CONCURRENT ENGINEERING: MODELS AND METRICS

by

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ABSTRACT

Today, many companies are interested in improving their competitive position in the marketplace, and hence, compete by bringing new products and value added services to the market in a timely fashion, at low cost and enhanced quality. Concurrent Engineering(CE), a new methodology and a systematic approach to the integrated design of products and related processes including manufacture and support is ideal, for this environment.

Organizations implement CE to achieve specific goals. This thesis focuses on the goals of time, cost and quality for implementing CE. The existence of specific models or methods of implementation of CE for specific goals has been investigated and metrics for specific models classified. Case studies of organizations implementing CE are outlined and differences in implementations pointed out. Organizations focusing on time put more emphasis on stages/activities between detailed specification and detailed design stages in a CE NPD process. Organizations focusing on quality and cost put more emphasis on the stages/activities between preliminary design and volume production.

Metrics for CE processes targeting specific goals have also been classified. However, it has been found that metrics are not restricted to specific goals.

RÉSUMÉ

De nos jours, la plupart des compagnies cherchent à améliorer leur position concurrentielle dans le marché. Pour ce faire, elles se font concurrence en introduisant des nouveaux produits et des services avec des valeurs ajoutées au marché dans un laps de temps toujours plus court, à des coûts moindres, et avec une qualité supérieure. L'ingénieurie simultanée est une nouvelle méthode qui a une approche systématique au design des produits et aux processus qui y sont reliés, incluant la manufacture et le support, et ce méthode est idéale pour cette type d'environnement.

Les organisations mettent en vigueur l'ingénieurie simultanée pour atteindre des buts spécifiques. Ce mémoire concentre son analyse sur les objectifs de temps, de coût, et de qualité pour l'implantation de cette nouvelle méthode. L'existence de certaines modèles ou de méthodes pour l'implantation de l'ingénieurie simultanée ont été recherchés et des mesures reliées à ces modèles ont été classifiées. Des études d'organisations qui ont utilisé l'ingénieurie simultanée sont presentées et les differences en exécution sont visées. Les organisations qui ciblent le facteur de temps s'appuient sur les étapes/actvités entre les caractéristiques détaillées de ses produits et les étapes de design detaillées dans le processus de développement de nouveaux produits utilisant l'ingénieurie simultanée. Les organisations qui ciblent plus les facteurs de coût et de qualité de leur produit ou service s'appuient sur les étapes/activités entre le design préliminaire et la production de masse.

Des mesures pour les processus de l'ingénieurie simultanée qui visent des buts spécifiques ont aussi ete classifiées. Par contre, la recherche a demontré que les mesures ne sont pas restreintes à des buts determinés.

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CHAPTER 1

1.0 INTRODUCTION

Increased competition in recent years has forced manufacturing industries to develop better products more quickly with greater quality and at reduced cost. This is because the companies that develop new products and value added services for a market in a timely fashion at high quality and low cost levels often grab the largest share of the market. This requires companies to change their practices so that they can develop products rapidly. Concurrent engineering, a new philosophy and methodology, is ideal for this requirement.

Concurrent engineering is defined as, "a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support", by the U.S Institute for Defense Analysis [23].

Concurrent engineering (CE) is a practice in which various life cycle values of a product from conception through disposal including cost, quality, schedule and user requirements are incorporated into the early stages of its design. It not only includes the product's primary functions, but also its manufacturability, assemblability, serviceability, recyclability and esthetics. CE necessitates the use of multi-disciplinary teams and computer based tools like Computer Aided Design, Computer Integrated Manufacturing, etc., and design for X-ability techniques like Design for Manufacture (DFM), Design for Assembly (DFA), Design for Environment (DFE), Design for Serviceability (DFS), etc. See Table 1.1 for definitions of these terms.

CE is largely an organizational challenge as it necessitates the involvement of various contributors from different functional areas, where the challenge is to break the barriers between the departments and to integrate them. This creates an environment in which the whole company participates in quality design for the customer. The methodology involves communication between different teams, i.e., early design reviews by a development team and applying value engineering/quality function deployment with the help of computer aided design and other computer based tools. The objective is to reduce the development lead time for new products as well as improve quality and manufacturability by removing design flaws at an early stage.

Over the years, CE has emerged as a new paradigm for product development because the old paradigm, i.e., 'Over the Fence Engineering' or 'Traditional Engineering' which is based on serial contributions by disparate functions along the value added chain, proved to be slow and non-adaptive to the present turbulent, manufacturing environment.

With increasing product complexities in design and rapid development in technology, the demand on companies' new product development process is increasing. As a result companies have started to use CE approaches for new product development. However, the goals driving the organizations in the implementation of CE differ with each organization. An in-depth case study on companies implementing CE by Swink et al. [22] identifies product introduction speed, product cost, quality, innovation and project risk as some of the drivers. Other possible drivers can be product complexity, company type, etc. Generally, companies tend to tailor their product development process according to their goals and use generalized product development metrics to measure the performance of both product development and product development process.

The objectives of this thesis are:

1) to investigate whether there are different or specific models for CE as implemented by different companies, and

2) to investigate whether metrics are specific for specific CE models or goals.

This thesis focuses on time (timeliness or time to market), cost (cost reduction) and quality (quality enhancement) as the goals driving organizations in the implementation of CE as a new product development tool. The results of this thesis will show that:

a) CE improves NPD processes when the goals for competing are time, cost and quality,

b) the implementation of CE NPD process depends on the specific goals,

c) the implementation of CE or the 'models' of implementation are different for different goals, and

d) metrics that help in measuring different product development attributes do not seem to be specific for specific or tailored CE NPD processes.

Chapter 2 explains the CE methodology applied for new product development. Case studies of CE implementation done by Swink et al. [22] are discussed in Chapter 3. Chapter 4 deals with case studies conducted as a part of this thesis and CE models. Chapter 5 deals with the summary of case studies. A classification of CE NPD metrics is done in Chapter 6. In Chapters 7 and 8 the results of this thesis and scope of future research are discussed.

Table 1.1 Glossary of Terms Associated with CE

CAD	Computer Aided Design involves computer software systems for assisting product designers. These systems (1) support design and layout of products and components, (2) display and manipulate images, (3) create drawings of completed designs, and (4) develop specifications for manufacturing the product.
CAE	Computer Aided Engineering assists design engineers in selecting components and materials for products and in performing engineering analysis, that is, mathematical modeling and analysis to improve the performance of designed products.
CAM	Computer Aided Manufacturing involves manufacturing processes assisted by computers.
CE	CE is a systematic approach to the integrated design of products and processes including manufacture and support.
DFA	Design for Assembly emphasizes easy assembly of components by using minimum number of parts, modular designs and, reduction of fasteners.
DFE	Design for Environment takes into account the impacts of design, manufacture, life-cycle, use and disposal of products on the environment by addressing key issues including toxicity, health and safety, service life, recycled content of manufactured material, reuse of products and disposal of alternatives.
DFM	Design for Manufacturability ensures using the minimum number of parts in a product, facilitating assembly, using standard components whenever possible and fitting the product design into the process that will be used to produce it.

DFMA	Design for Manufacture and Assembly is a technique combining DFM and DFA techniques.
DFR	Design for Recyclability ensures the use of recyclable materials to the maximum extent possible by taking the right disposal alternatives and economic re-use options into account.
DFS	Design for Serviceability ensures the serviceability requirements of the product by designing the replaceable items to be easily accessible, partitioning designs into modular functions (mechanical, electrical, etc.) and building in test and diagnostics appropriate to each application.
DFT	Design for Testability ensures the testability requirements of a product or system in a timely, confident and cost-effective manner for performance verification, fault detection and fault isolation.
FMEA	Failure Modes and Effects Analysis ensures elimination of poor design features by highlighting the areas or assemblies most likely to cause failure. This acts as a complementary tool to DFMA and QFD.
NPD	The activities and processes concerned with the development of a new product.
QFD	Quality Function Deployment is a system for translating customer requirements into appropriate working instructions at each stage of product development. QFD is extensively discussed in the following chapters of this thesis.
VE	Value Engineering is a method of analyzing a product or process, identifying the value of attributes associated with it and eliminating the hidden waste.

CHAPTER 2

2.0 CONCURRENT ENGINEERING METHODOLOGY

2.1 Product Development Approaches

Traditional engineering approaches to New Product Development (NPD) processes execute activities such as designing, testing, prototyping and production serially (see Figure 2.1). Further, often there exists a functional barrier within an organization, between different functional units, e.g., marketing, design, manufacturing, etc.

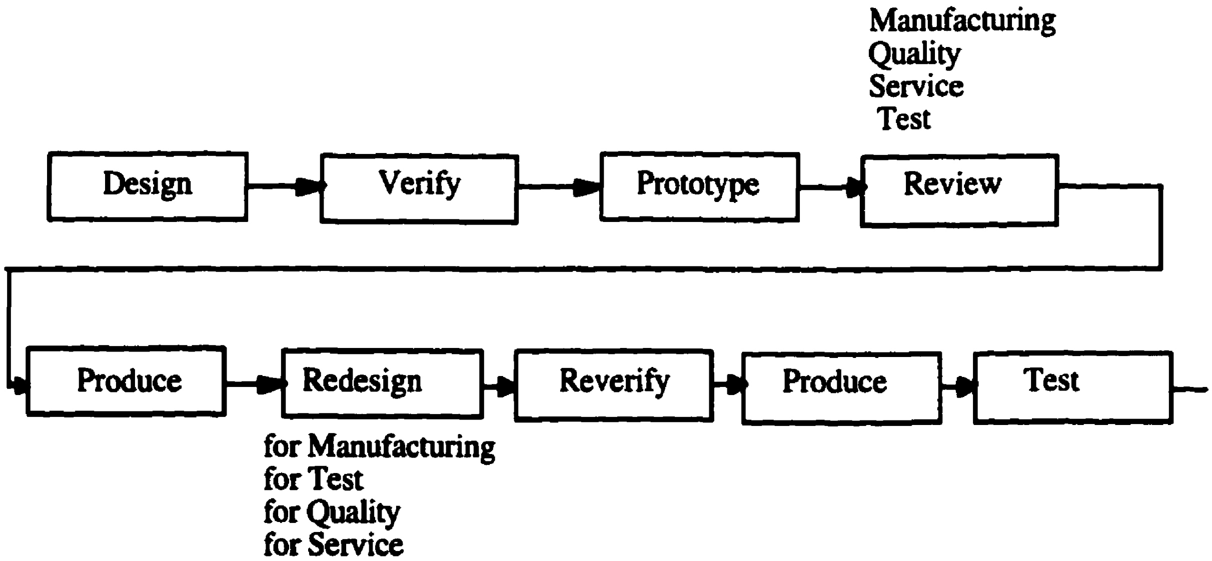

Figure 2.1 Traditional Engineering Approach [24]

In a CE approach, multi-functional teams work on different aspects of product development simultaneously. Some companies use a stage-gate process (see Table 2.1), which is a management technique for resource control and development verification which is used with both traditional and CE approaches.

Table 2.1 Stage-Gate Process Background

In a stage-gate process, 'stages' of activities are done by cross-functional teams followed by decision 'gates'. Even though the term 'stage-gate' suggests a serial or step-by-step methodology, the process emphasizes parallel activities and can be quite flexible. The intent of each gate is to assure a high quality of work performance by cross-functional teams during each stage and to make continue/abandon/recycle decisions on ensuing stages of work activities and project investments.

Each gate has predetermined inputs, decision criteria and outputs. Gate inputs correspond to the deliverables of the preceding stage of activities. Gate outputs are the orders to conduct ensuing stage activities.

