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AN EXAMINATION OF VARIOUS METHODS USED
IN SUPPORT OF CONCURRENT ENGINEERING

James P. Pennell
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March 1990

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James P. Pennell
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PREFACE

IDA Paper P-2138, *An Examination of Various Methods Used in Support of Concurrent Engineering*, was prepared for the Weapons Support Improvement Group (WSIG), Office of the Assistant Secretary of Defense for Production and Logistics (OASD(P&L)) in response to tasking contained in IDA Task Order T-B5-602 under contract MDA 903-89-C-0003. The objective was to evaluate the effectiveness of methods used in support of concurrent engineering.

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1. INTRODUCTION

1.1 PURPOSE

This paper is a supplement to IDA Report R-338, *The Role of Concurrent Engineering in Weapons System Acquisition*¹ [Winn88]. It is provided in response to specific tasking in Amendment 3 to IDA Task Order T-B5-602, Evaluation of Concurrent Engineering in Weapons System Acquisition, paragraph 4.g. It is based on information contained in [Winn88], and an informal working paper entitled, "An Examination of Cause-and-Effect Relationships in Concurrent Engineering," which was provided to the sponsor in August 1989. It is intended to show a relationship between the actions taken by companies and the cost, schedule, and quality improvements cited in the earlier IDA report.

1.2 AUDIENCE

The intended audience for this report includes people who want to start using concurrent engineering within their projects or programs, managers who are considering how to use concurrent engineering, and research directors who are developing programs to provide the methods and technologies needed for concurrent engineering. This paper is intended to help them understand how the methods used in support of other concurrent engineering efforts could be beneficial to them.

1.3 METHODOLOGY

The authors used information gathered in the earlier phase of the concurrent engineering task. They also conducted follow-up visits with companies contacted during the first phase and initiated new contacts. They combined data gathered during personal visits and interviews with information found in the professional literature to form the basis for the conclusions contained herein. The conclusions themselves are the result of the authors' assessment of the evidence and their judgement about its importance.

When organizing the data gathered to arrive at conclusions, the authors used several techniques usually associated with quality improvement. These techniques used were relatively simple and did not include statistical methods. The relationship between actions taken and results achieved were studied using Pareto diagrams, cause and effect

1. Sections of this paper are repeated verbatim from Appendix B of the original report.

graphs, and elementary grouping techniques. These techniques were developed by Ishikawa [Ishi82] to be used by hourly employees in factories. There are seven² such tools in all. Use of these tools was widely reported during the IDA concurrent engineering study. More advanced statistical methods were not applied because the scope of the effort did not permit design or conduct controlled experiments.

There are at least two perspectives of concurrent engineering. The first view sees it as a new skill or at least a departure from previous methods of developing products. The second holds concurrent engineering to be the collection of the individual methods or techniques that have been adopted by companies practicing it. Within this report, concurrent engineering is defined according to the first view, but the discussion concentrates on the individual methods (the second view). The individual methods are the most easily recognized external indications that a company has begun to practice concurrent engineering and have been the subjects of considerable speculation during previous meetings with government and industry representatives. Nevertheless, methods are not, singly or in combination, taken by the authors as defining concurrent engineering.

For the purpose of this paper, concurrent engineering is defined [Winn88 p. 2] to be

a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements.

Additional descriptions of the general concepts of concurrent engineering can be found in [Winn88 or Penn89].

The philosophy that sets concurrent engineering apart from traditional approaches is the emphasis on viewing activities as an integrated process. The president of one large defense contractor observed that concurrent engineering differs most from his company's previous approach precisely because of the new emphasis on process. The entire collection of activities needed to change an idea into a fielded, successful, profitable product-line is now viewed as a single process. This single process is now managed and optimized based on global optimization criteria, not the optimization standards of the different functional subgroups.

2. The seven tools are graphs, histograms, cause-and-effect diagrams, check sheets, Pareto diagrams, control charts, and scatter diagrams.

Concurrent engineering is basically an approach for integrating different activities, but it manifests itself in the application of certain tools and methods. Many people who observe it in practice have an easier time identifying the different methods or techniques (such as the Ishikawa tools) used than understanding the underlying integration of separate activities. Furthermore, although many of these methods are not new (either in this country or overseas), they seem to be new to managers who are unfamiliar with the concepts behind them. Although descriptions of the techniques which have been cited most often among companies practicing concurrent engineering are presented in this paper, the reader is cautioned that use of these methods is not, by itself, sufficient reason to conclude that a company is practicing concurrent engineering.

