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Customizing Concurrent Engineering Processes: Five Case Studies

Morgan L. Swink, J. Christopher Sandvig, and Vincent A. Mabert

Once hailed as the salvation of U.S. manufacturing competitiveness, concurrent engineering (CE) offers the potential for faster development of higher quality, more producible products. Unlike traditional, serial approaches to new product development (NPD), CE emphasizes cross-functional integration and concurrent development of a product and its associated processes.

As Morgan L. Swink, J. Christopher Sandvig, and Vincent A. Mabert explain, however, CE is not a plug-and-play process. Successful CE implementation approaches differ depending on such factors as product characteristics, customer needs, and technology requirements. We can better understand those differences by examining CE implementation in the five NPD programs discussed here: the Boeing 777 aircraft, the heavy duty diesel engine at Cummins Engine Co., the thermoplastic olefin automotive coating at Red Spot Paint and Varnish Co., the airborne vehicle forward-looking infrared night vision system at Texas Instruments, and the digital satellite system at Thomson Consumer Electronics.

Teams provide the primary integration mechanism in CE programs, and three types of teams appeared frequently in these projects: a program management team, a technical team, and numerous design-build teams. Depending on the project's complexity, an integration team may be needed to consolidate the efforts of various design-build teams. Task forces also may be formed to address specific problems, such as investigating an emerging technology.

Some projects emphasized collocation and face-to-face communication. Others relied on phone conversations, documents, and electronic mail. Projects focusing on design quality relied on formal presentations and periodic review meetings. Projects emphasizing development speed required frequent, informal communications. Programs addressing design quality required extended product definition and performance testing, with input from design engineering, marketing, and customers. Efforts to reduce development time involved small, informal teams led by design engineers and managers. Aggressive product cost goals necessitated intensive interaction between product designers and manufacturing personnel. Highly innovative products required early supplier involvement and joint engineering problem solving. Formal design reviews and shared design data systems aided information sharing between internal and external design groups.

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Introduction

The 1980s and early 1990s have witnessed a dramatic evolution in new product development (NPD) processes as global competition has led to shorter product life cycles and necessitated higher quality, more producible products. This period has also seen an increase in the complexity of products due to the rapid development of many new material and process technologies. These market and technology trends are expected to continue [13] placing even greater demands on the NPD process.

Many well-known companies have responded to these increasing demands by adopting concurrent engineering (CE) approaches to NPD, including General Motors, Chrysler, Ford, Motorola, Hewlett Packard, and Intel [3,25]. A conventional definition of CE is given as follows: "Concurrent engineering means developing the product and all its associated processes, that is, manufacturing, service, and distribution, at the same time" [16, p. 91]. Two primary aspects of CE reflected in this definition are cross-functional integration and concurrency.

Conventional NPD programs execute activities such as concept exploration, design, testing, and production serially. Furthermore, development activities are typically controlled by only one functional organization at a time (e.g., marketing, engineering, manufacturing). As each organization completes its design and development activities, it passes control and responsibility to the next function. In the CE approach, multifunctional teams work on multiple aspects of a new product simultaneously. Control and responsibility are shared among functions, and development activities are overlapped. In many ways, modern CE approaches are reflective of stage-gate development processes developed over the past decade [5]. Important management tasks for CE include goal setting and analysis, establishing and controlling means of cross-functional integration, and fostering communication between development team members [23].

The scopes of concurrent engineering approaches appear to vary widely from a narrow emphasis on "design-for-manufacture" objectives to more comprehensive, product life-cycle considerations. According to Nevins and Whitney [19], early CE approaches that focused only on identifying part fabrication issues early in the development process have given way to expanded approaches that include assembly issues and groups of parts in design decisions. The U.S. Department of Defense emphasizes "cradle-to-grave" considerations in development programs with the primary objective of coordinating decisions between different engineering functions [17]. Market-oriented approaches to CE tend to focus on integrating customers' needs and marketing strategies into design decisions, emphasizing the roles of marketing and R&D personnel in fostering information transfer between the two groups [18]. Recent authors have suggested an even broader view of CE, addressing larger environmental and societal cost issues [1].

Goals associated with CE implementations appear to vary as well. Trygg [24] maintains that early CE developments were aimed at improving quality or minimizing product acquisition costs, whereas more recent programs have emphasized reductions in product development time.

It is becoming clear that there are significant differences in the ways CE is conceived and implemented in different project, company, and industry contexts. Our review of the literature and early talks with managers suggested that CE implementation approaches may be

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influenced by product characteristics, customer needs, technology requirements, company experience, corporate culture, manufacturing issues, project size, and/or project duration. When these influences are important, managers need to identify the specific challenges of each project and customize their NPD processes accordingly.

The benefits of CE approaches have been frequently suggested. Compared with the traditional departmental-based serial approach, CE approaches can produce higher quality, more producible products, in less time [4,19,22,25]. However, there has been no empirical research that investigates the important relationships between dimensions of CE and the product and market contexts where they are applied. Craig and Hart observed that there exists "... a desperate need for empirical [research] ... which investigates the dynamics of functional integration, investigating such issues as *who* should be integrated and *when* and *how* this can be achieved" [7, p. 40].

This research explores the questions of *who* and *how*. We were interested in examining the scopes of CE implementations on NPD programs in different product and market contexts, that is, which functions are intensely integrated and which are not. We also sought to uncover salient differences in the objectives, methods, and modes of cross-functional integration and concurrency.

We studied five companies that have customized CE to meet their specific product and market needs. The firms represent a variety of product and market contexts and provide examples of a range of CE concepts and implementations. In this article, we point out key aspects of the different CE programs and relate them to the specific challenges of the projects. Important dimensions of CE programs are identified that should be useful to managers in assessing and addressing their NPD needs. The analysis presented in the article also provides a basis for future research of CE structural forms and applications.

