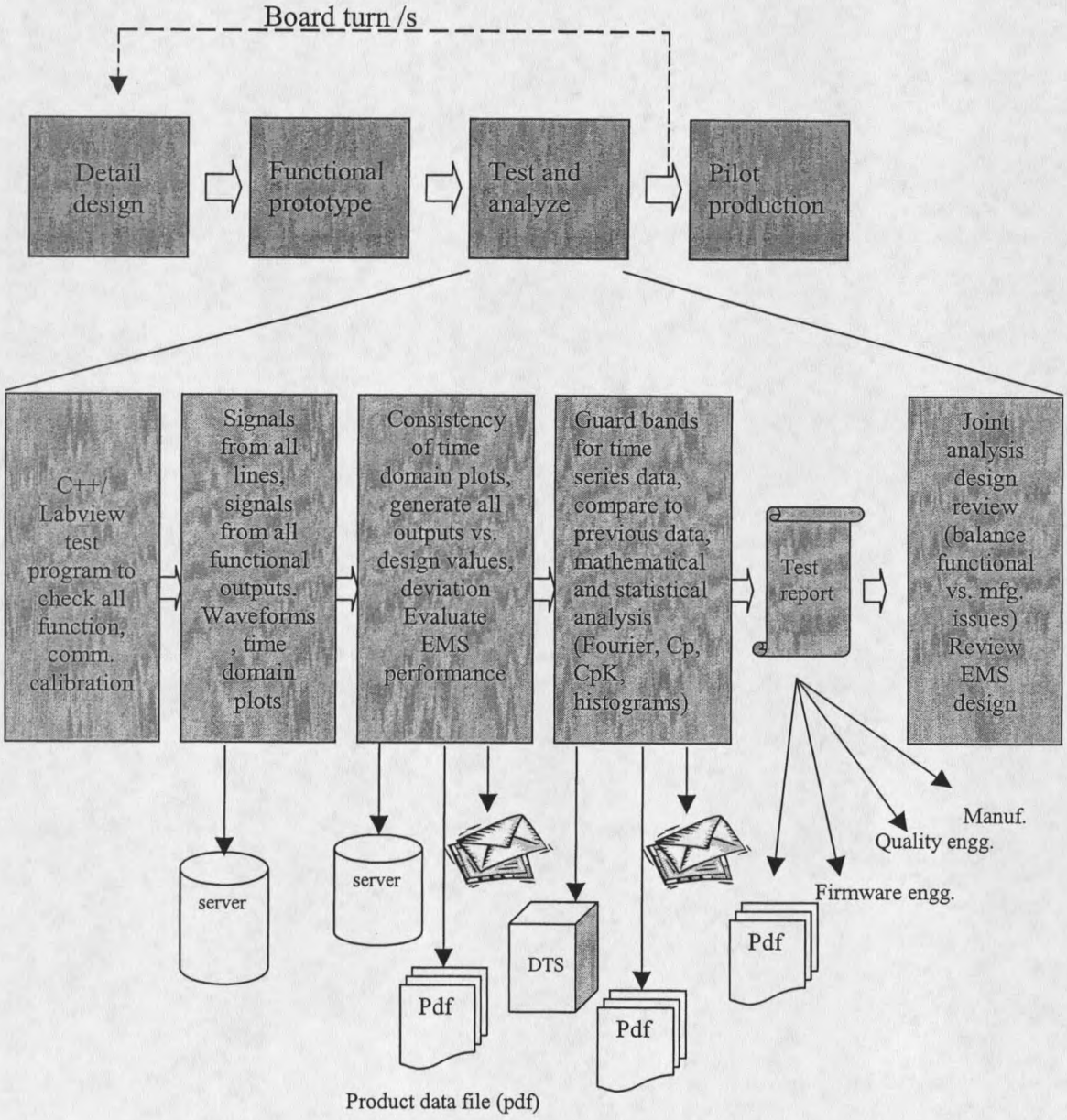

Figure 6.5 Information transformation during detail design

Then while the hardware engineer is reviewing the design, typically the quality or reliability engineer is using the test data to determine whether the design meets industry or company quality and reliability standards. The firmware engineer may also be carrying out test using the hardware prototype and comparing the results to the ones provided by the hardware engineer.

The design review that typically follows focuses on finalizing the design and resolving all issues related to firmware, manufacturability and reliability. A balance is usually struck between functional and manufacturing requirements in the design. The final test protocol and EMS design is also commonly discussed and finalized so that manufacturing engineers can start planning for pilot production and testing. Dynamics of these cross-functional discussions give rise to knowledge about the performance of the design and pave the way for a decision as to whether another the next design iteration is needed. This decision also signals the end of information transformation for this D-B-T cycle within detail design.

If the engineers are convinced that the design fulfills the product requirements then the design is frozen and pilot production is attempted. Otherwise the engineers initiate another D-B-T cycle (board-turn). Typically after 1-3 such board turns the design is frozen and all the necessary engineering documentation is compiled and added to the product data file and handed over to manufacturing for pilot production. During pilot production the engineers help solve problems in the design and also aid manufacturing engineers in testing the final product. This phase more or less signifies the end of the development process.

In summary, testing the preliminary design and analyzing the test data is typically simpler in comparison to detail design. The information transformation process during preliminary design is also less complex. The amount of test data generated and the amount of analysis needed and its complexity is also more during detail design. The hardware engineer has also to interact with many more elements such as different analysis software during detail design. On completion of the test during detail design many more people share the tests data analysis. The subsequent interaction between the team members is also far more intense. But the steps involved in information transformation remain more or less the same.

Transformation of data to information

Information transformation involves generating test data using EMS, capturing the data, and analyzing it using different tools, thereby converting it into information, storing and transferring this data and finally converting it into knowledge through interaction and discussion with other team members. From the description of information transformation during preliminary and detail design it is evident that the steps involved in information transformation more or less remain the same. Data is generated, and then captured, information created by analyzing the data and this information it is then converted into knowledge about design performance by sharing this information and subsequent cross-functional interaction and communication.

The role of the EMS during the information transformation process is however restricted only to generating the test data and conducting some preliminary analysis. It is

the engineer (typically hardware engineer) who does the major chunk of the work in transforming data into information with the help of the other elements in the information transformation system.

As seen in Figures 6.3 and 6.4, managing the process of information transformation requires numerous elements and complex interactions between them. To generate design performance information the design engineer has to be capable of interacting with the EMS, different test and analysis software, and other engineers. The information transformation process through which the design performance information is generated is a time-consuming process, and consists of complex interactions between the elements that constitute the system. The term system is used to signify that there are many elements (e.g., engineers, software) in the system that interacts with each other to transform information.