Of the many methods associated with concurrent engineering, some of the most striking come from the quality community. In gathering information for this report, the authors found that quality initiatives are inseparable from concurrent engineering. A participant at a recent cost/performance measurement workshop stated that, "... you cannot achieve TQM [Total Quality Management] without achieving concurrent engineering, because without addressing product and process issues simultaneously, and without an ability to solve the timing problem in the funding profiles of every one of our programs, you can't achieve [TQM]." [Ches89 p. 181] To illustrate, suppose Company A decides to implement a total quality program³ to improve the quality of their products and services. Typically, such a decision will lead the company to examine the principles of Deming [Demi86], Juran [Jura88], Crosby [Cros79], or one of the other experts on quality. Each expert emphasizes slightly different techniques, but the Deming approach with its fourteen obligations of top management is representative of what such a company would find. Five of the fourteen points are very closely tied to the practice of concurrent engineering⁴:

1. Create constancy of purpose for improvement of product and service.

3. Results of a survey conducted by the American Society for Training and Development and reported in the October 1989 issue of *Aerospace Engineering* indicate that among a panel of Fortune 500 executives, 57 percent of the responding companies have total quality as a formal strategic goal and two-thirds of the remaining companies expect that it will become a formal goal within the next three years. *Aerospace Engineering*, October 1989, p. 4.

4. From a handout at a workshop sponsored by George Washington University. The complete list: 1) Create a constancy of purpose. 2) Adopt the new philosophy. 3) Cease dependence on inspections to achieve quality. 4) End the practice of awarding business on the basis of price tag. Instead minimize total cost by working with a single supplier. 5) Improve constantly and forever every process for planning, production and service. 6) Institute training on the job. 7) Adopt and institute leadership. 8) Drive out fear. 9) Break down barriers between staff areas. 10) Eliminate slogans, exhortations, and targets for the workforce. 11) Eliminate numerical quotas for the workforce and numerical goals for management. 12) Remove barriers that rob people of pride of workmanship. Eliminate the annual rating of merit. 13) Institute a vigorous program of education and self-improvement. Education is required for changes in management. 14) Put everybody in the company to work to accomplish the transformation.

4. End the practice of awarding business on the basis of price tag alone. Instead, minimize total cost by working with a single supplier.
5. Improve constantly and forever every process for planning, production, and service.
9. Break down barriers between staff areas.
14. Put everybody in the company to work to accomplish the transformation.

A company whose management accepts these responsibilities will find (if it is typical of the companies visited during this study) it also has discovered the teamwork that leads to concurrent engineering. The teams, if they are sincerely improving their processes, will demand that the company provide the type of tools which are needed to support concurrent engineering. People will also find that continual improvement of quality is possible only when different functional disciplines cooperate.

Conversely, if Company B decides to implement concurrent engineering without first reducing the variability of its processes, it may encounter the following situation. Engineers are told to develop concurrently and in an integrated fashion a conceptual design and to begin developing plans for detailed design, manufacture, assembly, and support of a new product. If each functional specialty is not attentive to the accuracy and speed demands of the other groups, the effort bogs down. Specialists soon learn that they are wasting time because as they start to work out more detailed plans, they discover errors and inconsistencies in the information they are working with so that their results are wrong and they must redo the effort. Instead of saving time, lowering costs, and improving quality, they produce the opposite result. If the company simply automates existing processes, without first establishing a policy for managing and improving them, then the problems will remain. The companies visited during this study were emphatic about this point. Finally, the IDA report contains considerable information about quality initiatives because on the basis of many conversations with representatives of different companies, the authors conclude that successful application of concurrent engineering and attention to improved quality are inseparable.

Methods and tools are first presented in the context of their being solutions to various high-level problems that have been encountered by companies implementing concurrent engineering. This approach was suggested by a recent [NIST89] workshop on quality and productivity methods. The authors provide one possible framework that conforms to the NIST recommendation. The authors then demonstrate why other approaches to considering the various methods and tools, such as a strict ordering of which methods are "best" or a quantitative functional relationship of "cause-effect"

relationships, are probably less important for now.

1.4 SCOPE

Concurrent engineering spans the entire life cycle of a product [Fabr89], but most of the examples considered to date are drawn from the phases of product development that begin with detailed design and continue through initial serial production. When the benefits of using particular methods are discussed, the benefits are stated in terms of higher quality, lower cost, and shortened product development schedules.

The data contained herein are not the result of controlled experiments nor were they gathered through extensive survey. The authors believe that sophisticated statistical analyses are not appropriate. The data are the result of plant visits, reports from companies, and many conversations with engineers and executives from participating organizations. Although no company was surveyed in exhaustive detail, representatives from eighteen⁵ different companies contributed to this study. The individuals and their sponsoring companies represent commercial as well as defense sectors in industries that include piece-part manufacturing, system design and assembly, electronics, automotive, airframe, and ship construction. Of the eighteen companies, eleven provided data in sufficient detail so that case studies could be included in the previous report. IDA team members visited ten of the eleven.