Case Study Methodology

The criteria for selecting the firms included in the study were that they (1) had substantial experience in NPD, (2) were developing relatively complex products, (3) used concurrent engineering methods, (4) operated in highly competitive markets, and (5) collectively represented a diversity of product and market needs. Each of the firms we studied has been in the business of developing new products for over 50 years. All had well-defined and documented development processes as well as personnel and resources that were dedicated full-time to R&D organizations. Whereas each of the firms had developed hundreds of products in the past, the development projects we studied were among their earliest attempts at concurrent engineering. Thus, the firms were relatively equal in their levels of experience with concurrent engineering approaches.

The participating companies included the Boeing Company, Cummins Engine Company, Red Spot Paint and Varnish Company, Texas Instruments, and Thomson Consumer Electronics. The development efforts were studied at the companies were the 777 aircraft, the heavy duty diesel (HDD) engine, the thermoplastic olefin (TPO) automotive coating, the airborne vehicle forward-looking infrared (AVFLIR) night vision system, and the digital satellite system (DSS), respectively. Brief descriptions of the five product development programs along with company motivations and challenges are provided in Exhibit 1.

The demands posed by these technical, complex product development efforts pushed managers to use advanced NPD practices. After the completion of the projects, company managers considered the projects to be successful in meeting goals for design performance, product cost, and project timing. In all five cases it was anticipated that the new products developed would meet or exceed initial long-term profit expectations.

Data collection at the firms began with a 2- to 3-hour interview with one to four program participants, including the program manager or the manager tasked with implementing CE, lead product design engineer, and/or the manufacturing manager. We used a questionnaire containing 29 open-ended questions to structure the discussions. The questions addressed: (1) motivations, risks, and competitive pressures surrounding the project; (2) product complexity and technologies; (3) project scheduling and concurrency; (4) team personnel, organization, incentives, and authority; (5) definitions, motivations, and benefits of CE; (6) functional interactions and communication modes; (7) methods and tools used to promote CE; and (8) barriers and keys to success. The questionnaire was distributed in advance to meeting with participants so that supporting data and documentation could be prepared. Most of the interviews were recorded on cassette tapes for later review. For each firm, one of the managers attending the initial interview served as a contact for the project, providing access to docu-

Exhibit 1. Descriptions of NPD Projects Studied

Boeing Commercial Aircraft Division-777 Project

Boeing's 777 aircraft family incorporates new technologies such as digital avionics and advanced lightweight materials, and uses a dual-engine, two-pilot design that makes its operating cost per seat-mile approximately 25% less than those of the four-engine, three-pilot 747. The 777 family will eventually replace the 25-year-old 747 aircraft family.

The development of the 777 family was motivated by a market need for a high capacity, long-range aircraft with lower operating costs than the 747. In 1993 Airbus Industries introduced two new entrants into the high-capacity long-range market segment. Boeing needed a state-of-the-art aircraft to stay competitive in this important market segment. These market pressures convinced Boeing to invest the $4–5 billion needed to launch the first member of the 777 family.

Boeing undertook enormous financial risk in developing the 777. Consequently, a high quality, customer pleasing, flexible, and durable design was imperative. To recover enormous development costs the product needed to satisfy a diverse set of customer needs. The basic design also needed to be durable and flexible enough to last well into the 21st century, producing aircraft able to withstand decades of commercial service.

Cummins Engine Company—HDD Project

Cummins Engine Company designs and manufactures diesel engines used in heavy-duty and midrange trucks, power generation equipment, buses, light commercial vehicles, industrial products, and marine products. The company recently developed a new heavy-duty diesel (HDD) engine used primarily in large trucks.

The project was motivated by a significant drop in market share for a very successful, but dated, existing product. Customers had migrated to newer, more advanced engine designs offered by competitors in this engine class. Recent product introductions by competitors and strict 1998 federal emission requirements created pressure to get the new product to market quickly. However, the project's highest priority was to create a high quality, durable design. Cummins warranties engines of this class for 400,000 miles, and many engines will log over a million highway miles during their lifetimes. The company suffered significant warranty expenses in the late 1980s from an engine that was produced with a latent design defect. It did not want a repeat of this expensive and reputation damaging experience.

Red Spot Paint and Varnish—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, started 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 initially 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 arena. Otherwise, Red Spot would be seriously disabled in sustaining a profitable position in the auto coatings marketplace.

Texas Instruments—AVFLIR Project

An electro-optical night vision system was recently developed by the Texas Instruments Defense Systems and Electronics Group. The product converts infrared radiation into visible light and supports video projection, guidance, and data processing functions on aircraft. We use the pseudonym, AVFLIR (airborne vehicle forward-looking infrared system), to identify the product.

The AVFLIR project was driven by needs to improve the cost, weight, video resolution, maintainability, and reliability of an existing system. Design requirements were approximately 95% complete at the beginning of the project. The product required no new technologies and the timing of project activities was not particularly aggressive. Thus, the primary challenge of the project was to simultaneously maximize product performance and affordability. The new units would replace systems already being used in the field.

Thomson Consumer Electronics—Digital Satellite System

Thomson Consumer Electronics designs and manufactures televisions and peripheral equipment that are sold to consumers under the RCA label and other brand names. Thomson recently introduced a Digital Satellite System (DSS) for home television that offers the consumer a smaller receiving dish, clearer television reception, and the capacity to handle a larger number of channels than traditional home satellite systems. The DSS represented an enormous opportunity for Thomson; profits in the first year were projected to exceed the profits of all of Thomson's combined television sales.