The elements of the information transformation system include the other functional members on the team, CAD tools, test software, analysis software and the information management system. The coupling between these elements is loose; typically the hardware engineer is the primary integrating factor. For example the CAD system does not talk to the EMS, nor is the test software integral to the EMS, nor does the analysis software integrate with the information management system (i.e., analysis tools cannot transfer data analysis to the server). The human element in the system (typically the hardware engineer) forges the links between these elements, as shown in Figure 6.6. It is the engineer who learns the test software, and writes the test code and downloads it onto the EMS. The engineer also has to choose the analysis software, learn it and then

apply it. The engineer has also to download the test data from the information management system (e.g. server), analyze it and transfer data and reports using existing information management system (e.g. computer network). The linkages between the other elements are weak (as shown by dashed lines) or non-existent.

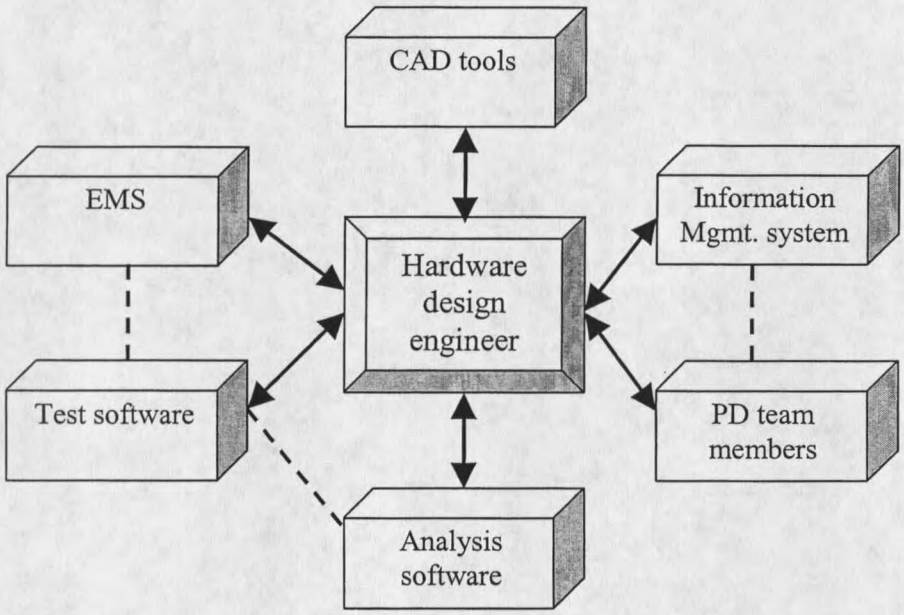

Figure 6.6 Elements of the information transformation system

Implications for EMS

From the information transformation process it is evident that EMS is currently only one element in the system. So even if the EMS were made faster or more versatile it would not offer substantial benefits in terms of reducing developing time or effort. To optimize one element in the system (i.e., a faster and more versatile analysis software) without a mind to optimize the information transformation system as a whole, would most likely have limited impact on development speed and flexibility.

System performance will improve however, when the linkages are made more efficient. When the interactions between the different elements are made more seamless, the information transformation process as a whole will improve, which should reduce the overall development lead-time weeks if not months.

One way to improve the linkages is to enhance the capabilities of the EMS is by enabling it to take over the role of other elements in the system. Combining some of the elements involved in information transformation, for example, combining test software / analysis software with the EMS, could hold positive gains. In such a case, the engineer would then have only to interact only with the EMS to run the test, capture and analyze the test data. The fewer linkages that the engineer has to manage the easier and faster the information transformation process will be.

It is primarily data and information that is flowing during information transformation within a D-B-T cycle. Therefore another alternative of making the information transformation process more efficient would be to enhance the role of the information management system.

Enhancing the role of the information management system.

Information management has been given considerable importance in the literature and numerous researchers have stressed on managing this resource better (refer to chapter 2, pp.19-27) At all four firms the information management system is only used to store data so that team members can access it easily. But the role of the information management system could be extended from just that of a common means of storage and

retrieval to that of managing the linkages between the system elements. It has untapped potential for making the process of information transformation seamless and faster. Shifting the onus of establishing linkages between the system elements from the engineer to the information system holds numerous benefits for the PD process. At the end of his study of Sony, (Numata, 1998) proposed a new model of an information management system that links different elements involved in PD and makes information management more efficient.

The model of the information management system illustrated in Figure 6.7 is similar to the model conceived by Numata and currently adopted by Sony. But the model in Figure 6.7 is only a concept and does not represent a tried and tested solution. It is aimed at redefining the links between the elements in the information transformation system and making the information transformation process more seamless. This model also has a positive effect on the links between the human elements in the system.

The new information management system mainly consists of two main elements, the information acquisition system that stores current information, and the knowledge base that stores past product information. Both are accessible to all the team members through the standard data interface, which interconnects all the PC 's used by the PD team.

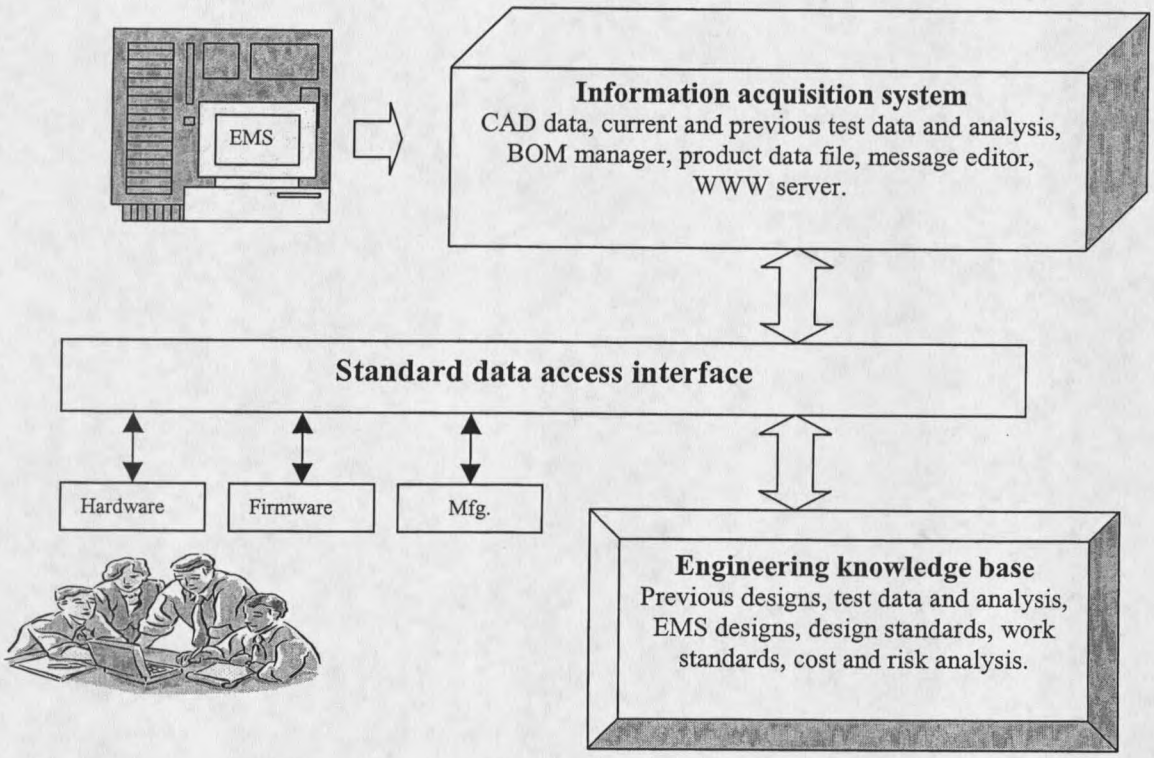

Figure 6.7 New model of the information management system

Key elements of the information system

Information acquisition system: The information acquisition system consists of the tools that are needed for generating design performance data, converting it into information and storing it. The structure of this system remains common across all the PD projects carried out by the firm. But the contents of this module are customized for the project in question. The information acquisition system contains all the data and information that is generated from the start of the project, which includes CAD data, test