5. Aerojet Ordnance, Allied Signal, AT&T, Bell Helicopter, Boeing, John Deere, DuPont, General Dynamics, Grumman, Hewlett-Packard, Honeywell, IBM, ITT, Martin Marietta, McDonnell Douglas, Newport News Shipbuilding, Northrop, and Texas Instruments

2. METHODS AND TECHNIQUES

A recent workshop [NIST89] at the National Institute of Standards and Technology (NIST) examined topics related to improvements in quality and productivity. The participants included in their recommendations the observation that too much of the discussion of changes in these areas has addressed techniques instead of the problems for which the techniques provide a solution. In response to such concerns, this section is organized according to the various problems which the methods are designed to address.

The first problem is convincing the people affected by the change that the status quo is not satisfactory. Discussions with people in several companies confirmed the importance of solving this problem. One company that had analyzed its technical problems and designed a better way of solving them delayed implementing the changes when management learned that employees were not convinced of the need for the changes.

Despite the importance of solving the motivational problem, the previous IDA study produced no data concerning tools or methods that were useful in finding a solution. The authors were most concerned with examining the methods and tools that had been already identified. Consequently, this paper will not address methods or techniques for dealing with the motivation problem.

The remaining problems are often encountered by companies responding to three tasks:

1. Determine what the customer wants.
2. Establish control of existing processes.
3. Improve the process so as to provide what the customer wants at lower cost and in less time.

The apparent simplicity of the tasks is deceptive; accomplishing them is challenging. For example, one of the companies visited related how it wanted to start its improvement by first examining the existing process and then analyzing it to find out how it could be improved. When writing down what employees actually did, the company discovered so much confusion that management could not accurately describe the process. Instead, management decided to describe the process as they thought it *should* be. Having described an ideal process, they could compare it with people's daily activity. In private

conversations, workshop participants confided that many companies do not have well-defined processes for most of their critical product development activities.

2.1 DETERMINE WHAT THE CUSTOMER WANTS

As companies begin to view a *process* as a collection of activities, they often develop a concept of internal and external customers. An external customer is the person who has the money and who may be persuaded to exchange that money for products and services. Each employee views the internal customer as follows: "My internal customer is the co-worker who accepts goods or services from me and adds additional value to them before they are delivered to the external customer."

Satisfying the internal customer is a critical item, but it is so closely associated with the concept of process definition that further discussion of this item will be deferred until Section 2.2 which deals with process control.

To satisfy the external customer, the first requirement is to capture the "voice of the customer" (VOC) in terms that the engineer can understand. This is not the same as translating the engineer's concept of the need into a presentation intended to arouse the customer's desire for a better system. During the several workshops that were part of this task, participants clearly voiced the opinion that capturing the VOC is both necessary and difficult.

Multifunction teams may be used to capture the VOC and representatives of marketing will usually take the lead role. Surveys may be used at this stage. Additionally, the value of sending the engineer out to the customer should not be overlooked. The "Blue Two" program sponsored by the Air Force allows engineers to spend time in the field observing maintenance operations on fielded systems. Several companies that participated in this program report that it is an excellent vehicle for communicating some of the user's needs to the engineer. At least one company is conducting supportability awareness training for designers who must perform maintenance tasks while wearing chemical warfare protective suits.

Another technique for capturing the user's requirements and mapping them into product and process parameters is called *quality function deployment* (QFD). QFD originated in Japan and has been practiced there since the mid-1970s. It consists of techniques [King87] for creating and completing a series of matrices showing the association between specific features of a product and statements representing the VOC. It is taught in several versions, notably Macabe's four matrices showing product planning, part deployment, process planning, and production planning; Fukahara's House of Quality approach; and Akao's matrix of matrices.

QFD uses teamwork and creative "brainstorming" as well as market research to identify customer demands and design parameters. The correlation between the demands and the design parameters is ranked and normalized. Parameters of competitor's products are also identified and ranked. The top-down design process continues as functions, mechanisms, failure modes, parts and subassemblies, new concepts, and critical manufacturing steps are identified and traced to critical customer demands and competitor's products. Matrices are a means of recording the information to show correlations. The customer demands are often used to distinguish the rows of a matrix and product features are listed for the columns. Marks in the entry where rows and columns intersect are used to show how product features help to satisfy the customer needs. Positive and negative correlations among the product features are given in a triangular table above the matrix. The triangular table, atop the matrix resembles a roof, hence the term "house of quality". Figure 1 shows an example of a "house of quality".

One of the reported advantages of using QFD is that it reduces changes as a design enters production and decreases the time needed to get a design into production. Hauser [Haus88] reports the case of a Japanese automaker using QFD who reported reducing start-up costs by 20 percent in 1977, by 38 percent in 1978, and by 61 percent in 1984 when compared to its experience before using QFD. One of this company's suppliers reported reducing the number of engineering changes during production deployment by more than half.