The DSS was made possible by new legislation in the early 1990s that increased access for television programming on satellites. Recent refinements of digital compression technology made the DSS technically and economically feasible. The satellite project was initiated by Hughes Electronics in 1991. Thomson, a leader in compression technology, was awarded a contract in January, 1992 for the development and production of uplink and reception systems.

Rapid development was critical for the DSS project. Completion of the product design and development was contractually tied to a satellite launch date that had been specified well in advance of product development. If the launch deadline was missed, the product introduction could have been postponed by as much as 2 years. Thomson, Hughes, and several key suppliers had to work closely together to combine their expertise in digital compression, consumer electronics, satellites, and uplink technology.

mented data and personnel information, including company reports, press releases, program charters, organization charts, planning documents, and project schedules. Numerous follow-up discussions with study participants were conducted primarily via phone, fax, and regular mail.

In the next section of the article we examine how the companies customized their NPD processes to meet the specific challenges of their NPD projects. We then describe how these challenges influenced the cross-functional integration and concurrent development employed in the programs.

NPD Program Challenges

The challenges faced by the new product development efforts we studied were largely reflected by **program priorities** and **project characteristics**. Table 1 provides a brief comparison of the five projects on these two dimensions.

Program Priorities

Customer desires and competitive threats were the primary drivers of program priorities on the NPD programs we studied. The programs addressed customer desires by communicating intensively with key customers, by paying close attention to design quality issues, and by setting goals that met or exceeded customer requirements. The firms responded to competitive threats by offering a product with a superior feature or lower cost than competitors' products, or by being the first-to-market. Program priorities, therefore, reflected market demands for design quality, production costs, and product introduction speed.

Design Quality. An apt definition of design quality

Table 1. A Comparison of Challenges in the New Product Development Projects

	Boeing 777	Cummins Engine HDD	Red Spot TPO	Texas Instrument AVFLIR	Thomson DSS
Program priorities					
Design 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

in our study is "fitness for customer use." Design quality can differentiate products via superior product performance, features, reliability, serviceability, durability, and aesthetics [9].

To produce a high quality design, the Boeing NPD process encouraged cross-functional integration and communication. Signifying the importance of teamwork and communication, the first 777 produced was named "Working Together." Communication was a priority not only between internal groups, but also with customers and suppliers. Representatives from the first four major airlines to purchase the 777 participated as members of the development team. In addition, Boeing's "design-build" teams included representatives from many of the project's approximately 100 major suppliers.

Boeing also made a major investment in computerized design tools to help its designers produce high quality designs. The 777 was designed entirely using three-dimensional digital design technology. A common data base allowed 777 designers around the world to access up-to-date designs for any of the 700,000 numbered parts in the aircraft. The three dimensional modeling capabilities of the design system allowed designers to fit parts together electronically in order to identify and correct design problems before physical parts were produced. The design system included 1700 computer workstations in Seattle, more than 500 elsewhere in the U.S., and 220 in Japan.

To maximize durability and reliability the 777 program utilized only field-proven technologies, backed by extensive testing. The three-dimensional design system enabled designers to execute performance and stress analyses before physical parts were produced. Physical prototypes were laboratory-tested under severe environmental conditions before any parts or systems were incorporated into the first aircraft. The aircraft itself was then rigorously flight tested. This extensive testing throughout the development process convinced the FAA to certify the 777 for extended over-water flights within weeks of the first customer's delivery. Normally a new aircraft must prove its reliability with at least 2 years of commercial service before the FAA will grant this important certification.

Like the 777 project, Cummins' HDD project emphasized cross-functional integration and communication. The Cummins NPD team included external suppliers and internal representatives from virtually every function that played a role in designing, manufacturing, or supporting the new engine. These representatives formed 15 cross-functional teams that were organized into what Cummins referred to as a "tapestry of design."

An important aspect of design quality for the Cummins HDD was the ability to meet a wide range of customer needs. Customers can select from a few different types of turbo-chargers, alternators, electronics packages, and other components. Because the HDD engine is a relatively high volume product, Cummins cannot offer its customers a high degree of product customization. Consequently, Cummins produced a robust engine design that could be easily adapted to perform effectively in a number of different use scenarios. This required extensive experimentation and testing of design alternatives to identify specifications that provided good performance over the widest possible range of use environments.

To assure that the engine design would satisfy a broad range of customers, Cummins sent its marketers and engineers to meet with fleet owners and truck drivers throughout North America to learn about their business and engine requirements. In addition, Cummins formed advisory boards comprising key customers and distributors. Their comments and suggestions greatly influenced design decisions. The resulting engine design was intensively tested in the laboratory and on the road to assure that it satisfied customer needs.

Product Cost. Product cost is often a high priority in designing incremental, next-generation products. When new technologies or other product differentiation dimensions are absent, product cost becomes a primary basis of competition.

Attaining low product life-cycle costs was a high priority on the Texas Instruments' AVFLIR project. Manufacturing-design integration was prioritized in the design process. Process design activities were started early in the development process and manufacturing representatives had sign-off authority on final designs. Process engineers, NC programmers, and tool designers were co-located with design engineers to insure that they addressed manufacturing concerns. Overall, 90% of the program personnel were co-located.

An organizational unit within the Defense Systems and Electronics Group called Systems Producibility Engineering (SPE) was responsible for implementing CE on the AVFLIR project. Members of the group have expertise in many areas of manufacturing producibility, including metal fabrication, electrical systems, optical equipment, and printed circuits. Systems Producibility Engineers served on all the AVFLIR project teams to assure that the product was affordable, producible, reliable, testable, and easily maintained.