data and analysis, BOM database and the product data file. This system is volatile in the sense that it is current and being updated as PD progresses.

Another characteristic of the information acquisition system is that it is capable of managing soft information. This is possible because all of the formal and informal communication that takes place between the team members through e-mails and reports is structured and stored on the system. For example consider a typical case when a certain hardware test has been completed and results are made available on the acquisition system. The subsequent online discussions between the firmware and hardware engineers are crucial in deciphering the test data and results. The system stores this discussion and links it to the test data and this could help other engineers do their job more effectively. For example, the manufacturing engineer can view all the test results as well as draw conclusion from the discussion between the hardware and firmware engineers and take decisions instantly rather than wait for the next meeting to get inputs from others. Having all the necessary information potentially helps effective and efficient decision making at the end of the D-B-T cycle. The quicker decisions are made the faster the PD effort will progress.

An important consideration for the design of this system is to establish compatibility for the different software that are used. The system must be capable of absorbing all forms of data, establish compatibility, and store it. For example the system must be capable of storing CAD data, EMS test and analysis data and store it and present it to team members through one interface.

Engineering information server: This module stores the knowledge base of the company and is common across all development projects. Its purpose is to prevent the common mistake that almost firms make of 'reinventing the wheel'. It carries lessons learned from previous development project and helps engineers build on the knowledge of others. It stores previous designs (product as well as test system designs), test and analysis data and related engineering information.

Design standards are also carried by this database, which are not industry standards but rather company standards born from successful products. When a firm designs, develops, tests and successfully launches a new product the engineers can use the design and convert it into design standards which at least ensures that if future design meet the same standards there is some confidence that the design will not fail. This aspect of formulating designs standards is absent in Numata's model currently adopted by Sony. This idea resembles the principles successfully adopted by Toyota. At Toyota, lessons learned from one project or success stories at one plant are converted into company standards and adopted across the firm (Sobek, et al., 1998).

But design standards that are to be used as benchmarks are critical and therefore needs to be fool proof, i.e., they need to be comparatively static. By static we mean that information in the knowledge base should be updated infrequently as compared to the information in the acquisition system. But yet they must be kept relatively up-to-date to ensure their usefulness. Information from the information acquisition system should go into the knowledge base on completion of the project and after comprehensive checks

and filtration. Since this knowledge is the asset of the firm the software should be company specific so that the knowledge is retained within the boundaries of the firm.

Standard data access interface: This is an interface used to access both the information acquisition systems and the knowledge base. All the PC's used by the PD team including the ones on their desks, in labs, are interconnected so that information can be sent to or retrieved from the other two modules. This also enables the PD team members to effectively communicate and interact with each other via e-mail or instant messaging.

Summary of important characteristics of the new information management system

This model of an information management system has many attributes that make it more effective than current systems in managing engineering information for NPD.

- The information system manages the linkages between the elements of the information transformation system rather than the engineers.
- Process is standardized for entire PD not team or functions.
- It encompasses standard written communication from standard data access interface to information acquisition system and is also capable of handling soft data. (refer to discussion on information and knowledge management in chapter2)
- Systematic and precise information is available to the PD team at all times, so it also ensures timeliness of information. (refer to discussion on information and knowledge management in chapter 2).

- All sources of information needed for decision-making during testing and data analysis are available at one location.
- Supports SBCE because it makes continuous interaction and communication easier.

Applicability of the model

To consciously reorganize and improve the current information management system and model it on the lines of the one shown in Figure 6.7 will require investment both in terms of capital and effort. It will also require a new infrastructure, relevant training, and investment of considerable engineering hours since PD engineers need to be actively involved in its development.

The most important consideration for this model is to establish compatibility of the different software that are commonly used in PD, predominantly during designing and testing. Both, the information acquisition system and the engineering information server must be capable of absorbing all forms of data, for example CAD data, test data, analyzed data and store it and then present it in one interface. Ideally commercial software that could be standardized across the firm could accomplish this. But currently such software is not readily available.

An alternative means of designing this system could be by making use of a Unix or Windows environment. If the firms choose to adopt a new Unix/Microsoft environment or modify the current one, they need to first classify the different types of

data and information and software either into client or server type. The 'client' includes workstations commonly used by the PD team that contain the user software, such as the CAD and test software. The major part of the two modules, information acquisition system and information server is the 'server' that stores and manages the engineering information. This Unix or Microsoft environment should be designed with certain privileges for accessing and updating data and information in the new information management system.

In a typical instance when the hardware engineer finalizes a design and saves it on the 'server', other team members can access it. They may suggest changes using another CAD document or Word file, which then gets attached to the original CAD file. But only the hardware engineer has the privilege of doing engineering changes.

Similarly the hardware or test or firmware engineers can view the design and plan the EMS and test protocol accordingly and then store the information back onto the server. When a test is carried out, the test data along with the analysis can be stored onto the server, from where the firmware engineer can access it and do his/her own analysis. Any similar tests carried out by the firmware engineer or any feedback offered can also be made part of the original file. At the same time other functions such as manufacturing engineers can be given 'read' privileges, allowing then to access the EMS designs and test results for facilitating their own planning.

The back and forth communication that commonly takes place between engineers viewing the test results can also be integrated with the test information. Thus any PD team member accessing the test information file on the server is updated not only with

the latest information but also with reactions and comments provided by other team members. This environment therefore promotes continual virtual interaction between team members.

But choosing to redesign the information system will require considerable effort in designing, installing and running the new system. The minimum costs of installing and running such as system can be roughly estimated at around 200,000 $ /year. But once it is in place, PD organizations will likely reap benefits in terms of seamless integration between the elements in the information transformation system. Faster information transformation is closely linked to shorter development cycles and therefore offers potential savings since new products will now be developed faster.

Information system and PD organization

The PD team will need to define the structure of the information acquisition system and procedures for managing information that best suites the needs of the project. These procedures need to be defined at the start of the project, which can then be made into standard operating procedures (SOP's) for the duration of the project. Since the new information management system is designable to a certain extent it suits both the heavyweight as well as the lightweight PD team.