Some U.S. companies have developed techniques for establishing the requirement and translating it into product features. Responding to the strong guidance contained in R&M 2000 [Unit87], one aerospace company recently formed a multifunction task team for the SRAM II competition [Winn88 p. 102]. Using locally derived natural work groups they translated reliability and maintainability requirements (topics that had been traditionally viewed by many engineers as "emotional issues") into identifiable and measurable design characteristics. Another company is reported to have created a special facility where potential customers can validate their requirements in a system that is designed to capture and compare needs independently of the rank or seniority of the proponent of a particular statement.

Despite the substantial benefits that QFD appears to offer in the design of complex systems such as military systems, its application to such tasks has not been publically reported.⁶ Only four of the companies visited during this study reported using QFD. At least one executive of a leading aerospace company characterizes QFD as a grossly simplified application of the principles of system engineering.

6. The authors are aware of an application of QFD to the Advanced Launch System, but have not seen it reported.

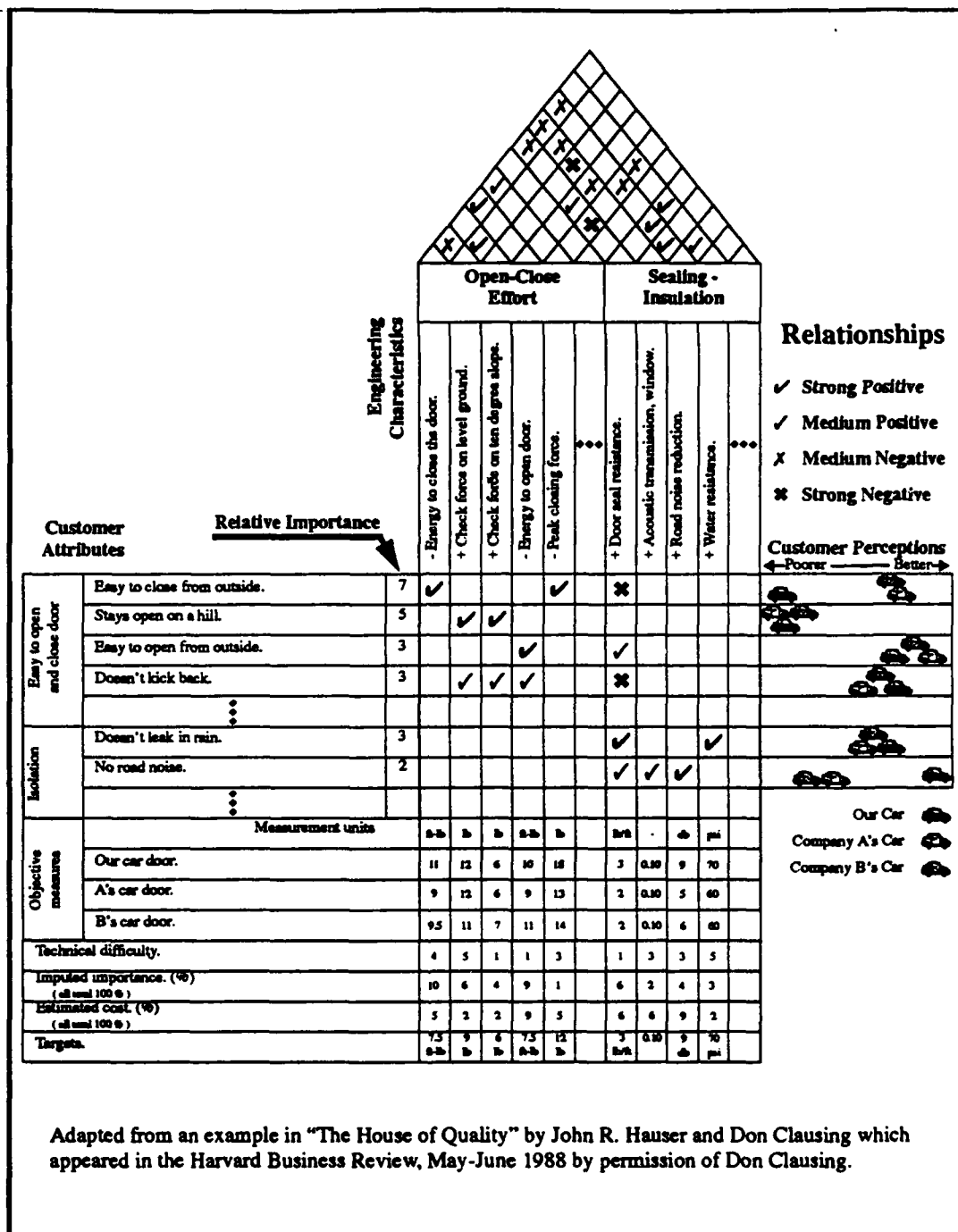


Figure 1. The House of Quality

Whatever methods or techniques are used, the importance of determining the customer's requirements is shared by the majority of the participants in this study.