The Cummins HDD engine project addressed manufacturing concerns throughout the project by including manufacturing engineers in all phases of the product design. Managers focused attention on producibility issues through a series of prototype builds. Prototypes were built using full-scale production equipment whenever possible, thus bringing production issues to the surface early and spurring interactions among suppliers, designers, and production personnel. To support this approach, suppliers were identified and included in design processes early in the project. Producing manufacturing hardware before the engine design was stabilized required some expensive rework of production tooling, but managers felt the up-front cost was more than offset by a smoother manufacturing ramp-up and a more producible product.

Boeing faced significant product cost challenges on the 777 project due to stiff competition from Airbus and the deregulation of the airline industry. Reflecting this concern, manufacturing personnel played much greater roles in the design of the 777 than on any previous Boeing platform project. Design-build teams were all co-led by design and manufacturing engineers. Boeing also facilitated communication between the design and manufacturing groups by constructing a large design complex located adjacent to the final assembly production facilities.

Product Introduction Speed. The opportunity costs of delaying a product's market release are often substantial. Consequently, the timing of a new product's entry into the marketplace may be critical for its eventual success. Intuition suggests that when opportunity cost is high, management should prioritize development speed [14].

Development speed was critical on the Thomson DSS project. Thomson completed the design and development of the DSS in 75 weeks, which is comparable to Thomson's normal development time for a new television that involves no new technology. By meeting a required satellite launch date, Thomson had the first DSS on the market and established its RCA name as a market leader. Later entrants to the DSS market were expected to have to offer lower prices and more features to capture market share from Thomson.

Several features of Thomson's NPD process addressed the need for speed. First, the project's priority and visibility within the firm allowed it to receive a large commitment of organizational resources, including a doubling of engineering capability. Second, rather than take the time to develop new technology expertise in-house, the company employed suppliers with expertise in key technologies and included them in the project in its earliest stages. Third, more than 20 major design activities, both internal and external to the firm, were executed simultaneously, including software design, signal definitions, communication network design, and customer integrated circuit designs. Fourth, the Thomson development process formalized a high level of communication between groups who performed parallel activities to insure timely information exchanges. Hughes required Thomson's participation in two major reviews, in keeping with the Department of Defense model on which Hughes bases its product development processes. However, Thomson went well beyond these requirements by initiating its own regularly scheduled meetings and design reviews and by issuing team-based incentives. Fifth, Thomson developed manufacturing facilities for production of the DSS much earlier than in its typical NPD projects. Production of the DSS required reflow soldering of multilayered printed circuit boards, a manufacturing technique that Thomson had not previously used. To avoid last minute problems with this new technology, manufacturing acquired reflow soldering equipment and installed it while the DSS was being designed. Designers sent product samples to manufacturing periodically to aid the installation process.

Speed was also a critical element of 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 would be 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 subteams were formed to complete specific tasks. For example, the Emergency Response Group was an important subteam responsible for quickly testing and evaluating numerous substrate samples.

Project Characteristics

Project characteristics such as project complexity, needed innovation, and technical risk greatly influenced the CE implementations we observed.

Project Complexity. Project complexity is a function of the number of people, functional areas, and outside suppliers involved and their degrees of interdependency. Boeing's 777 development effort was the most complex project we studied. It involved over 7000 people located in countries throughout the world, as well as hundreds of suppliers. Boeing attempted to minimize complexity by formalizing a hierarchy of design-build teams organized along the lines of physical aircraft components. At the top of the hierarchy was the "Total Airplane" team, led by the directors of manufacturing and engineering for the 777. This team was responsible for all aspects of the aircraft's design. Reporting to this group were nine "integration teams," responsible for structures, avionics, payloads, and other major systems. Design responsibilities were further delegated through multiple levels of the hierarchy. The lowest level teams designed individual parts and components. By dividing responsibility along the lines of aircraft components, the teams with the highest degree of interdependency were closest to each other in the design organization. This allowed conflicts and interdependencies to be addressed at relatively low levels of the organization.

The tremendous emphasis that Boeing placed on communication also helped mitigate many of the potential problems arising from the program's size and complexity. The use of a common database and the close physical proximity of most of the designers improved communications across the design organization. Suppliers and customers from around the world frequently came to Seattle to work on-site with Boeing engineers. Boeing also sent its representatives to work directly with suppliers. Communication between product designers and key suppliers was frequent, allowing problems to be resolved quickly.

Innovation. The level of innovation in NPD projects is often an important determinant of development time and product quality [3,10]. The degree of innovation in a project is a function of the number of unique product components or development tasks that are new to the developing company.

The Thomson DSS project illustrates the effects of high innovation on CE. The DSS product required extensive development of new mechanical devices, electrical components, and software. A key emphasis of the program was the integration of external parties who had expertise in the required technologies. The primary locus of communications was between design engineers and technical experts from the different vendors and partner firms, who frequently communicated face-to-face. Numerous formal design reviews also fostered the integration of internal and external organizations.

Non-design-oriented groups were not as closely involved in the Thomson DSS project as in the other projects we studied. Much of the marketing research had been accomplished previously by Hughes, so marketing functions had little influence on design decisions. Manufacturing personnel were also not integrated with the product designers. Instead, manufacturing and design personnel were placed in separate teams with separate budgets; integration of manufacturing and design issues occurred primarily at the top levels of project management.

Technical Risk. High levels of innovation in NPD projects are often associated with significant technical risks that result from the importance and uncertainty attached to new technological developments. Red Spot faced a major technological risk with the TPO substrate development. To mitigate the risks of falling behind in this important new technology, Red Spot staff participating in capability discussions and shared information on-site at the OEM that applied TPO coatings. Red Spot marketing and engineering representatives developed influential relationships with Ford engineers and OEM personnel 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. Through its aggressive development and sharing of process experience, Red Spot quickly and convincingly demonstrated its technical capability for TPO coatings.