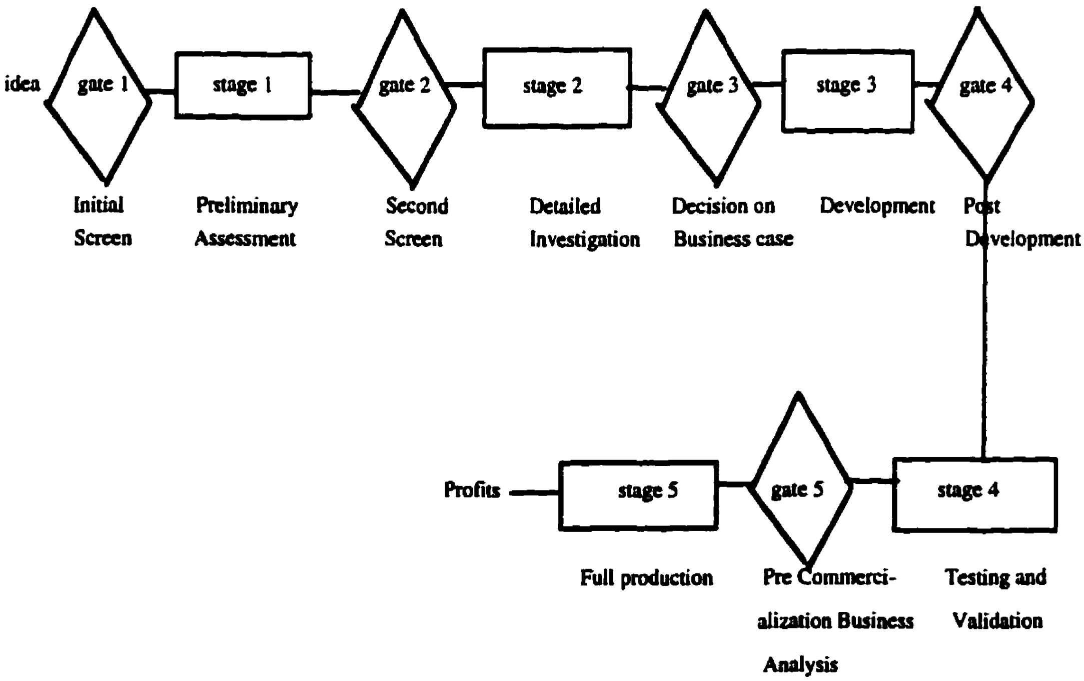

Figure 2.2 General Flow Diagram of a Stage-Gate Process

In the following sections, CE NPD structure and process are discussed.

2.2 CE Introduction

"Concurrent Engineering is a systematic approach to the integrated, simultaneous design of both products and their related processes, including manufacturing, test and support." [24]

Product development capabilities are the basis for successful competition if companies want to improve their position in the marketplace by developing their products on time at a reduced cost and improved quality. Successful product development requires approaches that can organize the process, reduce waste, provide products to meet customers' needs and also respond to global competition by competing effectively.

In general, the process of new product development involves the following stages:

1. Requirements identification
2. Concept design and specifications development
3. Detailed design
4. Prototype development
5. Testing
6. Process design and planning
7. Pilot production
8. Volume production

For any NPD process, stages 1-8 are usually in series and some of the stages may or may not be in parallel. In a concurrent engineering approach, stages are conducted as much as possible in parallel and overlap in time (see Figure 2.3), unlike a traditional product development approach where most of these activities occur sequentially. Concurrent engineering necessitates the simultaneous participation of different functions within an organization, e.g., marketing, R & D, manufacturing, design, etc., during each of the above mentioned stages. As a result, integration is promoted and barriers between various functions are broken. Concurrent engineering is essentially the collaboration of many people from different departments representing the various perspectives of a product. Tradeoffs regarding producability, testability, serviceability, etc., are made in real time. This results in the anticipation of problems and bottlenecks, and helps to eliminate them as early as possible avoiding the delays in bringing a product to market.

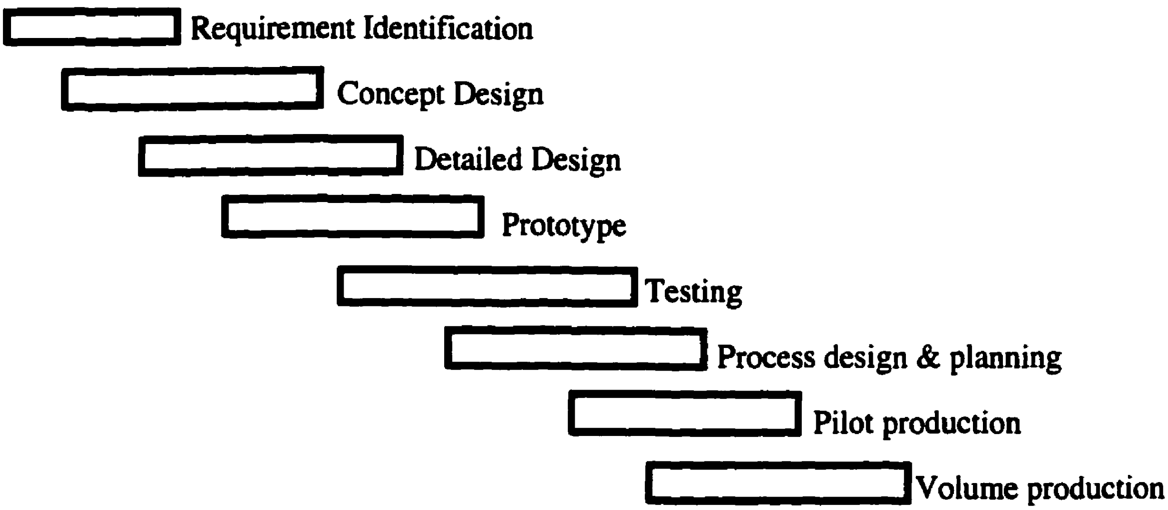

Figure 2.3 Concurrent Product and Process Development

The whole focus of CE is on a 'right-the-first-time' process rather than on a 'redo until right' process that is so common in the traditional engineering approach.

2.3 CE NPD Structure

In today's market, products are experiencing shorter life spans owing to the following reasons: (1) companies use product succession as a strategy, (2) faster cycles respond better to customer needs and (3) the rate of product obsolescence is increasing due to fierce competition and rapid technological advancements. As competition forces shorter product life cycles, companies have to develop their products faster. The effect of design on overall product cost is significant as the majority of product manufacturing cost and other life cycle costs are determined at the design phase.

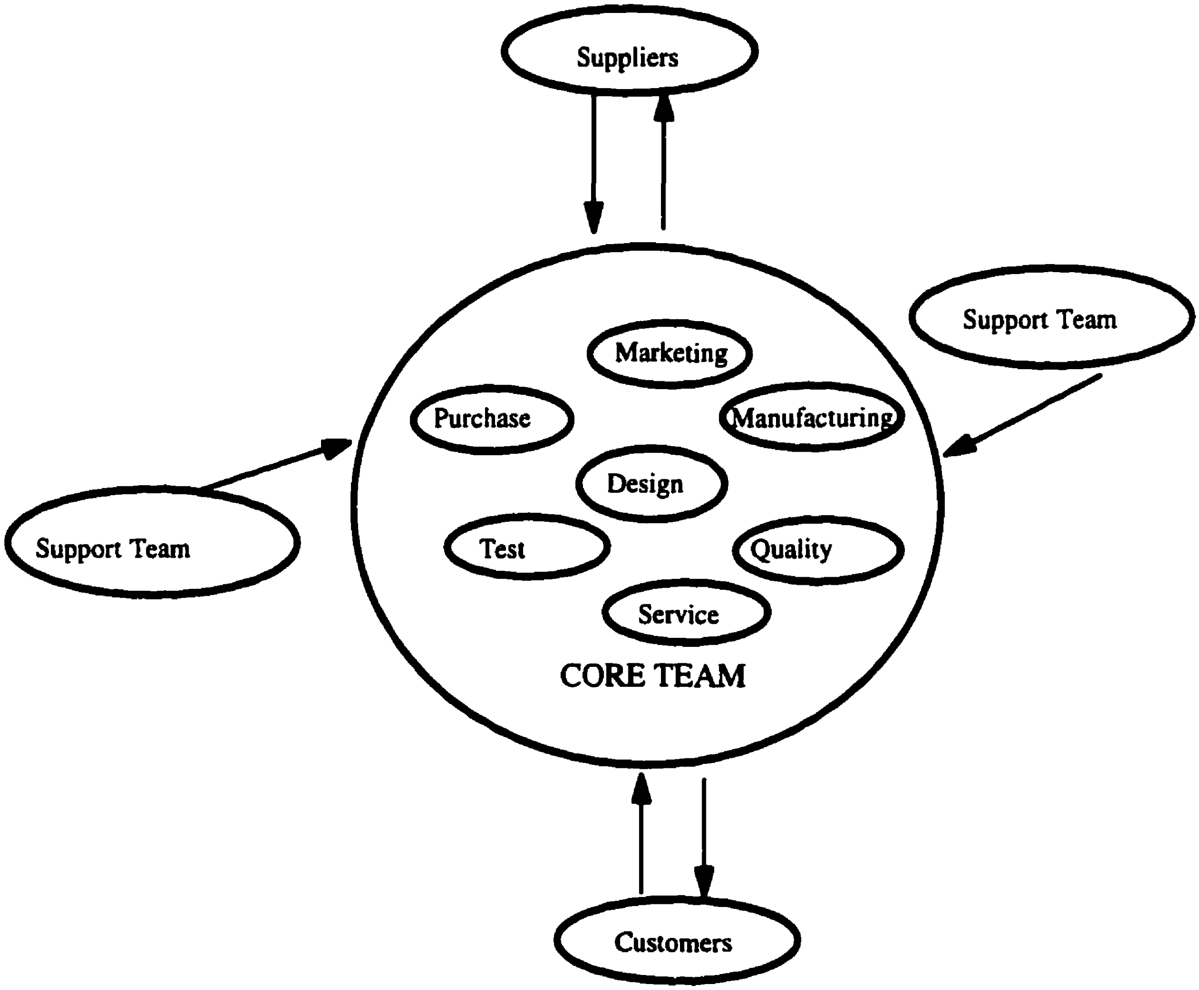

Figure 2.4 Interacting Groups in Concurrent Engineering

Organizations practicing concurrent engineering restructure their activities from traditional methods. As a consequence of rapid product development, more and more companies today are employing the cross-functional team approach in product development [1]. A cross-functional team may be composed of experts from marketing, design, engineering, etc., and any other functional area that has a vested interest in product development. The cross-functional team is the core team involved in product development (see Figure 2.4).

Team dynamics and most of the team activities depend on interpersonal relations and culture of the team members. What would be of interest, then, is to know how the team functions.

2.3.1 Team leadership and dedication

A cross-functional team, like any other team, is often led by a leader who is responsible for the team's activities. Most of the teams, today, are, however, led by engineering managers [4]. A team leader motivates, coaches and guides his team. Also he instills a sense of common commitment to a team's task throughout the product development effort. Though co-operation and goal congruence is improved with cross-functional teams, responsibility and accountability for a project's success depends wholly on the individuals involved. Wheelwright & Clarke [25] have mentioned that the productivity of engineers assigned to more than two projects simultaneously is significantly reduced with each project. The members of a team, then, should be dedicated and committed to the project task, to contribute in an efficient manner to the project.

2.3.2 Team autonomy

As the primary information providers and decision makers are part of the team, communication between them must be effective to achieve the project task. If the team members are co-located or located close to each other, communication is effective and increased. Face to face communication that occurs when team members are co-located helps to accelerate product development by increasing mutual understanding of constraints, limitations and potential problems [27]. However, conflicts and 'clash of ideas' are sure to occur when different functions collaborate. Decision making, then, becomes a critical task. Team empowerment and team autonomy are practiced by companies, though at different levels, to help teams in the decision making process. Zirger & Hartley [27] suggest that by decreasing the number of decisions for which approval is required outside of the project team decreases the development time. In fact, a study by Gerwin & Moffat [6] points out that withdrawal of team autonomy causes serious repercussions and slows down the product development effort.

2.3.3 Team rewards

Team members meet quite often to discuss the various product development problems and also project progress. This helps the team to take some crucial and important decisions to keep them on track. In fact, the senior level management of many companies conducts progress reviews and performance assessments of the teams to check the performance of the teams in achieving their goals. Teams are rewarded based on their performance. Companies practice cash incentives, promotions, celebratory dinners, plaques and business profits as team rewards [3]. Some companies also publicize the success of their new product and the team responsible for that through the print media. Still, devising appropriate rewards to promote co-operative multi-functional teamwork remains an unresolved challenge. Though team rewards promote co-operation and team work, some kind of training for the team members is necessary while working in a team as it involves interpersonal and organizational issues.

2.3.4 Training

Training plays a vital technical and cultural role in the institutionalization of the team. Training could be in the form of formal workshops, courses or programs employed by a firm to impart special skills to its team members. Frank Hull et al. [12] say that even engineers who are trained in different tools and technologies need some formal training in organizational practices and new product design protocols. Training builds team dynamics and also instills a sense of mutual respect and trust in its members.

A point to be noted here is that, the number of teams used, the selection of a team leader as well as members, team skills and other team dynamics is wholly an organizational issue.