2.2 ESTABLISH CONTROL OF EXISTING PROCESSES

2.2.1 Defining the Process

The first challenge for management is to adopt the view of their activities as processes. The concept is applied at different levels of granularity. For example, at one level the construction of an entire ship might be viewed as a process, whereas at another level, a process might consist of preparing specifications for the placement of electrical cables within a ship's compartment. A process⁷ can be an engineering task, a manufacturing task, or an administrative task.

The methods used to define and describe a process include flow charts, brainstorming, and computer-aided modeling. The Department of Defense (DoD) has several standards which describe processes for producing weapons systems, computer software, or various supporting studies.

Figure 2, provided by an AT&T employee⁸ who participated in the concurrent engineering workshops, shows a process as a "black box." It depicts the relationship among a process, the supplier, and the customer. In the figure, the internal structure, such as control points, controls, and measurement points, are suppressed.⁹

The concept of a "process" is not new. Each company contacted has historically defined various steps to be performed in the production process. King [King87] traces the science of describing processes to Frederick Taylor's studies of manufacturing in the early 1900s. Engineers, particularly industrial engineers, designed procedures used in manufacturing processes. Once these procedures were translated into steps that the supervisors and workers could understand, the task of managing and improving the process became feasible.

Deming's concept of operational definitions [Demi86] has been used to determine whether the description of a process is clear and unambiguous. Operational definitions

7. If a company has not previously considered that activities are viewed as processes and they wish to learn more about this concept, then there are several good sources of information. During this study, the IDA team found that AT&T, IBM, and Hewlett-Packard had remarkably similar programs for dealing with the concept of process management. The AT&T approach, called "Process Quality Management & Improvement" (PQMI), is described in a set of guidelines that include step-by-step procedures for establishing process control. PQMI is described in Roger Ackerman, Roberta Coleman, Elias Leger, and John MacDorman, *Process Quality Management and Improvement Guidelines*, Publication Center, AT&T Bell Laboratories (1987).

8. A similar figure appears in Roger Ackerman, *op. cit.* p. 8.

9. Processes have internal structure, control points, and measurement points, but these details are addressed when the detailed implementation of the process is described.

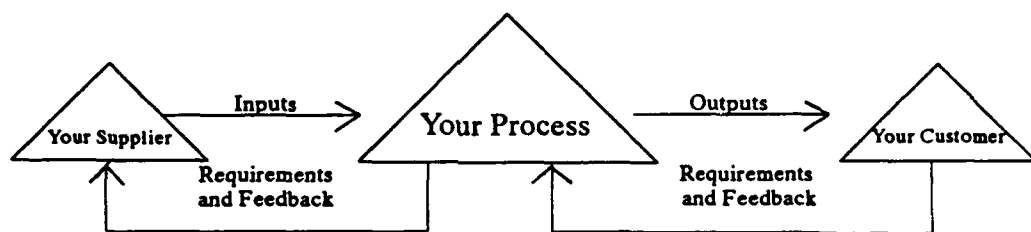


Figure 2. The Process Model

tell the workers what is to be done in terms that provide a way to verify whether or not the procedure is correctly followed.

The adoption of formally specified steps for the design process has been a more recent development. The design process is more difficult to describe because it involves creative activity and, when implemented, it varies considerably within and among companies. Because design has been perceived as an inherently creative process, some practitioners resist reducing the process to anything that might resemble mechanical procedure. In some instances [Nevi89] insufficient knowledge and tools for manufacturing design, lack of accurate data on field failure modes, and inadequate performance models of the product and production systems hinder development of better models of the design process. Although tools to support product design synthesis and analysis (at least parts thereof) are available, describing a process for *concurrently* designing the product and its production process (much less its support system) is a formidable challenge.

Despite the obstacles, both government and industry have made progress in discovering better design processes. The DoD and the Services have provided some guidance in DoD 4245.7-M, *Transition from Development to Production*, NAVSO P-6071 *Best Practices*, and USAF R&M 2000 *Process*. The research community has several initiatives (e.g., [Merc87 and DARP87]) for improving productivity and many of these are concerned with the problem of improving the design process.

During this study, process management was mentioned seven times (among seventy-five total citations of some method or tool) as a factor in improving quality or productivity, making it one of the most frequently mentioned factors. One company reported immediate benefits from the effort of establishing the process. They found that much of the work they had been performing was entirely unnecessary.

2.2.2 Measure Process Characteristics

Once a process has been designed, the person responsible for improving it determines which characteristics are important and how they are to be measured. The selection of the correct characteristics is an important matter and is generally the result of consultation with others who are familiar with a process, its customers, or its suppliers.

If possible, continuous characteristics are superior to simple pass-fail measures. For example, the observed diameter of a drive shaft is a better measure than just noting whether the diameter was within the specification. The actual diameter would be a better indicator because it provides information that might indicate one cause for items that are too small and another for those that are too large.