The Thomson DSS project also faced great technical uncertainty. New broadcast standards, new digital compression technology, and unique relationships with new suppliers and partners created many potential risks. Thomson attacked these risks in ways that reduced uncertainty. For example, digital compression standards were not well defined at the beginning of the DSS project. Thomson decided early on to pursue an as yet unapproved set of standards for the design. At the same time, Thomson personnel participated on standards adoption committees outside the firm to monitor discussions and vigorously promote the standards they desired. In addition, backup plans and resources were developed to quickly react to changes in the standards. The final standards were approved only 3 months before Thomson started mass production of the DSS.

Customizing Concurrent Engineering Processes

All of the projects we studied used cross-functional teams and executed some development activities concurrently. However, implementations of cross-functional integration and concurrency varied according to the specific needs of the projects. Table 2 summarizes the differences in the CE programs for the five firms. In the following sections of the article, we describe the dimensions of cross-functional integration and concurrency we observed in the five projects and relate them to different program and product contexts. Key practices we observed are summarized in Exhibit 2.

Dimensions of Cross-Functional Integration

Empirical research has demonstrated that the integration of functional specialty groups is positively related to NPD success [6,15,20,21]. However, past research of NPD has focused primarily on interactions between marketing and R&D, or between manufacturing and R&D ([11] presents a notable exception). In fact, different functional representatives in CE programs often have different levels of interaction.

Table 2 lists the different primary objectives of integration we observed on the five projects studied. Note that the number and scope of integration objectives is correlated with the number of groups that had significant interaction and influence on design decisions. The eight major functional groups that play important roles in the product development process are illustrated in Figure 1. Product designers are at the heart of the development activity. They are charged with coordinating and completing the product development tasks on a timely basis. Within the product design function, numerous specialty areas (like electrical systems, mechanical design, software, etc.) must be integrated so that performance and cost targets are achieved. Customers provide important information regarding product features, performance requirements, ease of use, reliability, etc. Marketing personnel aid in gathering this information and supplement it with intelligence regarding competitors' products. Suppliers, partners, and regulating groups can have substantial influences on the design engineering group, especially when major components of the system design activities are new or have been subcontracted. Manufacturing and support engineering can play crucial roles in assessing manufacturing and product support requirements and in designing the processes needed to produce and maintain the product. Because no single group can be the repository of all the knowledge needed to complete NPD, these groups must integrate their knowledge of techniques, processes, and data.

The case studies indicate that the levels and modes of interactions between these key groups vary significantly from project to project. The Boeing and Cummins projects provide examples of interactions involving a broad set of constituents from many functional areas within and outside the firm. Red Spot and Texas Instruments illustrate types of integration that are more focused along the vertical dimension shown in Figure 1. The primary concentration of interactions at Red Spot was between customers and design engineering. At Texas Instruments interactions between design engineering and manufacturing were prevalent. The Thomson DSS project provides yet another focus of integration, along the horizontal dimension between designers, suppliers, regulators, and partners.

Teams are fundamental for promoting integration in CE programs. Although team arrangements varied in the projects we studied, three organizational levels of teams frequently appeared: a program management team, a technical team, and design-build teams. Figure 2 illustrates relationships between the teams.

Program management teams typically included the program manager, marketing manager, finance manager, operations manager, aftermarket manager, and design managers. This group provided management oversight and planning, approved large resource allocations, approved and controlled the project budget, and managed the project schedule. Many of the members were part-time participants on the project, except for those members who were also members of the technical team.

The technical team reported to the program team and provided technical oversight, approved key design decisions, and maintained consistency among design elements. Engineering managers from design and functional support areas were typically members of the technical team along with representatives from mar-

Table 2. Dimensions of Concurrent Engineering for the New Product Development Projects

	Boeing 777	Cummins HDD	Red Spot TPO	Texas Instr. AVFLIR	Thomson DSS
Cross-functional integration					
Primary objective(s) of integration	Resolve customer and competitive uncertainties, reduce development time and product cost	Resolve customer uncertainties, reduce development time and product cost	Resolve technical uncertainties very quickly	Reduce product cost and weight, improve performance and maintainability	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-mfg. co-leadership	"Tapestry of design" including program, technical and design-build teams, design-mfg. 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/technical team, design leadership, mfg. teams separated from design
Communications	Formal, face-to-face communications, design database, co-location	Face-to-face communications, co-location	Informal, face-to-face communications, periodic meetings	Regular meetings, face-to-face communication, co-location	Electronic and face-to-face communications, formal design reviews
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 components design activities	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 overlap	High—product definition and design overlap

keting, service, manufacturing, quality assurance, test engineering, CAD/documentation, key customers, and suppliers.

Design-build teams comprise the third level of project organization we observed. The membership of these teams replicated the technical project team at lower levels of the product structure. Each team was oriented around a particular product component, with responsibility for delivering designs, prototype hardware, process plans, sourcing strategies, quality engineering, maintenance plans, and after-market support plans. Many times these teams were co-led by design and manufacturing engineers who maintained high degrees of design authority and budget control. Suppliers and counterpart engineers from partnering companies also got involved at this level.