The knowledge base within the new information management system should be comprehensive, i.e., contain all kinds of engineering information needed for NPD. It will therefore be suitable for any development project that the firm chooses to undertake. The new information management system can also be easily designed to handle information other than engineering information, such as logistics, cost and project planning data. This

can be beneficial both to project managers and also other functions who are related but typically not a part of the PD team such as procurement engineers. Its applicability can therefore be easily extended to serve the entire organization.

Information management system and management

Top management needs to provide resources for designing and maintaining such an information management system. The project manager on the other hand has to ensure that PD team updates the system continually and ensure that the system is functioning properly. The information managements system in turn could help the project manager to monitor progress. This is because it is capable of storing both technical as well as project management data (e.g. schedules, task dependencies etc). The information management system can potentially help the manager to coordinate PD activities and view problems that might potentially delay the completion of the project.

Information management system and the PD process

The PD team has to redefine its operating procedures for managing information so that they are integrated with development activities. The information system will in turn ensure continuous communication between the different functions within the PD team and as a result issues gets highlighted and hammered out sooner rather than later. To exploit the benefits offered by this model, PD engineers should make the system central to all the engineering activities and stress on continual interaction via the new information management system.

Since the engineers will now have different kinds of information such as design information, test data, analysis software, information about previous designs available at one place and also easily accessible decision-making will be potentially faster. The flow from one D-B-T cycle to the next will therefore not only be smoother but the overall development time will also reduce.

Summary

In this chapter the information transformation process, through which test data is transformed into useful design performance information, has been introduced. The information transformation process was then explained in context of preliminary and detail design. It was also shown that the information transformation process is result of the complex interaction between the different elements in the information transformation system.

Understanding the information transformation process is critical to redefine the role of EMS in the PD process. In the course of discussion it was also established that the role of EMS could be enhanced by effectively managing the linkages between the different elements in the information transformation system.

To accomplish the above and also reduce overall PD development time a new model of an information management system was introduced and its constituent elements, working and probable benefits explained. Along with this the possible implications the new model will have on the PD organization and processes was also

discussed. The last section of this chapter discussed the implications of the new model on the PD organization and processes.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The primary goal of this research was to better understand the role of electronic measurement systems (EMS) in new product development (NPD). The project evolved into addressing two research questions:

1. How is the EMS used in the design-build-test cycles of electronics product development?
2. What is the role of EMS in the management of engineering information at these firms?

To address these questions, an in-depth investigation was carried out into the PD process at four diverse electronic firms. Data was collected through semi-structured interviews and analysis was carried out using qualitative data analysis techniques, namely grounded theory. The analysis resulted in two major themes, hardware-firmware-test integration triad and information transformation. Chapter 5 and 6 explain these themes and also the role of EMS in them.

The main purpose of this chapter is to provide some conclusions on how the EMS could be used in D-B-T cycles and management of engineering information. This chapter also provides some related recommendations on how PD at can be improved at the four firms in our sample and then concludes with directions for future research.

Enhancing the role of EMS in the H-F-T triad and D-B-T cycles.

The Hardware-Firmware-Test integration triad results from the common practice of breaking the development effort into separate hardware and firmware development

cycles that must then be integrated, often with great difficulty. This integration problem gets compounded because these two groups must also develop test systems (EMS) for testing their designs. The H-F-T triad gets further complicated because manufacturing is also trying to ensure design for manufacturing (DFM) issues are being considered and that engineering EMS is suitable for manufacturing tests system.

Effectively integrating the development efforts of these three development groups to ensure that the CQT targets for the product are met become a major task for management. As explained in chapter 5, management at 3 of the 4 firms attempts to address this issue by offering mostly organizational solutions. These include defining the hardware and firmware requirements at the beginning of the project and then making then the basis of all further discussions and interactions between the groups. These firms typically freeze the design concept even before the testing phase and then go about a structured way of development so that further problems and conflicts can be prevented. Once the design concept is frozen they test it, resolve hardware-firmware issues and iterate on the same design. These strategies don't necessarily guarantee that the result will be the optimal design because the entire design space has not been mapped. This thesis suggests an alternatively that adopting Toyota's set based concurrent engineering (SBCE) approach instead of the current hardware centric point-based concurrent engineering approach will not only help simplify the integration problem but will also offer a better design to meet product requirements (Sobek, et al., 1999).

One way of being set-based requires engineers to come up with multiple concepts, build partial prototypes and test them. Adopting SBCE will also have implications for the design of the EMS. Secondly the literature review has also established the importance of

frequent and early experimentation by means of prototyping and testing (Thomke, 2001). The literature review has also highlighted the advantages of testing in parallel instead of sequential testing. To support these strategies, the EMS therefore must be capable supporting early experimentation, and also capable of providing a comparative evaluation of the performance of multiple designs. A single EMS should be capable of testing all the prototypes, aid the engineer in analyzing the data and also provide a comparative evaluation of one design against the other.

To achieve this the current capabilities of the EMS could be enhanced in a number of ways. To aid early experimentation the some form of simulation capabilities could be made part of the EMS. None of the firms in our sample used any form of simulation to anticipate the possible performance of their designs. The designs were mainly based on the designer's knowledge and previous experience. The only evidence of any early experimentation was the breadboard that engineers sometimes build to test some critical aspect of their designs. If some form of simulation could be integrated with the EMS then the engineer could potentially build a breadboard, test it using the EMS and then simulate the remaining parts of the designs that were not bread boarded. Even though it is difficult to simulate the entire design in one instance and understand the complete working of the printed circuit board (PCB), a building block principle could be used. The engineer could breadboard and test one part of the design, then simulate another part, evaluate the performance and then redesign and simulate further. This capability will not only help the engineer understand the design better but also possibly anticipate problems earlier rather than during actual testing.

One way in which the EMS could support multiple designs and parallel experimentation is by having the capability to be connected to multiple prototypes, send out the same input signals to the prototypes and record the output signals concurrently. These outputs would then be stored and at the end of the test the EMS would be able to organize this data, provide some form of preliminary and analysis including a comparison and contrast of the outputs from the multiple prototypes. This form of preliminary analysis would greatly help the engineer in evaluating the performance different designs. This capability would work on prototypes that represent designs that are somewhat similar, for example designs with similar components but with alternative layouts.

But in case that the prototypes represent designs with alternative technologies or components then the EMS will need a different set of capabilities. The EMS will still need to test these prototypes in parallel because testing them sequentially will not only consume more testing resources but also engineering hours. The EMS will now need to store multiple test programs and run the tests in parallel. The combination of test instrumentation that is part of the EMS may be different as compared to the first alternative. The EMS should be capable of sending different input signals and recording the outputs. At the end of the test the EMS should aid the engineer in organizing the test the test data, analyzing it and evaluating the performance of the different prototypes against some common parameters.