Selecting appropriate characteristics and deciding how to measure them is particularly challenging for white-collar processes. Some companies are attempting to measure such processes as software development, purchasing, billing, and product design. These efforts are less mature than those in manufacturing, yet the expected payoffs are substantial and the number of companies involved seems to be increasing.

2.2.3 Bring the Process Under Control

A process is said to be "under control" if it produces output with consistent regularity. The metric of regularity differs for various applications. For example, the measure might be the time to produce a product, the weight of an object, or some other characteristic that is important to the process' customers. Whatever metric is chosen, a process that is under control will produce products whose measured values vary within a predictable range.

An observer who is willing to perform sufficiently precise measurements will always find variability among products produced by a process. Wheeler [Whee86] relates the maturation of the awareness of the role of variation in process measurement and credits Walter Shewart and W. Edwards Deming with important contributions in understanding that observed variation may be the result of controlled or uncontrolled processes. When the measured variation of a process can be explained by the assumption that the underlying probability distribution of the measured characteristic is fixed (identical, independent distribution), then the process is said to be controlled.

Statistical Process Control (SPC) is one of the most widely used tools for determining whether observed variation is the result of normal fluctuation of a controlled process or the result of some special, uncontrolled cause.

SPC assumes that measured characteristics of stable processes will have a common distribution (in a probabilistic sense). That is, different sample groups of the product from the process will have the identical statistical distribution of the characteristic.

Statistical process control selects sample groups and conducts simple statistical tests to verify the hypothesis. As long as the tests do not show that samples have different distributions, one assumes that the process is stable and concentrates on incremental improvements for the process.

If a test indicates that the distributions are not identical, then one looks for the special causes of variability. In addition to statistical process control charts, Pareto diagrams, cause and effect diagrams, and PERT charts are used to find special causes of variability. When such causes are found, they are eliminated. This algorithm is repeated until the process becomes stable. When a process is stable, further improvement can only

be achieved by changing the process.

There are many excellent texts describing SPC and a partial listing can be found in [Penn89]. The American National Standards Institute guide [ANSI85] is a good place to start.

During the IDA concurrent engineering study, process management and use of SPC were the most frequently mentioned tools. Tools (or methods) were mentioned a total of seventy-five times in case studies in [Winn88]; of these citations, fourteen mentioned use of SPC or process management as part of a concurrent engineering or TQM program.

Managers in the United States and Japan have used statistical techniques to measure performance and they have implemented management techniques that are consistent with Shewhart's and Deming's concepts about variation in processes. The reported results have been reduced product variability, improved product quality, and reduced cost of nonproductive activities such as inspection and rework. Benefits of establishing control of a process have been reported as about 30 percent cost savings through improved quality.

A stable process that yields products which satisfy the customer's needs may, at some time, become unstable. Instability may arise from special causes as previously noted. Continued monitoring of the process through statistical process control can detect the transition to an unstable state; hence management may infer the presence of special causes. A process that continues to pass the tests isn't always a stable process, but the probability is very small that a unstable or chaotic process will continue to produce output that satisfies SPC criteria.

Several different charts are used in SPC for conducting these tests. When the value of the characteristic can be measured, the $\bar{x}$ and R charts are used; when the fraction of defective products is the characteristic being measured, the p chart is used; when the overall number of defects is being measured, the c chart is used; and when the overall number of defects per unit is measured, the u chart is used. Use of these charts is explained in [ANSI85].

Hayes [Haye88] describes four increasing levels of process control: reactive, preventive, progressive, and dynamic. Reactive and preventive control deal, respectively, with detecting abnormal variation and preventing its repetition. Progressive control seeks to improve the process so as to reduce variation while dynamic control allows the company to alternate among several processes while maintaining progressive control on each. Concurrent engineering requires all four levels.

In addition to SPC, other statistical tools are available for evaluating processes. In the late 1950s, Page [Page54] and Barnard [Barn59] introduced *Cumulative Sum Charts* (CUSUM) which respond more quickly to change in mean level. (DuPont is currently using more than 15,000 of these charts.) Hunter [Hunt86] describes a technique for maintaining control charts that can be used as a predictive tool. The technique, exponentially weighted moving average (EWMA), is a statistic that gives less and less weight to older data. A plotted point on an EWMA chart can be given a memory that controls the rate at which its importance is diminished. Control limits on the predicted values are used to show when the predictions become unreliable and preventive action can be taken.

Taguchi [Tagu86 p. 88] outlines four steps to achieving on-line process control: 1) optimize the measurement interval; 2) from the measured value, predict the mean characteristic value during the next interval; 3) determine the optimum correction for differences between the predicted value and the target value; and 4) change the signal value to achieve the desired correction. He provides recommended formulae for determining the optimum correction interval, the prediction of the characteristic value, and the amount of correction.