Exhibit 2. Summary of Concurrent Engineering Practices

- Functional groups integrate their knowledge of techniques, processes, and data. However, the intensity of interactions among groups varies according to the needs and challenges of the development program.
- Teams are fundamental organizational forms for promoting integration.
- Team arrangements include: program management team, technical team, design-build teams, integration teams, and task forces.
- The number of teams varies due to the size and technical complexity of the program.
- Teams are often constituted by:
  - A mix of part-time and full-time participants
  - Members from inside and outside the firm
  - Members who participate on several different teams simultaneously
  - Design and manufacturing co-leadership.
- Teams are often given:
  - Budget control and access to required resources
  - Authority and responsibility for designing a product subsystem or component and the processes needed to produce it.
- The modes, frequency, richness, and formality of communications among project participants varies according to information complexity and according to design and timing challenges.
- At least three opportunities exist for concurrent processing of development activities:
  - Project phase concurrency: Simultaneously developing market concepts, product designs, manufacturing processes, and product support structures
  - Design concurrency: Overlapping design disciplines (e.g., system, software, electrical, and mechanical engineering) so that system level and component level designs are produced concurrently
  - Product concurrency: Overlapping of separate but related new products requiring coordination between NPD programs.
- As more types of concurrency are attempted, the number of relationships that must be managed increases rapidly.
- As degrees of overlap among activities become more intense, decisions that are dependent on information from upstream processes become more uncertain. Consequently, the risk of rework grows.

Two additional types of teams were identified, integration teams and task forces. The complexity of some product development projects required that integration teams be formed for major subsystem levels. For example, Boeing consolidated design-build teams to deal with product variants and customer-unique requirements. On the other hand, task forces were usually formed to address some specific problem. For example, a task force might be assembled to evaluate an important design tradeoff or to investigate an emerging technology.

The number of teams utilized on the projects varied due to the size and technical complexity of the program. For example, the Red Spot TPO project involved only a few teams, whereas the Boeing 777 project required more than 200 teams. The compositions of the teams also varied to meet the particular needs of the project. In general, increased integration of design and manufacturing groups at lower levels reflected a greater priority on manufacturability. Boeing, Cummins, and Texas Instruments all integrated design and manufacturing engineering at very low project levels, whereas Thomson used a cross-functional program team but split design and manufacturing responsibilities into separate teams at lower levels.

The CE projects also varied significantly in the modes of communications between functional representatives. Some projects emphasized face-to-face communication and went to great lengths to provide co-location and personal contacts. Other projects relied heavily on phone conversations, documents, and electronic mail as primary communication media. Most group communications existed in the forms of meetings and design reviews. However, the formality and regularity of these meetings varied. Projects that highly prioritized design quality tended to rely more than others on formal presentations and standing periodic review meetings. Communications on projects that emphasized development speed were more frequent, informal, and ad hoc.

Layers of Concurrency

Our study suggests that three layers of concurrency existed in the projects we studied. Conventional approaches to concurrency address sequential stages of the product life by overlapping design and development activities. This emphasis is depicted in Figure 3 as project phase concurrency. For the projects we studied, project phase concurrency involved simultaneously developing market concepts, product designs, manufacturing processes, and product support structures.

We also identified concurrency at two other levels: design concurrency and product concurrency. Design concurrency involves the overlap of design disciplines (e.g., system, software, electrical, and mechanical engineering) so that system level and component level designs are produced concurrently. The simultaneous

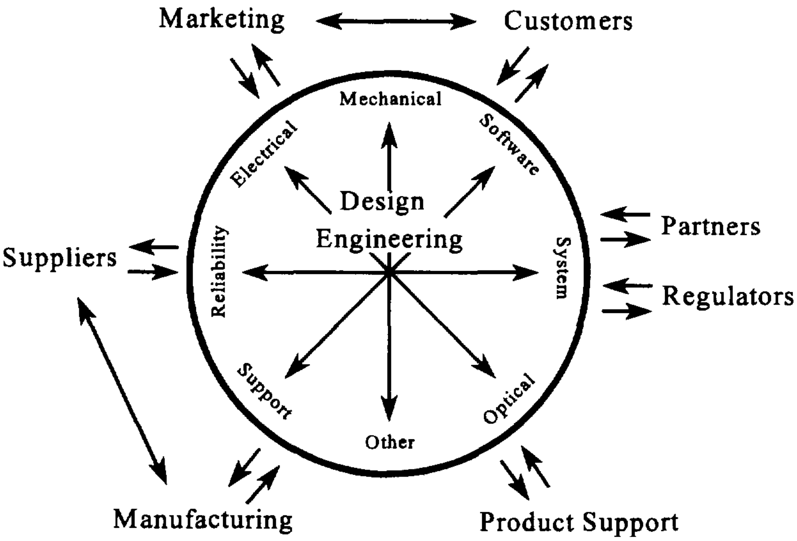

Figure 1. Interacting groups in concurrent engineering.

development of the satellite, uplink equipment, and receiver reflected design concurrency in the Thomson DSS project. Product concurrency is the overlap of separate but related new products requiring coordination between NPD programs. Product concurrency exists in the concurrent development of first-generation and next-generation products or in the development of separate product variants. Product concurrency was evident in the Thomson project. Many of the DSS team members began working on the next generation product (DSS2) even as the designs for the initial DSS were initially produced.

Assessing the Impacts of Program Characteristics on CE Programs

We analyzed the data from the five projects to identify linkages between NPD characteristics and the supporting CE program structures. Table 3 summarizes our findings and suggests relationships that should be explored in future research.