The core team might be assisted by some support teams whose members are also drawn from various functions in an organization. The function of the support team is to help the core team in the product development effort; it is not involved in the product development effort on its own.

2.4 Concurrency of Activities

"Concurrent Engineering is intended to cause designers, from the very beginning of a design activity to consider all elements of product life cycle, from product concept through design, manufacture, service and even disposal including quality, overall business costs, time to market and customer needs. It necessitates the management to provide the right resources and expertise at the right time and at the right place." [24]

The core team and support teams take part in concurrent development of product and processes. Swink et al. [22] mention that, generally, three types of concurrency are practiced by organizations using CE approaches to product development (see Figure 2.5). They are as follows:

1. product concurrency: overlap of separate, but related new products requiring co-ordination between NPD programs.
2. project phase concurrency: simultaneous development of market concepts, product designs, manufacturing processes, product support structures, etc.
3. design concurrency: overlap of various design disciplines, e.g., hardware, software, mechanical, electrical, etc; and

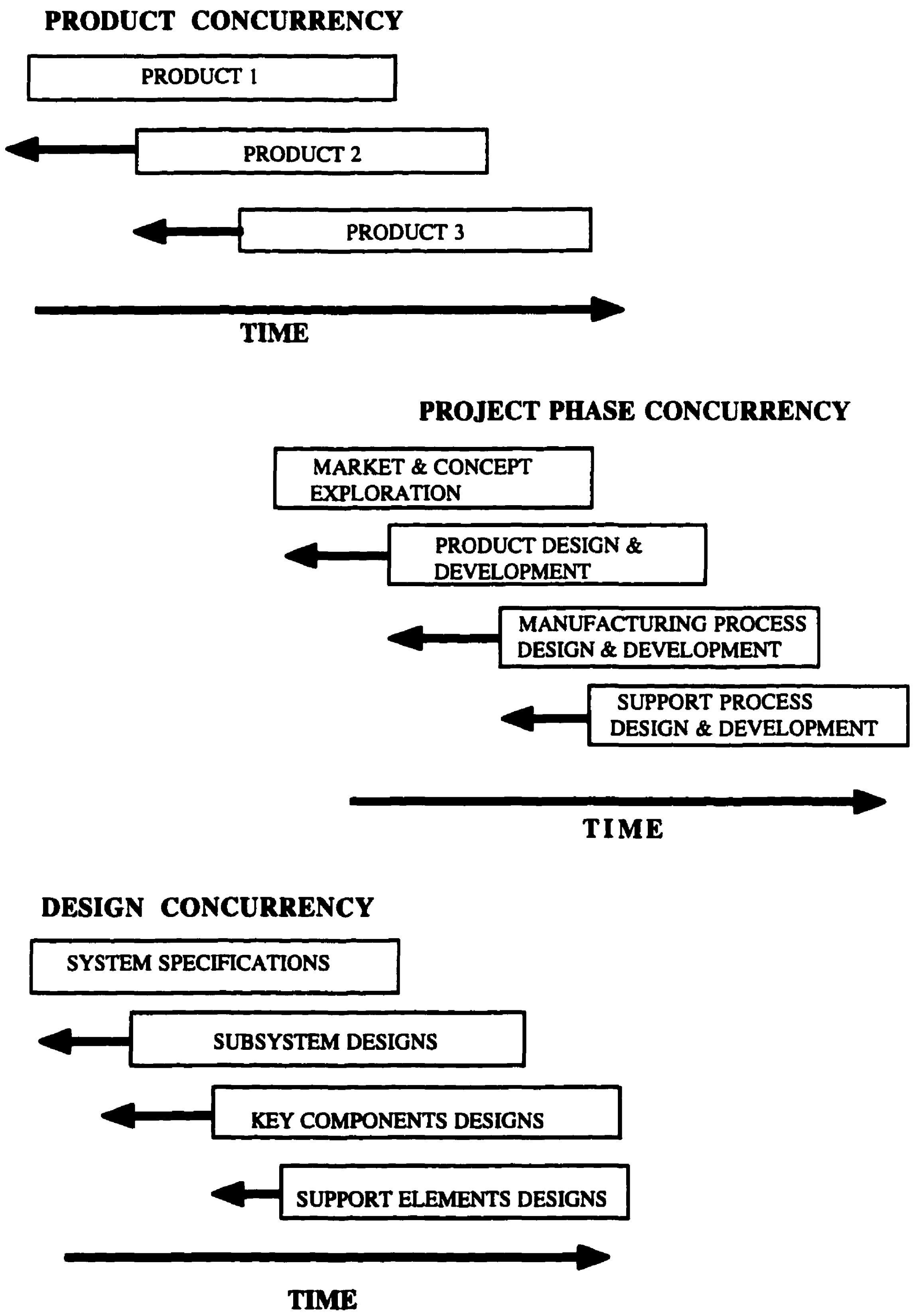

Figure 2.5 Three Types of Concurrency [22]

2.5 Design Integration

As concurrency increases, the impact of an upstream product development activity also increases. As a result, a number of design alternatives are examined before the final design is made. Liker et al. [15] mention a set based approach where designers explicitly communicate and reason about the sets of design alternatives, both at the conceptual and parametric levels. The sets are gradually narrowed through the elimination of inferior alternatives by the various collaborators until a final solution remains. This also helps in reducing the number of design changes and iterative loops that might happen in a traditional NPD process. However, all the concepts mentioned above can be achieved only if the information flow between the various collaborators is properly established.

Design activities can be overlapped or done in parallel ensuring good communication/information flow between the activities. Opportunities for overlapping can be created by sharing 'imperfect' information between activities and by starting the following activities before the preceding ones are completed [11]. However, it is risky to proceed with downstream phases where upstream information is preliminary or has not yet attained the final form. Also, it is not advisable to freeze the upstream design information early just for the sake of passing it downstream without knowing how closely the product information meets technical and market requirements [14].

Industries try to reduce design problems by using computer based tools for achieving design for X-abilities, where X denotes a wide range of performance attributes such as performance, manufacturability, serviceability, reliability, quality, etc. These methodologies have come to be known as DFX and are involved early in the design process. The main advantage of these methodologies is to identify upfront all the expertise required to meet all the product requirements and to make sure that nothing fails, thus, ensuring faster time to market, reduced cost and better quality. For example, the objective of Design for Manufacturability (DFM) is to develop product designs which are easy to produce and which have low cost, high reliability and superior quality. Design for Assembly (DFA) is a closely related process concerned with the requirements for assembly of components into finished products.

2.5.1 Use of computer based tools

Carol J. Haddad [10] observes that computer aided design and computer networking enhances product development. These technologies greatly assist information sharing and collaborative problem solving. Organizations have started to use automation technologies like CAD, CAE, and CAM to support the design process. The software systems assist design engineers in defining the geometry and specifications of parts and assemblies. Also, these systems help in performing simulations assisting the team to make proper design decisions. Customers and suppliers are also sometimes involved in the product development team to assist them in the product development task.

2.5.2 Customer involvement

Customer involvement in the team is very important as the final product eventually has to meet their needs. Customers take part in the design phase to voice their requirements and to assist in product specifications. This is quite often referred to as Quality Function Deployment (QFD) though not synonymously. QFD is a method for developing design quality aimed at satisfying customer demands into design targets and major quality assurance points to be used throughout the production stage.

2.5.3 Supplier involvement

Supplier integration in the product development task is practiced by many companies. A good supplier should be able to meet the technical and manufacturing requirements of a product. Moffato & Pannizzolo [18] suggest that the producer-supplier relationship can operate at various levels according to the amount of design entrusted to the supplier. A supplier could be involved directly in the development team and be actively involved in a 'co-design'. In other instances, the producer firm might carry out the design activity on its own and simply give the supplier the specifications required to make the component, or the supplier might autonomously design and produce the product. In any case, industries these days, have started considering suppliers' involvement in the product development team as a fundamental asset for long term success. Suppliers are involved as they can also offer new components or technologies that may help to lower costs, improve product performance or reduce design time.

2.6 Performance Measures

Any effort that is not measured cannot be improved and also will be wasted. Research has been going on in the field of metrics and measures for product development for many years. The available list of metrics is inexhaustive; however, the major task is to choose or develop a set of metrics and measures that will measure and give insight to the correct product development function and corresponding efforts. A lot of areas have been identified by academics and researchers in the recent past to which metrics have been applied: innovativeness [5, 9, 19, 26]; dedicated cross-functional team and team structure [1, 12, 16, 17, 19, 26, 27]; co-location [19, 27]; empowerment of team [27]; team rewards [1, 19]; early management and marketing involvement [2, 19, 26]; product complexity [19]; number of parts [23, 27]; number of functions [27]; idea generation and screening [1]; alternative/sets of designs [15]; number of design changes [2, 18, 19, 20, 26]; joint supplier designs [2, 15, 18, 23, 26]; concurrency/overlapping of activities [2, 26, 27];

information flow/communication between various functions [11, 15]; organization size [19]; number of customers [26]; training [19]; type of production system [19]; product yield [9]; use of techniques like JIT, TQM, etc. [8, 9]; use of computer aided tools like CAD, CAM, DFX, DFM, FEA, etc. [23]; and many other variables, such as market share, internal and external support, capital invested, return on investment (ROI), product variety, material suitability, durability, revenue growth, etc.

The use of metrics depends on the particular application. Concurrent engineering needs a series of measurement criteria in order to evaluate the CE process itself as well as its performance. It will be demonstrated later in this thesis that companies tailor their CE processes according to their development goals. Then, metrics which can show the extent of achieving these goals need to be used. In Chapter 6, metrics for a CE NPD process which target the goals of time, cost and quality are classified and explained in detail.

2.7 CE NPD Goals and Challenges

The goals of a CE NPD process can be, shorter time to market, lower product development costs, higher product quality, lower manufacturing costs, reduced service costs, etc. The accomplishment of these goals, however, requires an integrated approach. The organization should be (1) strategically integrated, meaning, its activities should be linked to its goals, and (2) functionally integrated, which necessitates the involvement of many people to work together more effectively.

CE is an organizational challenge. It needs a cultural shift in the organization from the traditional engineering environment to a CE environment where openness of the organization, excellent communication, frequent interaction, harmony and close interdependency between the various units within an organization play a vital role, since the whole of the organization takes part in the quality design of the product. A high level of integration, co-ordination and information exchange is needed within the organization. The management of the organization, then, has to develop and nurture its human capital through continuous training and skill building programs in order to 'fit the change'.

CE implementations by various organizations and their goals for implementation are discussed in the next two chapters.

CHAPTER 3

3.0 CE IMPLEMENTATIONS

There are significant differences in the ways CE is implemented and conceived in different project, company and industry contexts. CE implementation approaches may be influenced by product characteristics, customer needs, technology requirements, corporate culture, manufacturing issues, project size and/or project duration. The goals associated with CE implementations also vary.

Generally, the goals associated with NPD are time, cost, quality, innovation, etc. This thesis focuses on time, cost and quality as the goals/drivers for the implementation of CE. Other drivers like innovation and flexibility were not selected owing to the following reasons.

1. Breakthrough innovation is associated with significant product differentiation and this entails a great deal of change of requirements and specifications during conceptual and preliminary design.
2. Compression of activities which is an inherent characteristic of CE can lead to a great deal of rework due to incomplete or unvalidated product requirements or technology capabilities.
3. Industries which stress innovation and flexibility do not necessarily use CE due to the above mentioned reasons.

Detailed case studies by Swink et al. [22] at 5 different companies considered quality, cost, timeliness, innovation, technical risk and project complexity as the goals driving the organizations for the implementation of CE. Different implementation approaches to CE were studied and a summary is shown in Table 3.1 and Table 3.2. The companies studied were Boeing Commercial Aircraft Division, Cummins Engine Co., Texas Instruments, Thomson Consumer Electronics, and Red Spot Paint and Varnish Co. These companies placed different priorities on the objectives of their CE NPD process depending on their corporate goals.

The five case studies by Swink et al. [22] and three case studies performed as a part of this thesis (refer to Chapter 4) were performed to investigate:

1. the implementation of CE in different organizations,
2. the differences in the implementation of CE NPD for different goals, and
3. if specific models or patterns of implementation could be established.

3.1 Case Studies by Swink et al. [22]

3.1.1 Boeing Commercial Aircraft Division - 777 Project

Boeing Commercial Aircraft division implemented CE for its Boeing 777 aircraft development. Their NPD process placed high priority on quality as the aircraft had to satisfy a diverse set of customer needs. The priority on cost and time was moderate.