2.3 IMPROVE THE PROCESS

After a company gains an understanding of its customer's requirements and establishes stable processes for producing goods and services, it is ready to enter the first phase of concurrent engineering: providing early consideration of downstream factors during early design. This phase can be accomplished using some combination of four techniques: expanding the use of teams, improving design evaluation tools, developing design synthesis aids, and careful application of standardization.

2.3.1 Remove Cross-functional Barriers

Multifunction teams are one method of facilitating the optimization of all important measures of a product's function—performance, producibility, ease of maintenance, reliability, cost, and quality. Management forms and joins a team whose members have specialized knowledge in different portions of a product's life cycle to concurrently engineer both the product and the downstream processes for production and support. Involvement of these people in the design, particularly in the early stages, has been shown to reduce the time for total product realization. For example, the participation of representatives of the manufacturing or production branch has resulted in designs that can be produced with fewer modifications.

Use of multifunction teams does not imply a need for abolishing existing functional specialties, however, some reorganization may accompany their introduction. One company had a special facility, called the prototype shop, whose function was the fabrication of prototype products, but they found that procedures used in the prototype shop did not adequately predict production problems. Consequently, this company abolished the prototype shop and began building prototypes in the main factory using production workers, machines, and procedures. The change helped to involve production personnel in the development process at an earlier stage.

Formation of the multifunction teams varies among different companies. Some organizations form process-oriented multifunction teams, and others product-oriented multifunction teams. Membership on the teams may remain fixed or it may vary over the life of a product. Teams are usually co-located, but the location can change as a product moves from design to production. Because personal communication is such an important feature of this method, the teams are usually small (fewer than 12 people), but some companies are developing "teams of teams". Multifunction teams have been used to some extent on weapons systems for at least the last 15 years.¹⁰

Seifert [Seif88] reports that teamwork was evaluated by the participants as being the most important factor in one large company's successful productivity improvement program. Whitney [Whit88 p. 85] calls multifunctional teams the "most effective way to cut through barriers to good design." More companies reported using multifunctional teams than reported using any other single method. Multifunction teams were the second most frequently cited technique in [Winn88]. Their use was mentioned nine times (out of seventy-five citations) as a method which contributed to cost, quality, and schedule improvement.

In some organizations, team members who represent production divisions are selected directly from those divisions. Other companies have created a new specialist, the producibility engineer who participates with the design team. One company using such a specialist said that communication skills were one of the most important qualities for a person to be considered for such a position.

A common observation is that use of multifunction teams improves the ability of designers to create subsequent designs that incorporate from the start features reflecting down-stream considerations.

10. Multifunction task teams were used to design the F-15.

2.3.2 Evaluate Downstream Implications of a Design

As companies bring together people from different disciplines to practice concurrent engineering, the team members quickly realize the need for various members to work at comparable speeds. One aerospace company reported that when it tried to include more rigorous treatment of reliability and maintainability features during concept development, the reliability and support engineers could not work as fast as the other engineers. The aerodynamic and structural engineers, for example, could rapidly evaluate the implications of different design alternatives while the logisticians were restricted to manual calculation to determine the effects of different alternatives. Realizing that a faster response was needed, the reliability and support specialists determined that they could respond more quickly if they were provided with tools that supported faster analyses. To allow the support specialists to keep up with the other team members, the company developed a set of computer-based evaluation tools that estimated the maintenance and support implications of important design features. With the new tools, the team was able to develop a design that not only met the reliability and maintainability requirements but also could be produced for significantly less than their previous designs. In this case, the faster evaluation tools were a response to the realization by certain functional specialists that a new mode of working was needed.

The particular aspect of a design that will be evaluated may differ according to the product technology. Examples of validation tools discussed during this study include computer-aided timing verification, logic analyzers, fault simulators and analyzers for electronic circuits plus thermal analysis tools, assembly and manufacturability analysis tools, and structural, reliability, and maintainability analysis tools for mechanical and aerospace products.

Fault tree analysis, reliability and maintainability assessments, and failure mode effects analyses are examples of tasks that have traditionally been performed during product development. Concurrent engineering seeks to bring the knowledge of the experts who perform these studies upstream in the design process so that these and other factors will be considered from the outset. Computer-based tools allow these experts to develop quantitative assessments of alternative configurations as they participate in early discussions of the design.

Design evaluation tools were mentioned by seven of ten companies visited during this study. One recent survey [IIE89 p. 80] reports that over 80 percent of the responding companies find that computer-aided design tools improve profitability and a similar number intend to expand their use of such systems during 1990.