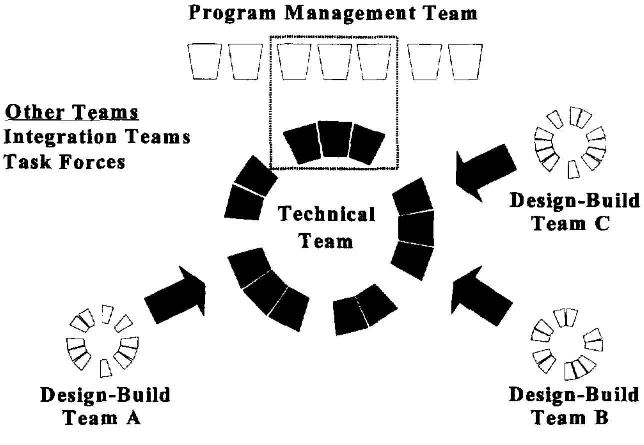

Figure 2. Concurrent engineering team structures.

Design quality pressures result from uncertainty or multiplicity in customers' needs. These pressures require that managers clearly define customers' requirements and analyze competitors' product offerings. Our findings suggest that reducing customer and product uncertainties requires intensive interactions between groups on the front end of the development process. If uncertainty in customer requirements is present, then a greater need exists for information exchange among marketing, customers, and R&D personnel. This finding supports the observations of Gupta, Raj, and Wilemon [12]. To resolve customer uncertainties, much effort is spent identifying customer needs and on translating customer language into design specifications.

For those programs facing high design quality pressures, many CE activities centered around extended product definition and performance testing. Design engineers established relationships with customers and participated in market analysis activities. Marketing personnel and customers participated in performance tests and evaluated test results.

When a single product needed to satisfy a wide range of customer needs, the development programs responded by creating robust designs or by designing product variants. Robust designs are those that perform well in many environments or that may be easily modified to satisfy multiple market needs. In the latter approach, product concurrency in developing a family of products provides a synergistic approach for satisfying a wide variety of customer needs.

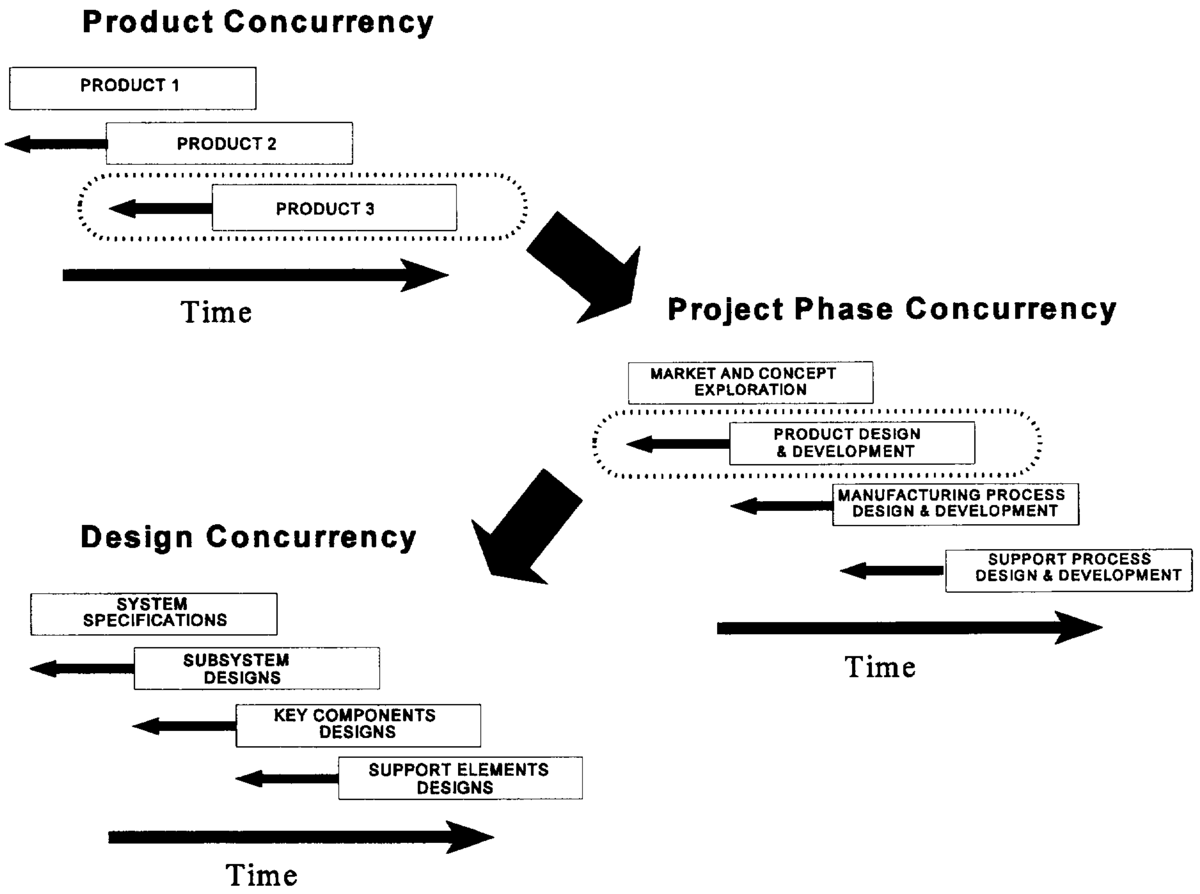

Figure 3. Different types of concurrency.

The programs in our study that experienced strong pressures to reduce development time tended to use smaller, less formalized teams with strong leadership roles filled by design engineers and managers. Project phase and design concurrencies were considerable on some programs. However, we observed that decisions made by product and process design groups were not as closely integrated. Less time was spent evaluating product design alternatives that were prompted by manufacturing or other support groups. Whereas communications between product and process design groups were frequent, they tended to be unidirectional. Also, manufacturing personnel exerted less direct influence on product design decisions.