To produce a high quality design, Boeing's NPD process encouraged cross-functional integration and communication. Customers and suppliers also took part in the design as members of the development team. Communication was given priority and was stressed between participating teams, customers and suppliers.

Table 3.1 Comparison of Challenges in the NPD projects [Swink et al. [22]]. Priorities and characteristics are listed as high, moderate or low

	Boeing 777	Cummins HDD	Red Spot TPO	Texas Inst. AVFLIR	Thomson DSS
Program Priorities					
Quality	**High**- long product life, stringent safety and performance requirements	**High**-significant warranty liability, varied use environments	**Moderate**	**Moderate**-challenge to improve performance and affordability	**Moderate**-customer needs fairly well defined
Product Cost	**Moderate**-increasing cost sensitivity	**Moderate**	**Low**	**High**-aggressive cost goals set	**Moderate**
Product Introduction Speed	**Moderate**	**Moderate**	**High**-first supplier to offer solution wins	**Moderate**-single source contract, schedule fairly aggressive	**High**-meeting satellite launch date critical
Project Characteristics					
Project Complexity	**High**-thousands of parts and people	**Moderate**	**Low**-essentially one product function, small number of personnel	**Moderate**	**Moderate**
Innovation	**Moderate**-new platform product built on many existing systems	**Moderate**-modular and architectural redesign	**High**-new product and application	**Low**-incremental redesign	**High**-new platform product
Technical Risk	**Low**-mostly proven technologies	**Low**-mostly proven technologies	**High**-new process, firm was inexperienced with substrate material	**Low**-no new technologies	**High**-many new components, communication standards

Table 3.2. Dimensions of Concurrent Engineering for the NPD Projects [Swink et al. [22]]

	Boeing 777	Cummins HDD	Red Spot TPO	Texas Inst. AVFLIR	Thomson DSS
Cross-functional Integration					
Primary objective(s) of Integration	**Quality** Resolve customer and competitive uncertainties, reduce development time and product cost	**Quality** Resolve customer uncertainties, reduce development time and product cost	**Time** Resolve technical uncertainties very quickly	**Cost** Reduce product cost & weight, improve performance and maintainability	**Time** Resolve technical uncertainties, reduce development time
Primary groups interacting with product designers	Customers, marketing, manufacturing, suppliers, partners	Customers, marketing, manufacturing, suppliers	Customers	Customer, manufacturing, suppliers	Suppliers, partners, regulators
Team arrangements	Complex hierarchy with many team levels including integration teams, design-manufacturing co-leadership	"Tapestry of design" including program, technical and design-build teams, design-manufacturing co-leadership	Essentially one team with changing membership plus task forces, design leadership	Program and design-build teams, design leadership, producibility consultant oversight	Single program/techn -ical team, design leadership, manufacturing teams separated from design
Communications	Formal, face-to-face communications, design database, co-location	Face-to-face communications, co-location	Informal, face-to-face communication periodic meetings	Regular meetings, face-to-face communication, co-location	Electronic and face-to-face communications, formal design reviews

Table 3.2. Continued..

	Boeing 777	Cummins HDD	Red Spot TPO	Texas Inst. AVFLIR	Thomson DSS
Concurrency					
Product Concurrency	**Moderate**-integration teams working on product variants and long range design	**Low**-some work on minor variations	None	None	**Moderate**- DSS2 work began in latter stages of DSS1
Design Concurrency	**Low**	**Low**	None	**Moderate**-overlap of some assembly and constituent component design actvities	**High**-uplink satellite, receiver developed concurrently
Project Phase Concurrency	**Moderate**-overlap in product and process design	**Moderate**-overlap in product definition, design and process design	**Moderate**-overlap in defining customer needs and product design	**High**-product and process design	**High**-product definition and design overlap overlap

Designers from many parts of the world took part in the design process. Major investment in design tools made it possible for the designers to access up-to-date designs for any of the 700,000 parts of the aircraft. The three dimensional modeling capabilities of the design system allowed the designers to fit parts together electronically. This helped in identifying and correcting design problems, and also in the execution of performance and stress analyses before physical parts were produced.

As quality was the main priority, to maximize durability and reliability Boeing used only field proven technologies. Physical prototypes were lab tested under severe environmental conditions. Extensive testing was carried out throughout the project in order to avoid any defects. The product development teams were all co-led by design and manufacturing engineers in order to cut down the development cost. Communication between design and manufacturing groups was facilitated by constructing a large design complex located adjacent to the final assembly production facilities.

As the project was spread throughout the world, and since it involved a lot of people and thousands of parts the technical complexity was very high. Boeing attempted to minimize the complexity by having several product development teams and by dividing the responsibility through multiple levels of hierarchy. By doing so, the teams with highest degree of interdependency were made to work close to each other. Communication between product designers, key suppliers and customers was frequent allowing problems to be resolved quickly.

As quality was the main priority, Boeing emphasized:

1. cross-functional integration and communication, and
2. field proven technologies and extensive testing.

3.1.2 Cummins Engine Company - HDD Project

Cummins Engine Company implemented CE in the development of its heavy duty diesel (HDD) engine. The project's highest priority was to create a high quality, durable design.

Like Boeing, Cummins HDD project emphasized cross-functional integration and communication. Cummins NPD team included internal representatives from design, manufacturing, etc., and also external suppliers. An important aspect of this project was to provide a high degree of product customization to the customers. This necessitated extensive experimentation and testing of various design alternatives which also helped to identify the specifications that provided good performance. As a result, a high quality and durable design was ensured.

To incorporate customers' needs in its HDD engine, Cummins sent its marketing personnel and engineers to meet fleet owners and truck drivers throughout North America. It also formed advisory boards with customers and distributors. Their suggestions and comments were given due consideration and were built into the design.

Manufacturing engineers were involved in all phases of the product design. Prototypes were built using full scale production equipment whenever possible, thus bringing production issues to the surface early in the development process and spurring interaction among suppliers, designers and production personnel.

As quality was the main priority, Cummins emphasized:

1. extensive experimentation and testing of design alternatives,
2. involvement of manufacturing engineers in all phases of product design, and
3. building of prototypes early in the process to identify problems.

3.1.3 Red Spot Paint and Varnish Company - TPO Project

Red Spot Paint and Varnish provides specialty paints and coatings, primarily to the auto industry. In 1991 and 1992 Red Spot's largest customer, Ford was experimenting with the use of thermoplastic olefin (TPO) materials as a substrate for exterior auto parts. These new materials had unique surface characteristics that required new paints and coatings.

Red Spot's existing product offerings could not be used with the new TPO materials. Consequently, Red Spot was not identified by Ford as a potential supplier of coating materials for TPO products. However, the company was invited to participate in data sharing and information development in this area so that it could aid in developing product specifications and learn about the technology. Red Spot's management realized that it was crucial for the company to develop a coating system that could compete effectively in this emerging area; otherwise, Red Spot would be seriously disabled in sustaining a profitable position in the auto coatings marketplace.

Speed was a critical element for Red Spot's development of TPO coatings. Red Spot used the timely development of test products and experimental results to prove to Ford that it was a capable and responsive supplier. To maximize speed and responsiveness, Red Spot used a small and flexible cross-functional team structure with few approval layers. The team included representatives from R&D, marketing, laboratory testing, technical services and manufacturing support. Under the project team, a small number of focused sub-teams were formed to complete specific tasks.

To mitigate the risks of falling behind in the development of new technology, Red Spot staff participated in capability discussions and shared information on-site with the original manufacturers of the TPO coatings. Red Spot marketing and engineering representatives developed influential relationships with Ford engineers and the personnel from the original manufacturers, and participated directly in defining the needs and uses of the product. Simultaneously, Red Spot engineers rapidly developed and tested numerous coating samples for TPO materials, thus saving a lot of time.

To emphasize speed, Red Spot:

1. used a small and flexible team structure with few approval layers,
2. participated in numerous discussions and shared information on-site, and
3. developed and tested coating samples simultaneously.

3.1.4 Texas Instruments - AVFLIR Project

Texas Instruments implemented CE in its AVFLIR project (airborne vehicle forward-looking infrared system). The AVFLIR converts infrared radiation into visible light and supports video projection, guidance and data processing functions on aircraft. The project was driven by needs to improve cost, weight, maintainability and reliability of an existing system. The product required no new technologies and the timing of the NPD activities was not aggressive. However, the primary challenge was to maximize affordability (cost). Priority on product performance (quality) was moderate.

Manufacturing-design integration was prioritized throughout the development process. Process design activities were started early in the development process and manufacturing representatives had an upper hand in finalizing the design. Process engineers, NC programmers, and tool designers were co-located with design engineers to address manufacturing concerns. As a result, design problems were eliminated, reducing the development costs. Members of the team had vast experience in many areas of manufacturing and production including metal fabrication, electrical systems, optical equipment and printed circuits. The engineers involved in the teams ensured that the product was affordable, producable, reliable, testable and easily maintainable.

As cost was the main priority, Texas Instruments:

1. emphasized manufacturing-design integration, and
2. co-located process engineers, NC programmers and tool designers with design engineers.

3.1.5 Thomson Consumer Electronics - Digital Satellite System

Thomson Consumer Electronics designs and manufactures televisions and peripheral equipment. They implemented CE in the development of Digital Satellite System (DSS) a new product for television that ensured consumers a smaller receiving dish, clearer television reception, and capacity to handle a larger number of channels than traditional home satellite systems.

Rapid development was the main priority of their project. A large commitment of organizational resources including a doubling of engineering capability was made to achieve faster time to market. Rather than taking time to develop a new technology, suppliers with experience in key technologies were made part of the product development task.

More than twenty major design activities including software design, signal definitions, communication, network design and customer integrated circuit design were carried out simultaneously. A high level of communication between internal and external groups which performed parallel activities was formalized to ensure timely information exchanges. Communication was primarily between design engineers and technical experts from different vendors and partner firms. Manufacturing and design personnel were placed in separate teams with separate budgets, and integration of design and manufacturing issues occurred at top levels of management.

The project faced a lot of technical risks and uncertainties. Thomson attacked these risks by taking the right action early on in the development process, to avoid delays downstream in the development process that could hamper the development task. At the same time Thomson personnel also participated in discussions with external agencies. Progress reviews and team meetings were properly scheduled. Team based incentives were practiced to reward the team.

As time was the main priority, Thomson:

1. committed sufficient resources,
2. established a high level of communication ensuring timely information exchanges between internal and external groups, and
3. avoided downstream delays by taking the right actions early in the development process.

3.2 Summary of Results by Swink et al. [22]

Swink et al. summarized the results for the case studies they conducted at the 5 companies as follows.

1. Projects focusing on quality relied on formal presentations and design review meetings
2. Quality programs required extended product definition and performance testing with input from design engineering, marketing and customers.
3. Projects focusing on speed (time) required frequent informal communications.
4. Efforts to reduce time involved small, informal teams led by design engineers and managers.
5. Aggressive product cost goals necessitated intense interaction between product designers and manufacturing personnel.
6. Highly innovative products required early supplier involvement and joint engineering problem solving.

7. Formal design reviews and shared design data systems aided information sharing between internal and external design groups.

Based on the case studies discussed so far, a relationship between goals and the type and degree of concurrency can be established as shown in Table 3.3. From the five case studies, it could be seen that various types of concurrency are used depending on the goals of the companies.

Table 3.3 Relationship between the Type of Concurrency and Goals

Goals / Type of concurrency	Time	Innovation	Cost	Quality
Product	Moderate	High	Moderate	Moderate
Design Phase	High	High	Moderate	Moderate
Project Phase	High	Moderate	High	Moderate

From these case studies, it is also clear that organizations implement CE in a particular way tailoring the process to achieve their goals. The next chapter focuses on CE Models, to analyze possible relationships and to establish any particular "pattern" in which organizations structure themselves to achieve their goals of time, cost and quality. The type and degree of concurrency with respect to goal relationship is also studied.

CHAPTER 4

4.0 CONCURRENT ENGINEERING CASE STUDIES

This thesis analyses the premise that specific goals for product development result in specific types of implementation or models for concurrent engineering. The investigation focused on 'patterns' of organizational structure of the CE NPD process, on the relationship among the various functions participating in the process and on the performance of the process. The review of different CE processes in Chapter 3 showed a relationship between process goals and the different types and degree of concurrency. More CE processes were studied to demonstrate that there is a relationship between goals and specific models for CE.