Another means of enhancing the role of EMS in D-B-T cycles would be by providing it with the ability to store test data, analyze it and aid the engineer in learning more about the design space as further tests are carried out. This capability would potentially help the engineers learn about the design space even more and aid

development of further designs. This may require the EMS to have some form of artificial intelligence and a large memory. The EMS should be capable of storing the results of a test and when data from the next test come in, analyze the new data and compare it to the previous data. If the EMS could trained or programmed to provide the engineer with a summary of how the design is progressing through the successive D-B-T cycles then the engineer could potentially understand the design space faster. Consequently fewer D-B-T cycles would be needed to meet product requirements and overall development time could be reduced.

Chapter 5 has also shown that pursuing modular design is another way of being set-based. The EMS could potentially aid engineers involved in designing and testing different modules to finally converge their designs onto a few feasible ones. To help accomplish this the EMS should made capable of integrating the test data from different modules and projecting the system level performance of the product when the modules are put together. This will require the EMS to have multiple capabilities; it must first be capable of comparing the performance of different prototypes and then evaluate how the test results from one module match the other. But to able to project the system level performance of the whole product with the information about the performance of the modules, the EMS will need some kind simulation capabilities. With a combination of simulation capabilities and available test results the EMS could estimate how well the product will function and meet the overall requirements. Any system level evaluation if made possible will help engineers in deciding the feasibility of their module designs and help them improve the design and finally converge onto an optimal product design.

Enhancing the role of EMS in information management.

Currently one of the major roles of EMS is to generate and store test data. The role of the EMS in design-build and test (D-B-T) cycles, especially in managing engineering information was therefore studied in-depth. The theme that emerged after data analysis is the information transformation process. Information transformation is the process by which test data is transformed into useful information and then into knowledge about the design performance. Information transformation is one of the most critical and time-consuming activities within the D-B-T cycle. Information transformation takes place through a complex interaction between many elements, including the hardware engineer, test and analysis software, EMS, information management system and team members. If the links between these elements are managed better then information transformation could be more seamless and faster, and consequently D-B-T cycles will become faster.

Recent PD literature has also given considerable importance to effective management of engineering information to enable engineers to get designs right the first time, reduce development costs and ultimately enable D-B-T cycles to become faster (Nonaka, 1990), (Numata and Maeda, 1998). In the literature review chapter certain attributes were directly linked to effective information management, which included ability of the information management system to aid interpersonal communication, ensure timeliness and accuracy of data, and ability to capture soft information.

This thesis suggests two ways of effective management of engineering information for NPD. The first suggestion involves adopting a new model of the

information management system that has been explained in chapter 6. The new model not only makes the information transformation process simpler but also provides the PD team with a common means of communication and availability of engineering information.

The second alternative for improving the current information transformation process is to enhance the capabilities of the EMS. The EMS currently is one of the main tools that aid help the engineer manage test data. However the engineer generating the tests data (typically the hardware engineer) has to interact with other elements such as test and analysis software to effectively generate the data and convert it into useful information (refer to discussion on information transformation in chapter 6 and Figure 6.5). Say for instance the test and analysis software were to be made integral to the EMS then the hardware engineer would have to manage fewer links and interact only with the EMS for all the testing needs.

Secondly the EMS could more effectively support the new information management system or any existing one if there was better connectivity between the two. This might require the EMS to be integral to local area network (LAN). Better connectivity will not only ease data transfer but also help the engineer access other software needed for analyzing the test data. In a typical situation while the test is being carried out by the EMS, the engineer could need access to some software or design information stored on his/her desk PC, that is not normally stored on public folders. Examples of this kind of information include engineering calculations, or test data analysis from previous designs. If the engineer can access this kind of related information with ease then the test and subsequent test data analysis will be completed that much faster. The test data, analysis and results from the test can also be stored on the server and

thereby easily accessed by other team members. The team members may still need to have a joint design review to resolve issues, but easier accessibility and availability of the test results will enable team members to do their own analysis and come prepared to the review session. This kind of system helps enhance two essential qualities of any information management system, which are, availability and timeliness of information. Current PD literature has highlighted these qualities as being crucial to good decision-making and problem resolution (Court, et al., 1997) (Lynn, 1998).

Thus by improving the connectivity between the EMS and the information management system the information transformation process will get a boost and help make the D-B-T cycle that much faster.

The new information management system along with the new capabilities of the EMS presents a solution for effective management of engineering information during D-B-T cycles, which in turn could have a profound effect on reducing overall PD time.

Other suggested improvements in PD processes

Enhancing the role of the EMS in D-B-T cycles and in the management of engineering information is one alternative of improving the PD process. The data collection also revealed a few other opportunities for improving the PD process at these firms. Analysis of the data collected also involved benchmarking PD practices followed at the four firms and comparing and contrasting them. When this benchmarking data was compared to literature on current world-class PD practices, it offered many insights. The suggested improvements are directed towards helping these firms exploit certain hidden

competencies and also overcome certain shortcomings in their NPD systems and processes.

Different role for customers and lead users

Recent studies have redefined the role of lead users and customers and extended their active involvement throughout the PD process (Muller, Poorter, Jong, and Van Engelen, 1996). Lead users are customers with knowledge and ability to contribute effectively to the designing and testing of new products. All four firms could identify potential lead users with the help of marketing and then build a communication channel (web-based communication) with them.

As explained in chapter 4 the program managers are commonly in direct contact with customers. In the new role however, the PD team should also interact one-to-one with customers, especially lead users. This interaction will not only enable flow of ideas but will also serve as a channel for getting feedback from the market. This interaction should begin during concept development so that lead users can offer constructive criticism from their perspective. But definitely considerable number of engineering hours will be required for establishing and maintaining these contacts.

Combining the concepts of lead user involvement with 'probe and learn' (Lynn, et al., 1996) process helps derive another innovative strategy. The PD team could release partially functional prototypes to the lead users and ask them to test and suggest improvements, while the testing is progressing in-house too. This strategy also ties in well with SBCE strategy since the PD teams can make use of lead users to test multiple concepts via partial prototypes. Information collected from these lead users will definitely

aid designers to come up with a better design during the design iteration following the testing of the prototypes. But taking into consideration the time needed for feedback and subsequent changes, this strategy will off course lengthen the PD cycle time.

Early manufacturing involvement

An active role for manufacturing also been stressed (chapter 4) because manufacturing has the potential to be a source of competitive advantage. But the data revealed that manufacturing is currently not an integral part of the PD effort even though it is commonly responsible for both prototyping and final production. Techcon, Unolaser and DC systems could potentially enhance their PD capabilities by having a manufacturing engineer on the PD team right from its conception. This would not only highlight DFM issues early on but also help shorten development time considerably. All the effort and time spent in bringing manufacturing engineering up to speed with the development before pilot production could be avoided completely and the documentation would also be simpler. Overall, giving manufacturing engineers the same status as the development engineers and running their activities parallel to those of designers holds substantial gains for these firms. This strategy however could involve some additional costs since the manufacturing engineer has now to be dedicated to the PD team and taken away from functional responsibilities for an extended period of time.