We found that aggressive product cost goals were associated with intensive interactions between product designers and manufacturing personnel. Extensive manufacturing prototyping using "hard tooling" and full-scale production facilities was also used to minimize product manufacturing costs. The early use of production tooling can elevate development costs, but product life-cycle costs are reduced because production problems are uncovered early in the design process. Manufacturing co-leadership on teams appeared to be common on NPD programs where product cost was a high priority. In addition, each team was given responsibility and authority for designing both the product element and the process needed to produce or procure that element.

It has been proposed that the product cost and manufacturing benefits realized from CE are most beneficial to incremental, low innovation, product development programs. As breakthrough projects offer significant product differentiation, the cost and manufacturing advantages derived from CE are of less importance [8]. Also, CE is often associated with the use of integrated manufacturing systems and process innovations that can actually work against product innovation [2]. The NPD programs we studied tended to support this theory. Manufacturing involvement in the development of the more innovative products tended to be less direct and at higher organizational levels than in the other projects.

For the higher innovation projects we studied, some primary interactions were between design engineers and technical experts who were external to the devel-

Table 3. Impacts of NPD Program Characteristics on Concurrent Engineering

Program Characteristics	Project Objectives	Impacts on Concurrent Engineering Approach
High priority on design quality	• Reduced uncertainty in customer needs and product performance • Robust or flexible design	• Heavy interactions among marketing, customers, and designers supported by customer preference translation aids • Extensive product performance testing • Low design concurrency • Potential product concurrency
High priority on product cost	• Design for assembly, manufacturability, serviceability, etc.	• Heavy interactions among suppliers, manufacturing, product support, and designers supported by design guides and production consultants • Extensive manufacturing prototyping using production facilities • Manufacturing-design co-leadership of teams • High project phase (product/process) concurrency
High priority on product introduction speed	• Reduced development time • Reduced design rework	• Heavy interactions between internal and external technical product design experts • Unidirectional communications with manufacturing and other support groups, limited emphasis on design for excellence • Smaller, less formalized teams and task forces • Product designers fill primary team leadership roles • High project phase and design concurrencies
High complexity	• Simplified development process • Communication	• Interactions with customers to eliminate complicating product features that are not highly valued • Well established hierarchy of teams, organized around elements of product structure, clear division of responsibilities • Integration teams that span portions of product structure • Increased co-location and formalized communications • Shared information systems (e.g., networked design data base)
High level of innovation	• Scope reduction • Communication	• Heavy interactions between designers and technical experts who represent customers or sources of technology • Less direct manufacturing influence in early development phases, integration primarily at high levels • Formal design reviews to promote data sharing between partnership firms • Shared information systems • Less project phase concurrency
High technical risk	• Reduced technical uncertainties • Effective exploration and scanning	• Heavy interactions and key relationships among designers and internal or external specialists and regulative authorities • Less concurrency for elements involving uncertain technologies • Product designers fill primary team leadership roles

opment team. These interactions enabled designers to deal with innovation uncertainties by reducing the internal scope of development. High levels of program innovation were associated with organizational and managerial factors such as early supplier involvement, strong communication links, and joint engineering problem solving. Formal design reviews and shared design data systems facilitated information sharing between internal and external design groups. In addition, very frequent informal communications occurred between leaders from the different design teams via telephone, electronic mail, or face-to-face.

Innovation is often associated with technical risk. In the programs we observed, new technological developments increased the need for interactions between designers and those team members inside and outside the firm who had the capabilities to reduce technical uncertainties. Since technical performance questions had to be answered before product support and production systems could be developed, product designers filled the primary leadership roles on teams, whereas manufacturing and other functions acted in supporting roles. The overlapping of product and process development tended to be less for product elements when product technologies were uncertain. For these product elements, process designers played advising roles. Detailed process design and hardware construction were often postponed until product performance parameters could be established.

Our findings suggest that formal communications within an explicit hierarchy of product development teams can aid in dealing with complexity. The complex projects we studied were often organized along both technical and program dimensions. A team was created for each of the many product subsystems and components. Design and manufacturing personnel acted as co-leaders of these design-build teams. In addition, teams along the program dimension were formed by grouping members at different levels of the program hierarchy (managers, lead engineers, etc.). Organizing teams in this way provided cross-functional inputs to both technical concerns and program issues. Networked CAD systems, co-location, and integration teams were used to improve information access and information quality in complex environments.

Conclusions

The five companies we studied have developed sophisticated CE processes to effectively manage their complex development programs. The experience of these companies shed light on the process of NPD and provide insights that can help other companies develop processes that are appropriate for their particular situations.

The analysis provided in this article should be interpreted in light of the characteristics of the companies studied. All of the development projects involved technically sophisticated products. The development of products in less complex arenas may not require the means employed by these companies. The involvement of engineering groups in development was probably more intense than it would be for many products. Also, development cost and product price may not have been as highly prioritized in the projects we studied as they would be for some simple consumer products. Finally, the customers for the Boeing and Texas Instruments products were commercial or government organizations with a keen understanding of their product needs. Consequently, the roles of marketing may have been somewhat diminished relative to the development of consumer products.

Concurrent engineering is a relatively new approach and is evolving rapidly as companies gain more experience. Several of the managers we talked with commented that their organizations were still learning about CE, but without exception the people we interviewed were enthusiastic about the positive influence CE had on the NPD process in their companies. Some of the companies documented savings in overall product development costs of approximately 20% and reductions in engineering design changes of 45%–50%.

More empirical research is needed to relate differences in implementations of CE to their root causes. Our exploratory analysis of five NPD projects notes key differences in market and product characteristics that influence the shape and substance of CE programs. More detailed theory and study are needed to explain different forms of CE and to prescribe appropriate levels and types of cross-functional integration and concurrency for given NPD program conditions.

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