4.1 Case Studies

Case studies were performed as a part of this thesis on three organizations using CE for their NPD process having time, cost and quality as goals. The organizations selected had different priorities for the goals of CE implementation. The three organizations selected for the study were Newbridge Networks Corporation (NNC), Canadian Marconi Company (CMC) and Nortel. While a formal CE process was implemented recently at NNC, the other two organizations have been practicing CE for quite some time.

processes. Also, project managers in these companies were interviewed and they served as contacts to gather further information. The processes discussed below are not specific to a given project but deal with the company's general processes.

4.1.1 Newbridge Networks Corporation (NNC)

Newbridge Networks is a world leader in designing, manufacturing, marketing and servicing a comprehensive family of networking products and systems that deliver the power of multimedia communications solutions to organizations in more than 100 countries throughout the world. Newbridge provides fully managed networks for transmitting voice, data, image and traffic.

NNC implemented CE for its ATMnet project. ATMnet refers to 'Asynchronous Transfer Mode Networks' which is a technology used to allow for the efficient transmittal of traffic (telephone, voice, video, etc.) at a high bit rate so that transportation of information becomes better as the need for high speed, low delay tele-communication and data communication increases. The main priority for the implementation of CE is to get the product to market on time. Cost and quality are important, but have less emphasis.

In general, the NPD process at Newbridge can be broken down into sub-processes as follows.

1. Concept
    - Business case analysis
2. Definition
    - Release functional specifications
    - Functional specifications
    - Hardware specifications/schematic review

3. Development

- Computer aided design
- Pre-prototype production
- Prototype production

4. Introduction

- Prototype review/design release notice
- In-service testing/new product introduction
- Control introduction/manufacturing release notice

5. Maturity

- Manufacturing discontinuity

6. Retirement

- Manufacturing discontinuity declaration

The project team is formed at 'kick-off' with members from R&D, Manufacturing, Test Engineering, Design, Approvals, Component Engineering and Production Engineering. Essentially only one team, the core team is involved throughout the product development task and a support team exists within the core team. The above mentioned functions interact concurrently. Project phase concurrency and design phase concurrency (refer to Chapter 2) exist throughout the product development task where concurrency exists between various phases of the project and also within the design phase (see Figure 4.1).

Legend:

BCA	Business Case Approval
RFS	Release Functional Specifications
FS	Functional Specifications
DV	Design Verification
DRN	Design Release Notice
IST	In Service Testing
MRN	Manufacture Release Notice
CI	Control Introduction

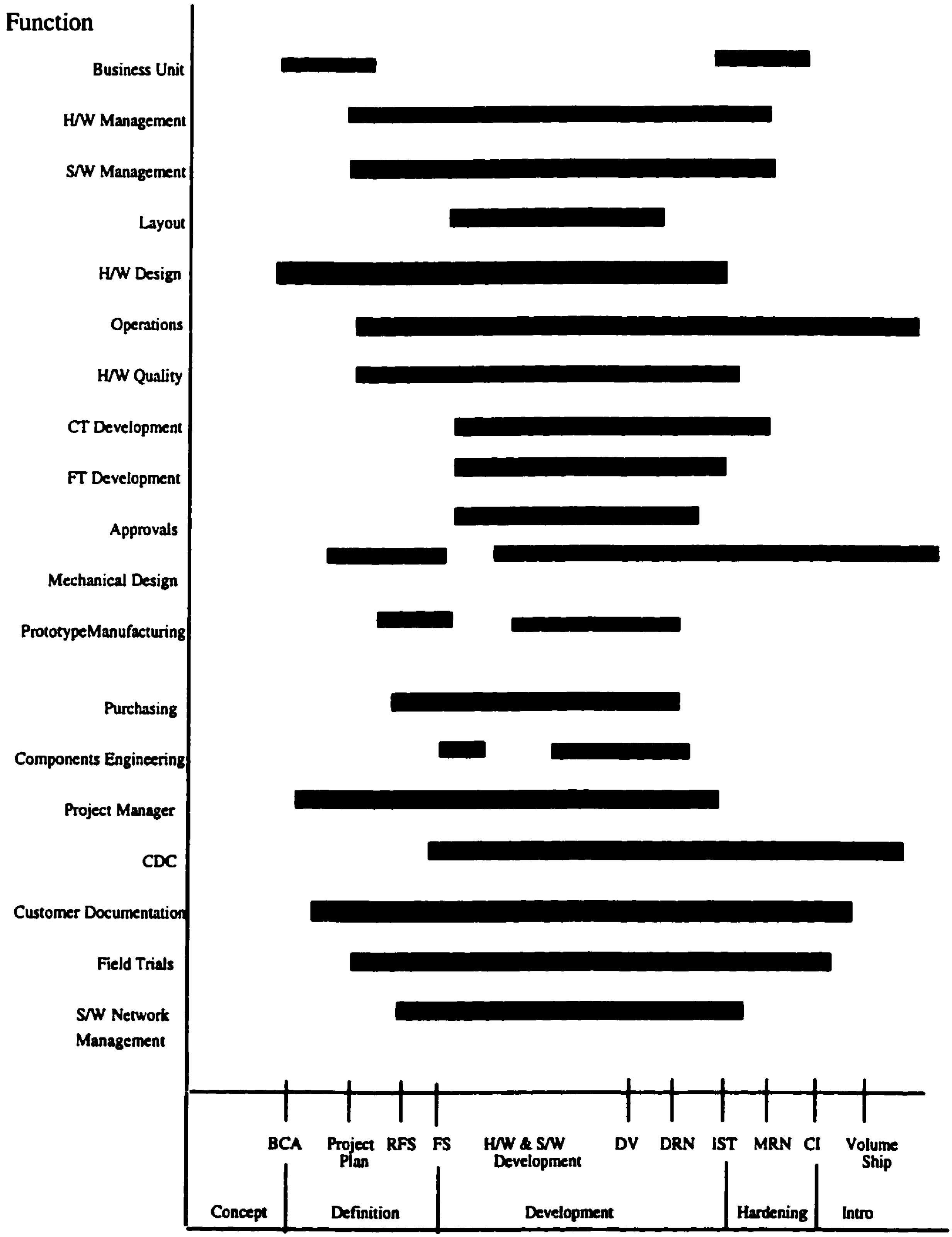

Figure 4.1 Functional Involvement in the NPD Process at NNC
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The team members are highly skilled and have vast experience in their respective functions. Resources are pumped in at the start of the project to accelerate the product development task. The members are all aware of their functional activities and are dedicated to the cause of the whole project. The team does not have a formal leader as the organization emphasizes project oriented roles over organizational roles. Engineering managers are the drivers of the team.

The test engineers and hardware design engineers are co-located to improve communication to ensure a more testable design. All other members also communicate well and have high resolution skills. The team is relatively autonomous and can make the right decisions at the right time. The team meets once a week to discuss the problems and various issues. The members of the team also communicate frequently by means of phone, fax, e-mail, etc.

Customers' concerns are considered and effectively built into the design by the design engineers. The number of design changes are reduced as a lot of design alternatives are considered pre-schematic before finalizing the design. The early integration of test engineering with design at the design verification stage helps NNC to find the design problems and to refine test applications. This also helps in delivering prototypes on time. The upfront involvement of manufacturing engineering helps to ensure its ability to manufacture the product with existing equipment and to handle new parts. Manufacturability, assemblability and serviceability issues are built into the design. The R & D unit takes part in purchasing, hardware, design, etc., which ensures better product and availability of different and better technologies for product development.

Design, test and manufacturing use computer based tools. Simulations are performed during designing which eliminates problems and also results in fewer design changes. The early involvement of test and hardware engineers makes available the functional test code before prototype production.

As time is the main priority, NNC:

1. pumps in a lot of resources at the start of the product development task,
2. emphasizes early integration of test and design engineers to ensure a testable design, and
3. involves test and hardware engineers early in the process to ensure the availability of functional test code before prototype production.

4.1.2 Canadian Marconi Company (CMC)

Canadian Marconi is a recognized world leader in the design, manufacture, sales and support of high technology electronic products, which include avionics, communications, surface transportation electronics and specialized electronic components.

CMC has been using CE for product development for quite sometime now. Their product development process is a stage-gate process (see Table 2.1). The main priority for CE implementation at CMC is reduced cost and increased quality.

In general, the NPD process at CMC can be shown as a sequence of stages (given below) with gates. See Figure 4.2 for a phase chart overview of the CE NPD process at CMC.

1. Marketing and engineering feasibility
2. Conceptual design and system requirements analysis
3. Top level design
4. Detailed design
5. PCB build and test procedures
6. System integration and verification

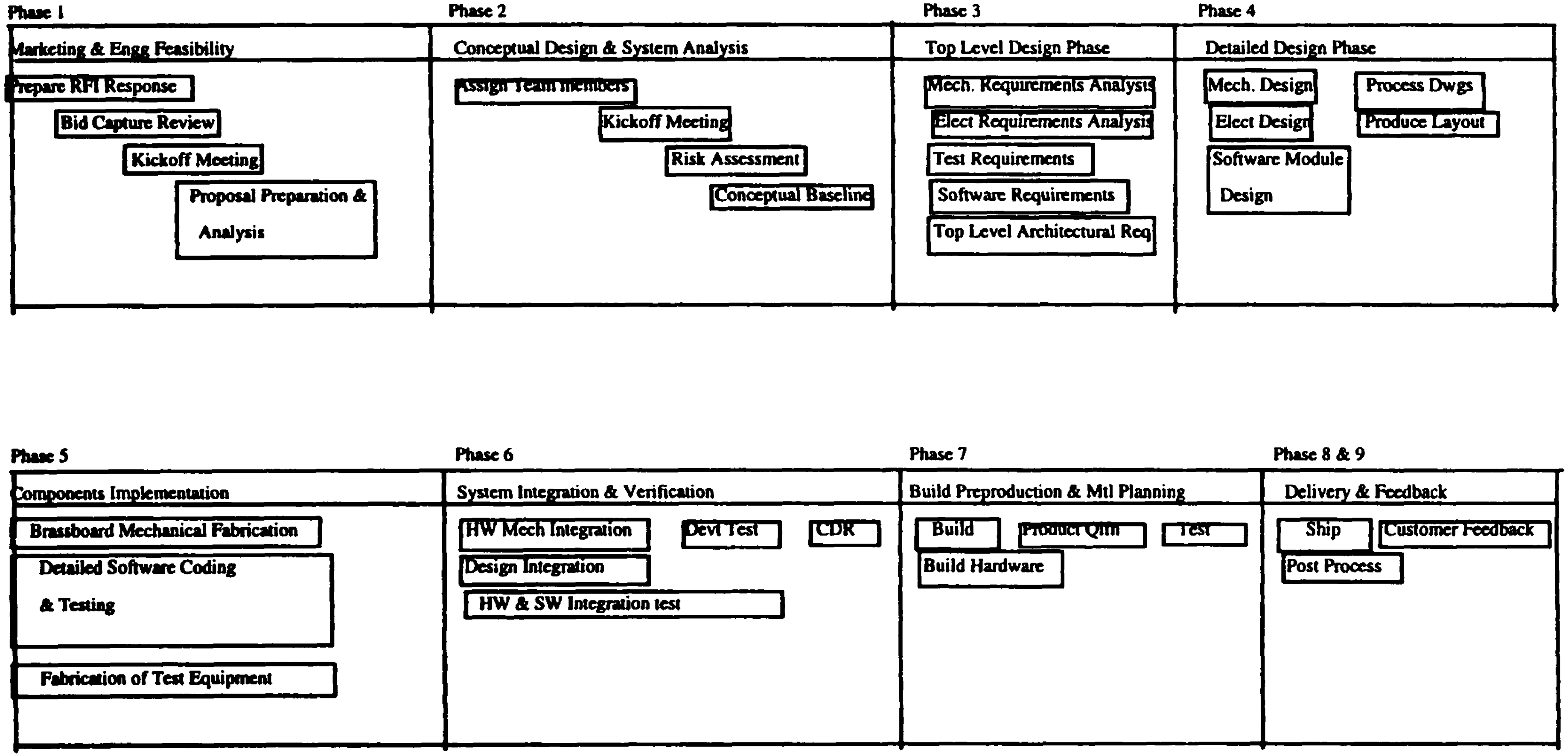

Figure 4.2 Concurrent Engineering Phase Chart Overview of CMC

7. Build pre-production & material planning
8. Qualification and development tests
9. Delivery and feedback from customer

Two teams, namely, one core team and one support team are involved in the product development task at CMC. The members of the core team include Program Management, Electrical, Mechanical, Hardware, Software Engineering, Supply Management, Manufacturing, Quality Assurance, Marketing, Customer Support, suppliers and customers. The support team also has essential members from the above mentioned functions except for the customers and suppliers. In addition to these teams, two other teams, namely, a Bid Capture Team (BCT) and a Components Action Team (CAT) are also involved. The mandate of the BCT is to review the proposal from the customer, in full detail, to ensure the complete understanding of technical and contractual requirements. The CAT includes members from Engineering, Components Engineering and Quality Assurance to build quality into the design of components. All the teams mentioned here involve themselves in the product development task right from the start of the project. As the process followed is a stage-gate process, each phase of the project follows the preceding phase in a sequential manner. However, concurrency exists in all phases including the design phase.