Greater stress on continuous communication

One of the main reasons for designing the new information management system (See chapter 6) was to promote continuous communication between the different functions in the PD team. Continuous communication should also be stressed between customers, suppliers and the PD team. One means of promoting this is to link them to the information acquisition module (pp. 20-24, chapter 6) via electronic media such as e-mail, instant messaging, or other means. This will not only facilitate communication between the PD team and customers/suppliers but also enable the PD team to access any product information they need and send it to anyone instantly. This is because the information acquisition module contains all the current product development information such as designs, test data and analysis. This means the PD team and the customers/suppliers will need to interface with only one media for all their communication/information needs.

Avenues for further research

Even though we have attempted to provide an in-depth investigation of PD systems and processes carried out at electronic firms, our sample size is small as compared to other such studies. But this research should be treated as a preliminary investigation into creating a better understanding of PD issues in this industry.

At end of chapter 5 we have reasoned and hypothesized that adopting SBCE principles will not only offer a better design solution, but also reduce the complex integration problem caused by the different development cycles commonly used by hardware and firmware engineering. In using SBCE we also proposed that breaking down the design effort into modules rather than hardware and firmware development groups will lead to a smoother development process and more optimal design. But right now this is true only in principle, how SBCE can be adopted and whether will be successful can only be determined by putting it into practice and learning through mistakes.

If adopting SBCE were to be treated as the next research project, then the first step would be to attempt modular design at two of these firms. The critical aspect in attempting modular design would be the careful planning needed for planning the modules. Testtek and Unolaser could be possible sites to attempt set-based practices because the products they build support modular design. For example the oscilloscope that Testtek makes could easily be divided into 4 modules: acquisition module, signal processing module, communication module and presentation module. The task of defining the interaction would be facilitated because the engineers have considerable experience in building oscilloscopes. The challenge would be in breaking up the conventional functional lines and forming small module development groups consisting mainly of 2 to 3 hardware and firmware engineers, one manufacturing, and one reliability engineer. These groups should then be necessarily collocated and encouraged to start concept development together. Team meetings that are commonly held every week could be used as a forum for communicating and integrating ideas. These groups could be

encouraged to use simulation, develop partial prototypes and use EMS to test and provide comparative evaluation of the alternative designs.

The focus of these activities would be on developing multiple designs of the modules, testing them early on and then slowly converging onto a single design where the four modules are integrated. To accomplish would require management backing and the resources to work almost full time with a PD team for the length of the project. But this project if undertaken should be treated as a learning exercise and procedures should be then refined slowly until set-based systems are firmly established within the NPD practice of the firm.

In chapter 6 we have proposed a new model for information management. Though this model is not entirely revolutionary, we have redefined the role of the different elements in the information transformation process. This idea is still in its infancy state and only Sony has successfully adopted a similar information management system (Numata and Maeda, 1998). Other firms still need to remodel their existing information systems system and exploit its advantages.

To put this system into practice the first step would be to determine what information needs to go into the information acquisition module and what will be the system requirements to accomplish it. Even though some of the information such as test data and designs exist in electronic forms, but the software used are different. The first challenge is to determine what software platforms to use to best integrate these different forms of information. The second challenge would be to modify the existing local area network (LAN) and make it compatible to the information acquisition and the knowledge

base. Modification of the existing knowledge base is also necessary because old product archives are commonly paper based and not organized to suit easy accessibility and learning.

Redesigning the information management system will not only require capital investment but also joint effort on part of the PD organization and researchers. The first task would be to determine which information is necessary when and how it can be leveraged, then the structure should be defined that best organizes engineering information. But in some sense the structure of the information management system will be firm specific, but the lessons learned from implementing such a system could be documented and then used by other firms.

If in the future, researchers pursue either of these ideas, the biggest challenge they will face is changing the mindset of engineers about PD practice that they are commonly used to. But such a situation is nothing that solid management support and success stories cannot rectify. Another factor to be considered is that no one system or model works in all firms, the trick is to follow the basic principles but adjust and adapt systems and procedures to suit the firm and its workings.

But before any of these two projects are undertaken a more in-depth investigation is needed with a larger sample and quantitative data. Implications of adopting SBCE or the new information management system on the PD system of any firm are huge, and therefore some form of quantitative analysis coupled with the current qualitative analysis is necessary.

Another possibility for extending this project with a quantitative approach would involve spending considerable time at the customer sites and conducting a microscopic

examination of how EMS are used during testing. This could involve taking into consideration the different capabilities of the EMS provided by different manufacturers including an evaluation of the capabilities of the test and analysis software. The effectiveness of these capabilities could be evaluated against certain measures of PD effectiveness. Correlations could also be established between the current capabilities of the EMS and the commercial test and analysis software provided by vendors.

A fourth possibility would involve conducting a time study of the activities involved in testing and then analyzing test data using EMS. This would require a large sample of firms involved in somewhat similar PD and having somewhat common engineering activities especially during D-B-T cycles. Establishing time scales for common activities during testing and analysis could offer insight into how D-B-T cycles can be shortened. Considering the engineering outcomes needed at the end of a typical D-B-T cycle, wasteful or non-value added activities could be identified. This could also help identify avenues for automating certain engineering activities using the EMS and thereby save engineering hours and possibly reduce PD time.

REFERENCES

Amami, M., and Beghini, G., 2000, Project management and communication of product development through electronic document management, Project Management Journal, 31: 6-19.

Ancona, D. and Caldwell, D., 1997, Making teamwork work: Boundary management in Product development teams, 433-442, Managing strategic innovation and change, Oxford University Press, NY.

Anderson, P. and Tushman, M., 1991, Managing through cycles of technological change, Research /Technology Management, Washington D.C.

Bell, D. and Thomke, S., 2001, Sequential testing in product development, Management Science, 47: 308-323.

Borland K, spring 2001, class notes, Qualitative educational research (EDCI 507-01), Montana state university publications, Bozeman.

Bowen, H.; Clark, K.; Hollaway, C.; and Wheelwright, S., 1994, Development projects: The engine of renewal, Harvard Business Review, 72: 110-120.

Brown, S. and Eisenhardt, K., 1995, Product Development: Past research, Present findings and Future directions, Academy of management review, 20: 343-378.

Burgelman, R. and Rosembloom, R., 1989, Research on Technological Innovation, management and policy, JAI press, Vol. 4.

Clark, K. and Wheelwright, S., 1992, Revolutionizing product development: Quantum leaps to speed, efficiency and quality, 1-27, 86-110, The Free Press, NY.

Clark, K.; and Fujimoto, T.; 1991, Product development performance, 167-204, Harvard Business school press, Boston.

Court, A., 1997, The relationship between Information and personal knowledge in new product development, International journal of Information management, 17: 123 –138.

Court, A.; Culley, S. and Mcmohan, C., 1997, The influence of information technology in new product development: Observations of an empirical study of the access of engineering design information, International Journal of Information Management, 17: 359-375.