The team members are all highly experienced and skilled, and all the members are committed to the task. The team leader is nominated according to the task. For example, if the task involves electrical design, the electrical engineer is made the team leader. In order to imbue the spirit of leadership in its personnel, CMC emphasizes leadership 'rotation'. The teams are moderately autonomous and have very high conflict resolution skills. The team members have frequent informal meetings and also communicate effectively through telephone, fax, e-mail, etc. Often the meetings are tailored for specific purposes like concept review, design review, progress review, etc. The members contribute to the cause of the project with lessons learned. CMC conducts performance reviews and teams are rewarded for the outcome.

Suppliers and customers take part in various stages of product development. As quality is one of the mandates for CMC, the customer's voice is given due consideration. An extended product definition at the start of the project and the customer's involvement throughout the project ensures a good quality product. Suppliers take part in the development process for the supply of necessary 'hard' and 'soft' tools. Hard tools are the specific hardware necessary to produce a particular product including cutting devices, jigs, fixtures, dies, etc. Soft tools comprise the machine programming tools for production automation equipment. Suppliers also take part during the prototype phase where long lead times have been identified as detrimental to the product development effort.

CMC emphasizes the use of CAD, CAM and other computer aided tools. Design, Development, Testing and Manufacturing use these tools. Tools like DFM, DFT, etc., are more common. Simulations are performed during the system design before full scale development and also during the simultaneous design of product and manufacturing processes. The members of the team are all trained to use these tools. Moreover, they are all trained to work in a CE environment. The members are 'cross-trained' to understand the concerns of other members and also to be available to 'fill the gap' when other members are not available. CE tasks and procedures are documented excellently.

As cost is the main goal, CMC emphasizes:

1. the team members to have frequent meetings to review the various aspects of product design and development, and
2. the use of computer based tools for design, test and manufacture.

4.1.3 Nortel

Nortel is a world-wide leader in the manufacture of broadband networks, wireless communication networks, etc. Increased quality and reduced cost are the mandates for Nortel. Its product development process is also a stage-gate process and concurrency exists within each stage. (see Figure 4.3)

One core team and one support team are involved in the product development task. The core team comprises of members from Project Management, Marketing, Engineering, Test Engineering, Operations, Manufacturing, R&D and customers. The support team helps in assisting the core team and has members drawn from the same functions. The members of the team are highly dedicated and committed as the team is formed right at the beginning of a project.

Communication between the members is made effective by means of telephone, fax, e-mail, etc. The members also meet to discuss various problems and issues. The design and test engineers are co-located in order to ensure a good testable design before the prototype phase. Customers take part in the design and testing stages to voice their opinions. This ensures a good quality design for the customer. External agencies for standards and testing also take part in the product development task to check various standards and procedures that enable the product to meet market and industry requirements on time.

As quality is the prime concern, frequent design changes are made before the final design is made available. Tools like DFM, DFA, DFMA and FMEA are used to facilitate design and to reduce the number of failures. Monthly meetings are conducted to review the progress of the project. Important decisions related to product design and quality are made during these meetings. Simulations are performed before proceeding with the product development task

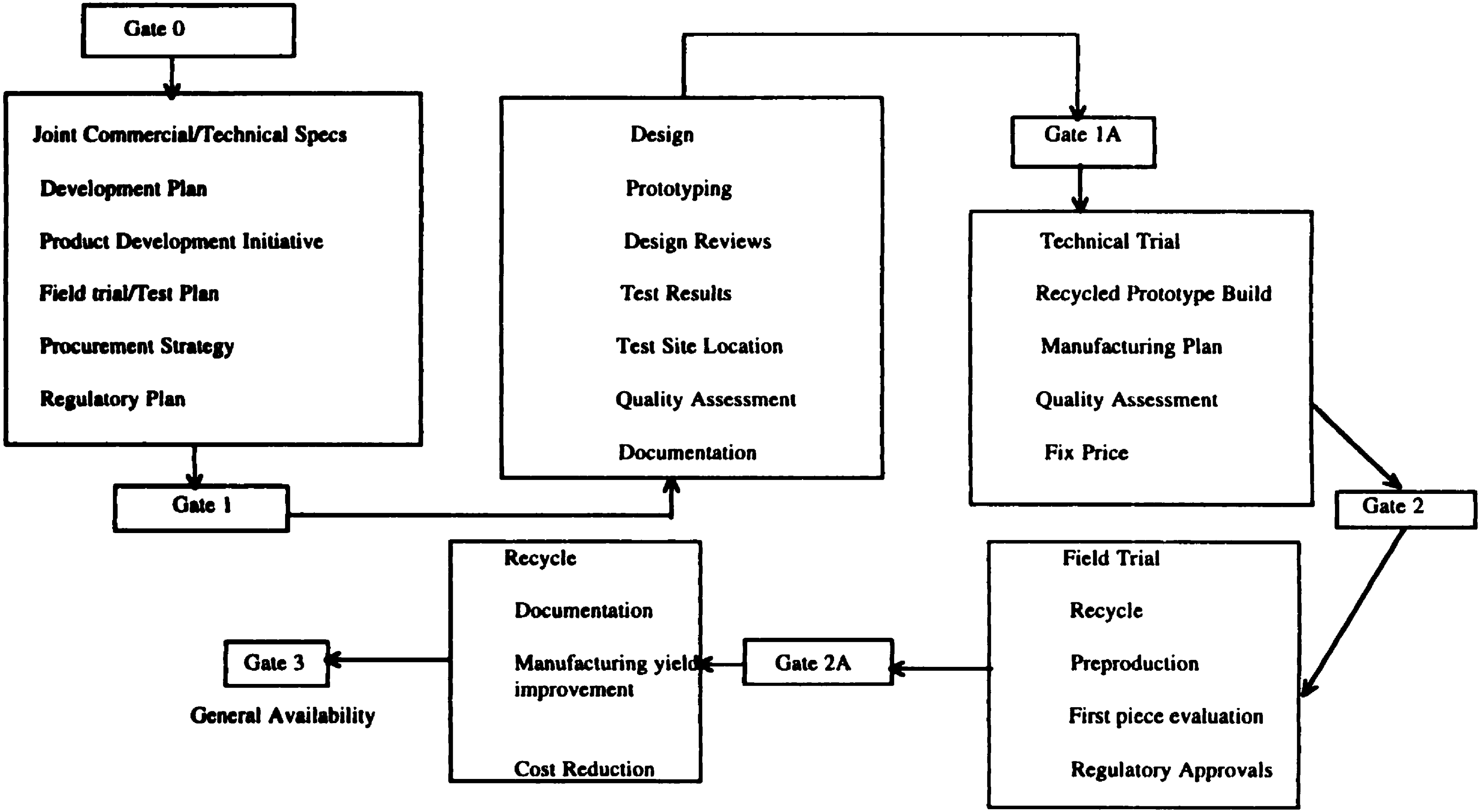

Figure 4.3 CE NPD Stage-Gate Process of Nortel

to check the feasibility of the project. Design, Development and Prototyping use a lot of computer based tools.

Management conducts a performance review of the team at the end of each stage. The teams are rewarded for correct decisions. Though formal training is not given to the members of the product development teams for a CE environment, Manufacturing and Operations are trained to understand each others' concerns.

As quality is the main goal, Nortel emphasizes:

1. customer involvement during designing and testing stages of product development,
2. consideration of many design alternatives, before the final design is made, and
3. extended product definition and performance testing to ensure high quality.

4.2 Goal-Concurrency Relationship

Table 4.1 Priorities and Degree of Concurrency

	NNC	CMC	Nortel
Goals			
Quality	Moderate	Moderate	High
Cost	Low	High	Moderate
Time	High	Moderate	Moderate
Concurrency			
Design Phase	High	High	High
Project Phase	High	Moderate	Moderate

Table 4.1 shows the relationship between type and degree of concurrency and process goals. NNC, CMC and Nortel indicated the relation of time, cost and quality to their processes. The degree of concurrency was implied from their process documentation. For example, NNC has high project phase concurrency and design phase concurrency as their main goal is time. Similarly Nortel and CMC have high design phase concurrency as their main goal is quality and cost respectively.

Product concurrency has not been included in the Table 4.1, as this data is not available. The data on the companies in Table 4.1 and Table 3.3 do not correlate exactly. The reason for this dissimilarity can be attributed to the fact that both CMC and Nortel use a stage-gate process where the process progresses in a sequential manner, and hence, the project phase concurrency is moderate in both the cases.

From the analysis of CE processes in this and the previous chapter, it is clear that companies implementing CE tailor their process to achieve specific goals and that they emphasize different aspects of the product development process. This difference in emphasis is discussed in Chapter 6. The next section deals with a summary of the observations of the case studies done at NNC, CMC and Nortel.

4.3 SUMMARY OF CASE STUDIES

Case studies were conducted on three organizations Newbridge Networks Corporation (NNC), Canadian Marconi Company (CMC) and Nortel which implemented CE NPD processes to achieve their goals of time, cost and quality (see Table 4.2). This work identifies that the companies used cross-functional teams. However, the team arrangements varied for the three companies. Six major functional groups, namely, design, manufacturing, testing, marketing, operations and quality primarily interacted as a cross-functional team. In the case of CMC and Nortel, customers' were part of the development teams. Suppliers were also integrated into the team in the case of CMC. Within the design function, areas like mechanical, electrical, software and hardware were seen to be integrated.

The number of teams and the number of team members involved in the product development process for the three organizations varied. In the case of NNC only one core team was involved in the product development task, and the support team was actually a part of the core team. In the case of CMC and Nortel there existed two separate teams, one core and one support. In addition to these teams CMC also had special teams called Components Action Team and Bid Capture Team. The disparity in the number of teams is attributed to the fact that the three companies have different product requirements, technical complexities, and operate in very different markets.

The team members were all highly experienced and skilled, and the teams were all very dedicated to the product development task for all three companies. There was no specific team leader in the case of NNC and Nortel, whereas, a team leader was nominated according to the product development task at CMC. This leadership sometimes 'rotated' giving equal responsibility to all the team members. The team members at all three companies were all aware of their functional activities and were committed to the product development task.

All the teams studied were moderately autonomous requiring senior management approval only under some special conditions. In order to facilitate decision making and for effective communication, test and design engineers were co-located in the case of Nortel and NNC. Team members communicated reasonably well by having face-to-face conversations and also by means of phone, fax, e-mail, etc. The team members met frequently to discuss the problems and progress with respect to the product development task. While teams at NNC met every week, team meetings were held once a month at Nortel. The team at CMC met frequently though the meetings were tailored for primary objectives like concept review, design review, etc. The team members contributed with the 'lessons learned' towards the progress of the project. The team at CMC also shared design databases which made the updates and design changes instantly available to other members. The teams at all the three companies used a lot of information technology tools and computer based tools for various purposes. Simulations were performed many times to check the physical and technical specifications. Design for Manufacturability, Design for Assemblability, etc., were used by the companies in the product development task. Other than design, testing and manufacturing also used computer based tools.

In the case of CMC, members were cross-trained in order to understand the requirements of other members and also to be sensitive to their needs. This also helped the team members in 'filling the gap', when the concerned team member was away or not available. In the case of Nortel manufacturing and operations engineers were trained to understand each others' concerns.

Computer based tools were used in various departments in order to achieve the benefits in terms of time, cost and quality. Team members at CMC and Nortel were trained to use the software to meet their requirements. At CMC and Nortel, performance reviews were conducted and the teams were rewarded for making proper decisions and for 'staying on track'.

A point to be noted here is that all three companies studied in this thesis, followed more or less the same CE NPD process. The CE NPD process involved 'concept exploration' as the starting activity and 'volume shipping' as the ending activity with a lot activities being done concurrently. Concurrency also existed throughout the process from concept exploration to volume shipping. Though not many striking differences could be found in the CE NPD processes of the three companies studied, the results of this study seem to concur with the results of Swink et al. [22] involving Boeing, Cummins Engine, Texas Instruments, Red Spot Paint and Thomson Electronics.

Table 4.2: Snapshot of Concurrent Engineering Practice for NPD Projects

	Newbridge Networks	Canadian Marconi	Nortel
Priority	**High-Time** Moderate-Quality Low-Cost	**High - Cost** Moderate - Quality Moderate-Time	**High - Quality** Moderate - Cost Moderate-Time
Type of Concurrency	Project Phase Concurrency & Design Phase Concurrency	Design Phase	Design Phase
Team Arrangements	Essentially one team with members from R&D, Manufacturing, Test Engg, Design, Approvals, Component Engg & Product Engg	Two teams - one core and one support. Core team - Program Management, Electrical, Mechanical, HW, SW Engg, Supply Management, Manufacturing, QA, Customer support, Suppliers and Customers, Manufacturing	One core and one support. Core - Project Management, Marketing, Engg, Test Engg, Manufacturing and customers
	Highly experienced, skilled and dedicated team Team formed at kick-off	Highly experienced and skilled team Team formed at Kick - off	Highly dedicated team Team formed at kick-off
	No team leader. Engg Manager "driver" of the team	Team leader is nominated according to the task. Leadership "rotates" within the team. Responsibility is shared	No team leaders
	Each member aware of all functional activities. Team has strong degree of ownership of product. Highly committed and hence no net increase in resources.	Highly committed team. Each member "cross-trained" to be sensitive to other members' activities	High commitment to project goal
	Relatively autonomous. Team members have high resolution skills Emphasis to members on project oriented roles than on organization roles	Moderately autonomous and Very high conflict resolution skills Performance reviews conducted and teams rewarded	Moderately autonomous Team is rewarded for achieving the targets and for taking right decisions
	FT Engr & HW Designer co-located.		Design and Testing co-located
QFD	Customers' concerns considered	Customer part of the team. Contributes at concept, development, testing, prototyping and post process stages Extended product definition and performance testing	Customers' concerns are satisfied. Customer takes part and testing stages.
Design Integration	Less number of design changes. Alternate designs	Suppliers and customers take part in various stages of	Relatively more design

Table 4.2 Continued.

	Newbridge Networks	Canadian Marconi	Nortel
	considered pre-schematic.	development.	changes
		Tools like DFM, DFA, etc., are used	Tools like DFM, DFA,DFMA, FMEA are used
Communications	Weekly meetings, Phone, fax, e-mail and face to face conversations Co-locations	Frequent meetings - informal, design databases etc.,.	Telephone, fax, e-mail and face-to-face conversations and monthly meetings
	Progress and Problems discussed	Short well planned meetings. Meetings tailored for primary objectives like design review, concept review etc.,. Each member contributes to the project with the "Lessons learned"	Progress and problems discussed
Funcional R&D involvement	R & D takes part in purchasing, Hardware, design etc.,. Ensures better product and availability of new technology	Not much of involvement	R&D takes part in estimating, pricing, finance, design & development.
Use of computer tools	Design, testing and Manufacturing use computer based tools	DFM, DFT, etc., are used. Design, Development, Testing, Manufacturing use these tools. Simulations performed for system design before full scale development and also for simultaneous design of product and manufacturing processes	Design, development and prototyping use these tools. DFM, DFA, DFMA are used and simulations performed.
CE Training	No formal training	Members are cross trained. Each member sensitive to other members' concerns and requirements	Manufacturing and operations are trained so as to understand each others' concerns
	CE Procedures and tasks defined	Excellent documentation of CE procedures and tasks	

CHAPTER 5

5.0 CE METRICS - A CLASSIFICATION

Metrics are measures that provide assessments and evaluations in a relative or an absolute sense [21]. Concurrent engineering needs a series of measurement criteria as the product development process involves concurrent and overlapping processes occurring across various disciplines in the organization. As span time is reduced, concurrency increases and hence, management becomes more critical and complex, metrics are very important.

Appropriate metrics and methods for qualifying the processes also vary considerably. Choice of appropriate metrics depends on the available data, its completeness, degree of overlap, ambiguity and so on. Effective metrics are those that are 'simple' in nature, easy to understand and based on various objectives of the organization [21].
Biren Prasad [21] suggests the following benefits from using metrics.
Metrics help in

- identifying the process bottlenecks and eliminating the root causes,
- serving as a tool for assessing and evaluating performance and efficiency,
- assisting teams in understanding engineering processes better,
- monitoring progress,
- identifying and minimizing product, process and organization complexity,
- increasing objectivity and improving productivity,

- evaluating competitors' products and identifying best product features and practices, and
- reorganizing the engineering tasks and making critical decisions earlier in the life cycle.

By intensely integrating the various functions in the product development process with respect to product and market concepts, specific areas of focus need to be identified and measured. Variables for measurement must be chosen in such a way that they indicate the performance of the product development process well. The list of variables available in the research literature is inexhaustive; however, the task is to determine a set of metrics that define the current product development function and effort. The metrics that are chosen should not only be meaningful for measuring today's environment, but also should be applicable for measuring progress in an ongoing manner. The specific measures used, however, should be quantitative whenever possible.

Though metrics for product development are available at large, metrics for product development processes which target specific goals are yet to be classified. This thesis focuses on time, cost and quality as the goals of the CE NPD process. This chapter deals with metrics targeted specifically for those goals (see Table 5.1). The ability of the metrics to indicate process performance and achievement of goals has also been shown.

Metrics for a CE NPD process should deal with the areas or dimensions of CE that are critical and significant in the implementation of CE, for example, cross-functional teams, team communication, design integration, use of computer tools, etc. Metrics have been classified considering the above mentioned factors. The metrics mentioned in Table 5.1 seem to appear largely in the research literature. Some organizations are using some of the metrics mentioned already. The cross-functional integration metrics by Goh & Ganapathy [7], timeliness of information transfers metric by Klapsis and Thomson [13] and use of computer based tools metric by Prasad [21] have been included in this classification along with other process based metrics. Apart from the process based metrics, a few productivity metrics that can measure the achievement of goals have also been classified. The list is not 'final' and more metrics can be added in future, which appropriately indicate process capability.

5.1 Cross-functional Integration Metrics

The performance of CE is predictably influenced by cross-functional team based factors, for example, the dedication of the team, communication among members, team member turnover, etc. Goh and Ganapathy [7] have classified a system of performance measures based on the above mentioned factors which are described below.

5.1.1 Team cohesiveness

This metric gauges the evolution of the team as a working group. The degree of cohesiveness is a function of the length of time that a team has worked together.

The measure of cohesiveness is given by

$$C=\sum_{i=1}^{s} w_i \bullet t_i,$$

where s is the number of subgroups in the cross-functional team, w_i is the proportion of subgroup i with respect to the total number of members in the cross-functional team and t_i is the length of time subgroup i has worked together. Note that, one person can be a member of more than one subgroup and one member can also form a subgroup.

This metric is a weighted average of the time the members of a cross-functional team have worked together. This allows for the possibility that a cross-functional team may have sub-groups of members who have worked together before, and therefore, be more cohesive than other sub-groups within the cross-functional team.

Table 5.1 Classification of Metrics for CE NPD Processes Focusing on Time, Cost & Quality

	Time	Cost	Quality
A. Process Metrics			
1. Cross-functional Integration			
a. Team cohesiveness	+	+	+
b. Team member absenteeism	+	+	+
c. Team member turnover	+	+	+
2. Design Integration			
a.. # of design changes	+	+	*
b. # of alternative designs	+	+	+
3. # of Activities Overlapped	+	+	*
4. Timeliness of Information Transfers	+	+	+
5. Use of Computer Based Tools	+	+	+
6. CE Training	+	+	+
B. Productivity Metrics			
1. Timeliness	+	+	*
2. Make time/ Span time	+	*	*
3. Design cycle time	+	+	+
4. First time yield	*	+	+

(+) sign indicates that the metric is effective for measuring desired goals

(*) sign indicates that the metric is not very effective for measuring desired goals

The higher the value of C, the higher is the cohesiveness. However, one drawback of this metric is that, even if the value of C is high, problems and difference of opinion among members can have a negative impact on the team's performance.

Cohesiveness among members is also related to mental health, adjustments, feelings of security, etc. [28]. Results of a study by Seashore [28] show that a high cohesive team has greater productivity and also there exists only less variation in productivity among members. Also, cohesiveness is related to opportunity for interaction among members and to the degree of prestige attributed by the members to their jobs.

The other metrics proposed by Goh and Ganapathy [7] are team member absenteeism and team member turnover. These metrics are suggested to be used in conjunction with the above mentioned metric.

5.1.2 Team member absenteeism

This is a count of the number of times that a team member has been absent from meetings during the existence of the cross-functional team. A high count for even a single member may indicate a poor participation of the members in meetings. It could also have an effect on the cohesiveness of the team. A high count for more than one member should serve as a warning to the team that it might fail to achieve its objectives.

5.1.3 Team member turnover

The team member turnover metric is a count of the number of turnovers during the existence of a cross-functional team. A high count indicates frequent replacement of members which may not be conducive to achieving high cohesiveness and a high level of communication among members during meetings. For example, if a member joins a team during the product development task, it takes a lot of time for that member to learn and also understand his role with respect to the product development task.

Again, these measures also serve as diagnostic tools to identify probable reasons for a success or failure of the product development task. The numerical values associated with a high and low value may vary with the team and organizations using them.

5.2 Design Integration

5.2.1 Number of design changes

This metric indicates the number of changes made during the product development task. The majority of a product's manufacturing cost is determined by the end of the design stage. As the number of design changes increases, it increases the design cycle time and increases the time to bring a product to market and also the cost. It can also be an indicator of poor quality of design.

'More' design changes is an indicator of poor performance and defeats the whole purpose of a CE process. 'Less' design changes on the other hand, indicate a good performance by the cross-functional team in solving all the design related problems earlier in the process. If there is a lower number of design changes, it is beneficial for the product development task. It also serves as a measure to indicate that the product is brought to the market on time at less cost and better quality. However, a point to be noted here is that, a clear distinction has to be made between design changes that are necessary for product development because of competitive and technical changes in the marketplace and those arising due to mistakes and lack of concurrency.

5.2.2 Number of alternative designs

This quantitative metric helps measure the process of obtaining the best design. When a number of alternative designs is considered, it gives a chance for the product development team to consider and reason about the different alternatives both at the conceptual and parametric levels. As a result the inferior alternatives are eliminated and one final design solution emerges. The more designs considered, the greater the chances for achieving high quality, reduced cost and good time to market.

5.3 Number of Activities Overlapped

Overlapping means doing various activities in parallel rather than doing them sequentially. By overlapping activities, the span time, i.e., the total time taken to complete the product development from concept until the product reaches market, can be greatly reduced.

Overlapping activities saves time due to 1) parallel processing of activities, 2) better and more timely identification of design problems, and 3) improved communication earlier and throughout the team.

This metric serves as an indicator of the degree of concurrency in the process. In general, the higher the number of overlapped activities, the higher the degree of concurrency and the shorter is the development time. A lower number of overlapped activities indicates a lower degree of concurrency in the process and may also indicate opportunities for improving the process to achieve objectives.

5.4 Timeliness of Information Transfers

This quantitative metric, proposed by Thomson and Klapsis [13] for information intensive processes, is very useful for a CE NPD environment.

An information transfer is a hand-over of knowledge from one individual or group of individuals to another during a process or project [13]. This communication of information is informal or formal. An information transfer typically marks the completion of a preceding activity and the beginning of a following activity.

A flow chart of key information transfers can be used to measure the progress of a project and also to predict the time to project completion. The timed data flow pattern can identify critical steps which can change with time, i.e., the dynamic critical path of work, and can, thus, assist to improve coordination among various functions.

5.5 Use of Computer Based Tools

This metric has been dealt with extensively by Biren Prasad [21] as the Value Characteristic Metric. He says that the first step in CE is to develop predictors or metrics for object based systems and the supporting analysis for assessing product and process behaviour. Many of the computer based tools are off-the shelf tools which a company can buy and integrate. Some are product specific and some are process specific.