Creswell J, 1998, Qualitative inquiry and research design- choosing among five traditions, Sage publications, Thousand Oaks.

Cusumano, M., 1988, Manufacturing Innovation: Lessons from the Japanese Auto industry, Sloan Management Review, 30: 29-39.

Denzin N and Lincoln Y, 1998, Strategies of qualitative inquiry, Sage publications, Thousand Oaks.

Fleischer, M. and Liker, J., 1997, Concurrent Engineering effectiveness, 1-24, 395-406, Hanser Gardner publications, Cincinnati.

Glaser B and Strauss A, 1967, The Discovery of Grounded Theory, Aldine publishing company, Chicago.

Griffin, A. and Page, A., 1993, An interim report on measuring product development success and failure, Journal of Product Innovation Management, NY.

Griffin, A., 1997, PDMA research on new product development practices, Updating trends and benchmarking best practices, Journal of Production Innovation management, 14:429-458.

Guba E and Lincoln Y, 1985, Naturalistic Inquiry, Sage publications, Thousand Oaks.

Hunkins F, 1972, Questioning strategies and techniques, Allyn and Bacon, Boston.

Iansiti, M., 1995, Shooting the rapids: Managing Product Development in Turbulent environments, California management review, 38: 37-58.

Iansiti, M., Verganti, R. and McCormick, A., 2001, Developing Products on Internet time: anatomy of a flexible PD process, Management science, 47: 133-150.

Krishnan, V. and Ulrich, K., 2001, Product development decisions: A review of literature, Management Science, 47: 1-21.

Kusunoki, K.; Nonaka, I, and Nagata, A., 1998, Organizational capabilities in product development of Japanese firms, Organizational Science, 9:699-718.

Levitin, A. and Redman, T., 1998, Data as a resource: Properties, implications and prescriptions, Sloan management review, 40: 1-15.

Liker, J.; Kamat, R.; Wasti, N.; Nazli, S. and Nagamachi, M., 1995, Integrating suppliers in fast-cycle Product Development, Engineered in Japan: Japanese technology management practices, Oxford University Press, NY.

Loch, C.; Terwiesch, C. and Thomke, S., 2001, Parallel and Sequential testing of design alternatives, Management Science, 45: 663-678.

Lynn, G., 1998, New Product team learning: developing and profiting from knowledge capital, California management review, Berkley.

Lynn, G.; Morone, J. and Paulson, A., 1996, Marketing and discontinuous innovation: the probe and learn process, California management review, Vol. 38.

Lynn, G.; Reilly, R. and Akgun, A., 2000, Knowledge management in new product teams: practices and outcomes, IEEE Transactions on Engineering Management, 47: 221-229.

McDermott, R., 1999, Why Information technology inspired but cannot deliver knowledge management, California Management Review, 41: 1-11.

Mitchell, G. and Hamilton, W., 1998, Managing R&D as a strategic option, Research/Technology management, Washington, D.C.

Muller, P.; Poorter, J.; Jong, J. and Van Engelen, 1996, Using the Internet as a communication infrastructure for lead user involvement in new product development, Proceedings of WET ICE'96, University of Groningen.

Nadler, D. and Tushman, M., 1997, Competing by design: A blueprint for organizational architectures, Oxford University Press, New York.

Nadler, D. and Tushman, M., 1997, Implementing new designs: Managing organizational change, Managing strategic innovation and change, Oxford University Press.

Nellore, R. and Balachandra, R., May 2001, Factors influencing success in integrated product development projects, IEEE transactions on engineering management, 48:164-174.

Nonaka, I., 1988, Towards Middle-up-Down management: Accelerating information creation, Sloan Management Review, Boston.

Nonaka, I., 1990, Redundant, Overlapping Organization: A Japanese approach to managing the innovation process, California management review, Vol. 32.

Nonaka, I., 1990, Towards middle up down management: Accelerating information creation, Managing strategic innovation and change, 494-505, Oxford University Press, NY.

Numata, J. and Maeda, Y., 1998, Engineering for knowledge amplification in new product development, IEEE International engineering management conference, : 241-246.

Quinn, J.; Anderson, P. and Finkelstien, S., 1997, Managing Intellect, Managing strategic innovation and change, 506-523, Oxford University Press, NY.

Scott, W. 1998, Organizations, 4th edition, Prentice hall, pp 1-120.

Sobek, D., 1997, Principles that shape product development systems: A Toyota – Chrysler comparison, UMI services, Michigan

Sobek, D.; Liker, J.; Ward, A., 1998, Another look at how Toyota integrates Product Development, Harvard Business Review, 1-12..

Sobek, D.; Ward, A. and Liker, J., 1999, Toyota's Principles of Set-Based Concurrent Engineering, Sloan Management Review, 40: 67 –83.

Terwiesch, C. and Loch, C., 1999, Measuring the effectiveness of overlapping development activities, Management science, 45: 455-465.

Thomke, S., 2001, Enlightened experimentation: the new imperative for innovation, Harvard Business Review, 67-75.

Ulrich, K. and Eppinger, S., 2000, Product design and development, Irwin McGraw Hill, Boston.

Ward, A.; Liker, J.; Cristiano, J; and Sobek, D., 1995, The second Toyota paradox: How delaying decisions can make better cars faster, Sloan Management Review, 36: 43-61.

APPENDIX A

DATA COLLECTION AND ANALYSIS TOOLS

INTERVIEW QUESTIONS

PRODUCT DEVELOPMENT ORGANIZATION

This interview is part of a joint research project undertaken by Montana State University and Tektronix Inc. We are seeking a better understanding of the role electronic measurement systems[1] (EMS) play in new product development (NPD), and how new technologies and capabilities impact new product development organization and processes. Please review the following questions aimed at understanding your NPD processes and use of EMS.

1. Personal background
    a. What professional degrees do you hold?
    b. How long have you worked at this company? What is your current position?
    c. Briefly describe your professional background.

2. Project team organization
    a. Please describe the typical team membership. What percentage of time is each member dedicated to the project?
    b. What is a general team structure and how does it relate to the overall organizational structure?
    c. Is the team co-located?

3. PD Process description
    a. What are the key phases and milestones of the typical PD project?
    b. When are prototypes made and how many?
    c. Are these phases unique for the project or standard for the whole organization?

4. Communication methods
    a. How does communication within the project team take place?
    b. Does the team hold regularly scheduled meetings? What is covered at such meetings?
    c. How do generators of test data and the users of the data communicate?

5. Control mechanisms

[1] Electronic Measurement Systems (EMS) – System consisting of data acquisition, analysis, presentation and related tools.

a. What are the budgetary and schedule controls?
b. What governs the project – time to market, quality, or market leadership?

6. Experimental strategy.
   a. Does your NPD process include Design-Build-Test cycles? If so, where in the process?
   b. Does your organization typically pursue design-build-test cycles in series or in parallel? How does the EMS support this strategy?
   c. Do you believe this strategy to be the most effective for your organization? Why or why not?