Prasad [21] also suggests 4 different types of sub-metrics with the areas to which they can be applied given within brackets as shown below:

1. Simulation and analysis (materials/features substitution or selection, simulation & analysis as an integral part of design, FMEA, etc.)
2. Product feasibility and quality assessment (product quality assessment, materials usage, features assessment, design for simplicity, etc.)
3. Design for X-ability assessment (Design for Manufacturability, Design for Assembly, Design for Compatibility, etc.)
4. Process quality assessment (Design for Quality, Design for Robustness, etc.)

Design for X-ability assessment metrics, e.g., DFM and DFA could be effective in reducing the number of parts or processes. Metrics for process quality assessment can be effective for ensuring a product's agility, such as gathering data pertaining to performance, precision, tolerances and so on. Simulation and analysis help to drive corrective action, such as material feature substitution or selection, assembly variational analysis, failure mode and effectual analysis, risk assessment and so on.

- The main advantage of this metric is that it formalizes and exposes errors and inefficiencies that may be overlooked in the complexity of the product development process.
- It helps to monitor CAD programs relative to specifications.
- This metric has an influence on designers and helps in getting their attention when parameters appear out of bounds or when processes appear out of control.
- This metric serves as a tool for failure analysis, variational analysis, risk assessment, etc.

However, a limitation of the metric is that it cannot be used as a metric for benchmarking one organization against another. For example, it would be difficult to assess and compare the performance of two organizations using the same computer based tools or tools of comparable sophistication, as there might be other factors like efficient communication, good interpersonal relations, etc., for one organization to perform better than another.

5.6 CE Training

This metric is defined as the number of hours spent on training per person (product development team members) in CE culture.

CE Training = Number of hours spent on training per product development member

CE can build a stronger, better skilled and more efficient company if the members of the product development team are trained in CE culture. Successful teams quickly recognize that concurrent design can stretch technical resources to the limit. They adopt techniques for reducing meeting time, making decisions more quickly and developing more efficient communication techniques. Though this metric deals with the investment in people, it helps to assess timeliness, cost reduction and enhanced quality.

5.7 Productivity Metrics

Listed below are some productivity metrics. These metrics can be applied to any organization and are not specifically meant for a CE environment.

5.7.1 Timeliness

Timeliness = Delivered time / Promised time

This is an indicator of company performance with respect to its strategic goals in terms of time. A value greater than one indicates that there have been delays in the process. For example, a process can be delayed because of lower resource commitment, improper communication, etc.

5.7.2 Make time / Span time

The ratio of make time to span time can be applied to various individual stages of the product development task (sub-processes) or to the entire process. Make time represents the total effort taken to complete any activity and span time represents the length of total time taken, i.e., the time from the start of the process until the finish. This metric helps to indicate critical points in a process and the amount of time delay at a point. It also helps to assess process performance for eliminating delays and wastage.

5.7.3 Design cycle time

Design cycle time = Time taken/ Design process

This ratio represents the time taken to complete the design process, e.g., mechanical design, electrical design, software design, etc. It helps in assessing the improvement in the design process. This also represents the impact of design changes and helps to control the change and leads to effective designs.

5.7.4 First time yield

First time yield = Products produced the first time / Total products produced

This metric represents the ratio of products produced the first time without rework to the total products produced for a given period of time. This metric naturally helps in assessing the quality of products and also serves as an indicator of the amount of rework occurring in the manufacturing process. It serves as a measure for increasing quality and lowering costs.

CHAPTER 6

6.0 RESULTS

Previous research in the field of product development has shown that product development processes are tied to organizational goals [22]. This thesis focuses on the CE process and the goals driving the process. Innovation, time, cost and quality are the principal goals for the implementation of CE. This thesis studies the existence of specific models in implementing a CE NPD process corresponding to the goals of time, cost and quality. In addition, metrics to evaluate the performance of the CE NPD process have been classified according to the goals of time, cost and quality.

6.1 MODELS

Organizations tailor their CE NPD process according to their goals. Though they tailor their processes for specific goals, the general NPD process followed by most companies is more or less the same. However, the emphasis on various stages of the NPD process is different for different companies depending on their goals (refer to Figure 6.1).

- Organizations focusing on innovation put more emphasis on stages/activities between concept generation and detailed specification.
- Organizations focusing on time put more emphasis on stages/activities between detailed specification and detailed design stages in a CE NPD process.

- Organizations focusing on quality put more emphasis on the stages/activities between preliminary design and volume production stages.
- Organizations focusing on cost also concentrate on the various stages between preliminary design and volume production in order to ensure the manufacturability of the design.

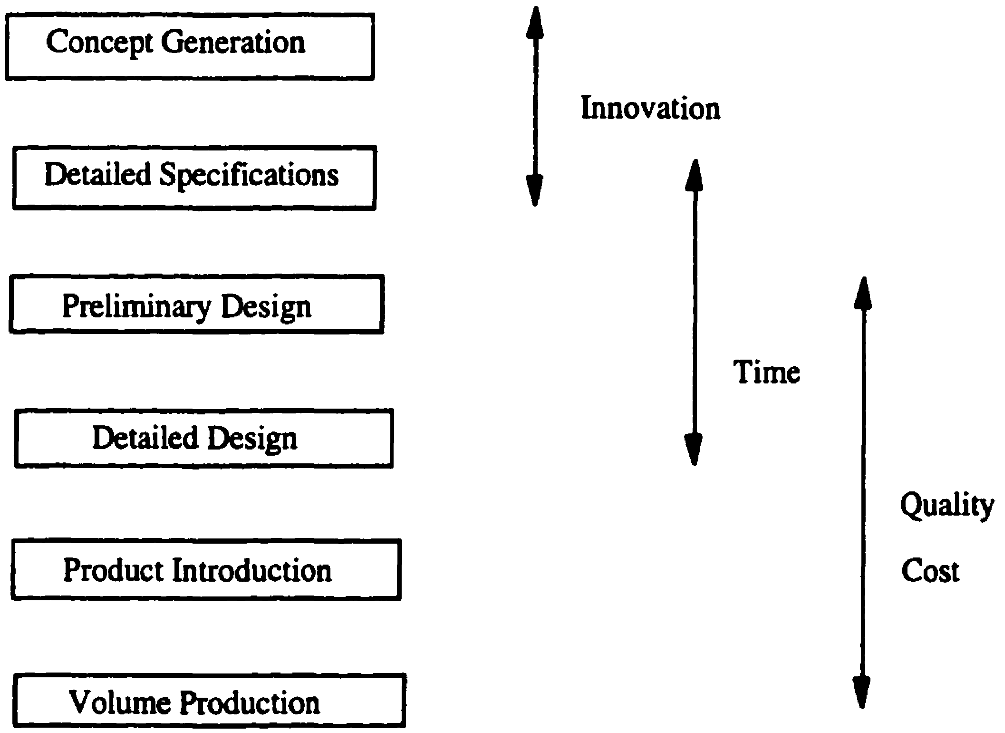

Figure 7.1 CE Models: Emphasis on Different Stages according to Specific Goals

The results were deduced from the three case studies that were performed as part of this thesis and from the five case studies performed by Swink et al. [22] as discussed in Chapters 3, 4 and 5.

In the following sections the above results are discussed with evidence from the case studies performed as a part of this thesis and those from the work of Swink et al. [22].

Fact 1:

Organizations focusing on **time** emphasize more on stages/activities between detailed specification and detailed design in a CE NPD process.

- NNC pumps in a lot of resources upstream to get a product out on time. The team has excellent communication between design and manufacturing engineers. Teams are relatively autonomous and have high resolution skills, which is important for the teams to get the product out on time. They are highly committed to the task, and hence, there is little net increase in resources until the finish of the project. NNC also emphasizes early integration of test and design engineers to ensure a testable design. The test and hardware engineers involve early in the process to ensure the availability of functional test code before prototype production.
- Thomson Consumer Electronics committed sufficient resources upstream in the product development process including a doubling of its resources to get the product into the market on time. It established a high level of communication between internal and external groups ensuring timely exchange of information. Delays downstream in the product development process were avoided by taking the right actions at the right time. Red Spot used small and flexible team structure with few approval layers in order not to waste time by waiting for approval from senior management. It participated in discussions and shared information on-site and developed and tested the coatings simultaneously to save time [22].

Fact 2:

Organizations focusing on **cost** put more emphasis on the various stages of the CE NPD process between preliminary design and volume production.

- CMC fosters intense interaction between design and manufacturing personnel. Design for Manufacturability is emphasized and the teams use tools like DFM and DFMA in order to ensure the manufacturability of the design and thereby to reduce cost of product development.

- With cost as their main goal, Texas Instruments emphasized manufacturing-design integration and co-located process engineers, NC programmers and tool designers with design engineers [22].

Fact 3:

Organizations focusing on **quality** put more emphasis on stages/activities between preliminary design and volume production stages.

- Nortel and CMC, where one of their priorities is quality involve customers and suppliers in product development. Though teams are not co-led by design and manufacturing engineers, co-location of design and testing personnel to ensure good quality is the case in Nortel and NNC. Extended product definition and performance testing are done at CMC and Nortel to ensure that the product meets the quality standards of the customers.
- To achieve quality, Boeing emphasized cross-functional integration and efficient communication. Only field proven technologies were used. Extensive testing was done at every stage of development to ensure quality. Cummins also emphasized extensive experimentation and testing of design alternatives to ensure quality. Manufacturing engineers were involved in all phases of product development at Cummins to improve the quality aspects of the design. Prototypes were built early in the process to identify problems and to eliminate them in the final design to achieve superior quality. [22]

6.2 METRICS

As mentioned earlier in this thesis, any effort that is not measured goes merely as a waste. Organizations tend to tailor their product development process for specific objectives but continue to use a generalized set of metrics for measuring and assessing product development performance. The metrics are not goal specific.

One of the objectives of this thesis was to classify metrics for CE NPD processes aimed at achieving time, cost and quality. This was done and shown in Table 5.1. As pointed out already, the metrics are used to measure certain product development process attributes, but the metrics are not restricted to measuring specific goals. This is because all organizations practicing CE NPD follow more-or-less the same process emphasizing different stages of product development corresponding to their goals.

Conclusions obtained from this thesis and scope of future research have been discussed in the next chapter.

CHAPTER 7

7.0 CONCLUSIONS

The study of the use of models and metrics in concurrent engineering has resulted in the following conclusions:

1. The experience with using CE in NNC, CMC and Nortel and in the companies studied by Swink et al. [22] shed light on the CE NPD process. Though the companies follow more or less the same process, their emphasis on various stages of the NPD process is related to the goals they wish to achieve.
2. There is a definite pattern in which organizations implement CE with respect to their goals. As a result specific models for CE NPD processes focusing on time, cost and quality can be derived and this is shown in Figure 6.1.
3. The degree of cross-functional integration and concurrency are different for different goals. This was summarized in Tables 3.1, 3.2, 3.3 and 4.1.
4. Generally, CE reduces the time necessary to perform the product development task. Hence, metrics for a CE NPD process generally focus on time reduction as an indicator of superior performance. However, when the objectives for a CE NPD process are specific, the metrics used should also be specific. The metrics classified in this thesis can serve as a 'start' for developing metrics for a CE NPD process targeted towards specific objectives.

5. Metrics can be classified according to the goals. However, the metrics are not restricted to measuring the accomplishment of a simple goal.
6. Finally, there has been a wealth of experience gained by the companies which have used CE. The lessons learned can help other companies to develop processes which will achieve their goals.

7.1 FUTURE RESEARCH

CE is a new approach and is evolving more rapidly as companies adapt to compete in the global marketplace. Companies use cross-functional teams and do activities concurrently to address their specific needs in product development. The goals for the implementation of CE are time, cost, quality, innovation, technical risk, flexibility, etc. The approaches to CE implementation are influenced by product characteristics, customer needs, technology requirements, corporate culture, manufacturing issues, project size, and/or project duration. This thesis has focused on time, cost and quality as the main goals for the implementation of CE. It has been shown that the approaches to CE implementation, the degree of cross-functional integration and concurrency are different for different goals.

The results of this thesis and previous research need to be interpreted with respect to product, market, company and industry contexts. More research is needed in the future to relate the differences in implementation of CE with respect to specific goals. More detailed study is needed to express the degree of cross-functional integration and concurrency existing in a CE NPD process as it relates to process goals.

Though metrics for product development are innumerable, specific metrics for the CE NPD process are needed. Metrics for any process change with the dimensions of the process, for example, the method of implementation, the people involved, their skills, etc. As organizations set very specific goals or objectives for their CE NPD processes, metrics will have to be developed which can measure the benefits of how process performance fits the specific goals. In such an environment goal specific metrics will be needed.

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