7. Please describe EMS's currently in place.
   a. What is the hardware configuration? Who are the manufacturers?
   b. What software if any, supports such systems?
   c. In what situations are the different types of equipment applied?
   d. What do engineers/technicians like and dislike about the current EMS?

8. What criteria are used in choosing EMS? How are decisions to purchase EMS's made?

9. How are current EMS's used?
   a. At what points in the PD process are the EMS used? By whom? For what purpose?
   b. How do you capture the data generated? Where does it go? In what form?
   c. How do you use this data? How do you analyze it?
   d. How is this data stored? Do you need to access it again? When?
   e. Is the current EMS compatible to other systems or tools used by engineers?

10. New EMS
    a. What improvements are engineers looking for in new EMS?
    b. Is connectivity / remote access an important feature for EMS in the future? Why or why not?
    c. How can applications of EMS change with new technology?

INTERVIEW QUESTIONS

PRODUCT DEVELOPMENT PROJECTS

This interview is part of a joint research project undertaken by Montana State University and Tektronix Inc. We are seeking a better understanding of the role electronic measurement systems[1] (EMS) play in new product development (NPD), and how new technologies and capabilities impact new product development organization and processes. Please review the following questions aimed at understanding your NPD processes and use of EMS.

1. Personal background
    a. What professional degrees do you hold?
    b. How long have you worked at this company? What is your current position?

2. Project team organization
    a. Please describe the PD organization structure?
    b. What is a typical team structure and composition?
    c. What percentage of time is each member dedicated to the project? Are team members co-located?

3. PD Process description
    a. Could you describe the PD process in terms of
        1. Phases / Milestones.
        2. Activities leading to every phase.
    b. Are these phases unique for the project or standard for the whole organization?
    c. Could you give time estimates for every phase?

4. Communication methods
    a. How does communication within the project team take place?
    b. Does the team hold regularly scheduled meetings? What is covered at such meetings?

[1] Electronic Measurement Systems (EMS) – System consisting of data acquisition, analysis, presentation and related tools.

5. Experimental strategy.
    a. Does your NPD process include Design-Build-Test cycles? If so, where in the process?
    b. Could you describe one such Design-Build-Test cycle?
        1. What would conceptual and detail design look like?
        2. What tools does the designer use for developing both?
    c. Does your organization typically pursue design-build-test cycles in series or in parallel? How does the EMS support this strategy?
    d. When are prototypes made in the PD process? What is the nature of these prototypes?
    e. Do you believe this strategy to be the most effective for your organization? Why or why not?

6. Current EMS and their use
    a. What equipment is currently used? What is the hardware configuration? Who are the manufacturers?
    b. What software if any, supports such systems?
    c. At what points in the PD process are the EMS used? By whom? For what purpose?
    d. How do you capture the data generated? Where does it go? In what form?
    e. How do you use this data? How do you analyze it?
    f. How is this data stored? Do you need to access it again? When?
    g. Is the current EMS compatible to other systems or tools used by engineers?
    h. What do engineers/technicians like and dislike about the current EMS?

7. New EMS
    a. What improvements are engineers looking for in new EMS?
    b. Is connectivity / remote-access an important feature for EMS in the future? Why or why not?
    c. How can applications of EMS change with new technology?

8. Hardware Software integration
    a. What is the software development cycle?
    b. What prototypes does software use for their development?
    c. What tools does a software engineer use in their Design-Build-Test cycles?
    d. What data transfer takes place between hardware and software?

DESIRED OUTCOMES OF INTERVIEWS

Questions	*Desired Outcome*	*Follow-up*
1.Personal Background	∘ Degrees held ∘ Experience (both outside and at Tek) ∘ Current position	What are the responsibilities in your current position?
2. Team Organization	∘ Team size. Functions represented in the team ∘ Co-location of the team ∘ Reporting within the team.	Which functions constitute teams? (Designers, process engineers, test engineers etc.)
3. Communication	∘ Common modes of communication ∘ Frequency and contents of meetings. ∘ Formal/informal means of communication ∘ Timing and nature of communication between generators and users of test data.	At what point does the communication start? When does it end? What decisions are made as a result?
4. Experimental Strategy	∘ Details and timing of designing, building and testing of prototypes in the PD cycle. ∘ Nature of these prototypes. ∘ Interaction within and between functions during a typical D-B-T cycle. ∘ Test protocol at different stages in PD.	What tools do designers use? How does conceptual, system and detail design take place? Who does the prototyping and what is the nature of these prototypes? Where in the process do these happen? What happens at every cycle? What tools are used for experimentation? (Simulation?)
5. Current EMS	∘ Types of equipment used. ∘ Configuration (block diagram) of these equipment. ∘ Software used. ∘ Applications of these equipment.	What is the setup?
6. Choice of EMS	∘ Decision criteria? ∘ Timing of the decision	Who makes the decision? Based on what? When are such decisions made in the PD process?
7. Use of EMS	∘ Points in the process where the EMS are used ∘ Means of data generation and it's form ∘ Means of data capture and analysis ∘ Storage of data and accessibility	How is a typical EMS used? What sort of data is generated? Form of this data? Why is it captured? How? How is it stored? How is the analysis done? Who does it? What tools are used? How are results generated?

7. Use of EMS	∘ Software used. ∘ Locus of work performed.	used? How are results generated? What reports are made? What information goes to whom? What is the interface between the EMS and tools used by engineers? What software is commonly used? What interaction takes place between different functions during this time?
8. Hardware Software interaction	∘ Flow charts of the development cycle for both. ∘ Co-relation between the two development cycles. ∘ Data transfer and interaction between the hardware and software engineers.	How does development of one group affect the other? What prototypes does the software group use? Any simulation used?
9. New EMS	∘ Improvements foreseen ∘ Importance of connectivity ∘ New applications	What do they dislike about the systems? What are the new trends? What kind of software will be more effective?

ANALYSIS CODES AND DEFINITIONS

(R) Team Organization

- Formation of team
- Functions represented.
- Involvement of every function
- Reporting
- Role of team leader
- Communication mechanism

(PC) Planning and concept development

- Preliminary designing activities.
- Preplanning and planning activities
- Feasibility studies

(M) Program management

- No. of phases
- Milestones
- Decision criteria at gates

(D) Designing

- Design activities
- Tools used
- Form of design and timing
- Coordination between designer and other functions

(T) Testing

- Test preparation
- Coordination between test engg. and other functions.
- Test protocol.
- Software used.
- Prototyping and its progression.
- Actual testing

(EM) Electronic Measurement Systems.

- Hardware configuration
- Progression from basic instrumentation to integrated systems.
- Test and system design and setup
- Working and software capabilities

(I) Test data management

- Mechanism of data generation
- Type of data
- Data generated when and how
- Data analysis
- Data storage and transfer

(HS) Hardware and software integration

- Chronology of events in hardware and software development.
- Coordination during designing, testing, and decision-making.

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