2.3.3 Apply Design Rules

Newton and Sangiovanni-Vincentelli [Newt86] in their survey of design automation tools, identify three classes of tools: design synthesis, design verification, and design management. Use of design rules to create a design is an example of a design synthesis method. The rules can be manual such as workbooks with design practices for a particular company or they can be included in the computer-aided design tools themselves. In digital electronic design, level-sensitive scan design (LSSD) and built-in logic block observation (BILBO) are examples of rules that will result in designs that are more easily tested. In mechanical design the use of group technology can provide designs that can be manufactured more easily in existing work-cells.

One of the most successful examples of design rules is the Design for Assembly (DFA) software tools provided by Boothroyd and Dewhurst Inc. [Boot85]. Use of DFA has been credited with savings of billions of dollars at several companies, but in this study, only one company reported DFA as one of the methods included in their concurrent engineering program.

Among ten sites visited, five reported use of some degree of design rules as part of their design process. The potential advantages of using design rules include the assurance that designs will be testable, can be manufactured with existing equipment, will be free of known defects, and can be assembled inexpensively. These advantages provide for smoother transitions at key points, thereby saving time and improving the quality of the final product.

2.3.4 Promote Standardization

Standardization is not normally associated with concurrent engineering, but the development of databases of standardized parts was cited by several companies as an element in their concurrent engineering program. As the number of unique parts used in designs decreased, purchasing, manufacturing, and design tasks were simplified. These companies ensured that the process of selecting and approving parts for entry into and retention in the database of approved parts was one which involved representatives of several functional groups. Thus, application of standardization was an important tool for improving certain white collar processes in these companies.

2.3.5 Use Integrating Technologies

Within the class of integrating technologies, two are of great importance: environment frameworks and description languages. The first holds the possibility of enabling a process of evolvable, tailorable, and universal automated tool integration. The second holds the possibility of standardized, automated communication of product

designs.

A design is created and refined over some interval. The process of creating a design and recording it as *the design* includes some amount of trial-and-error experimentation. Different alternatives are tried and discarded until a solution is achieved. One challenge of design management is that the process must allow freedom for the engineer to try new alternatives while maintaining control of who is allowed to alter the design and when they are allowed to do so. Procedures are also needed to select one version of the the several options being evaluated and to designate it as *the design*.

Additional work is needed to develop common standards for representing engineering information. Several workshop participants described the DoD Computer-aided Acquisition and Logistics Support (CALS) initiative and the Product Data Exchange Specification (PDES) effort as very promising programs in this area. Standardization efforts are also being conducted among international bodies. For example, the International Standards Organization Technical Committee 184, Subcommittee 4, Working Group 1 (ISO TC184/SC4/WG1) is developing a tolerance model. Their July 1987 working paper (Document 3.1.1.6) notes that as communication of product definition data comes to rely on digital communication instead of engineering drawings, the importance of providing unambiguous digital models increases.

Closely related to standards for representation, but at a slightly more abstract level, the concept of modeling provides a technique for supplying semantic meaning for an item of information. For example, one might wish to capture not only the design object, but also the designer's intent in creating the object. Models of products and processes may be represented as conceptual schema, or they may appear as mathematical expressions. Accurate models promote understanding of the process and simplify creation of integrated systems. Retroactive creation of information models is more difficult than defining two-way exchange standards between systems that already share the same information model. Consequently, many researchers consider it to be an essential first step.

Concurrent engineering teams up specialists who typically address designs using their own methods, representations, and manual and automated tools. Given the trend toward the use of automation for synthesis, analysis, and capture of designs, multifunction design teams will require tools and representations that work together easily. Integrating technologies are aimed at reducing the cost of evolvable, tailorable tool interoperability. At the same time, they have the possibility of drastically reducing the DoD cost of receiving and maintaining engineering data. Additional discussion of this technology may be found in [Linn86].

2.3.5.1 Environment Framework Development and Standardization

In several meetings of groups concerned with the technological aspects of concurrent engineering, some participants indicated that engineering environment frameworks are a significant facilitating technology for concurrent engineering.

An engineering environment framework is a response to the fact that as design complexity increases, the use of automated tools increases, but as the use of automated tools increases, complexity is added to the engineering process. Thus an effort to manage complexity of designs increases complexity of the engineering process. This point is exacerbated when designs are decomposed and addressed in highly interrelated subtasks or when specialists are required to address various aspects of a design. Such an approach requires the following characteristics and requirements:

- integrating and accessing information and automated tools easily;
- sharing multiple levels of design information in a controlled fashion;
- tracking design information;
- tracking design dependencies and changes, and propagating effects; and
- monitoring the design process.

These are characteristics and requirements that often increase as the use of concurrent engineering increases. Geographical dispersion of the team exacerbates the problem, because information sharing and control, process control, and perhaps even tool integration and access must occur over electronic networks.

To respond to these requirements, a framework is needed for tool integration based on information sharing. It should offer a standard, extensible set of services and interfaces to be used by applications. It should control and allocate data resources, provide concurrency controls, archiving, and a query capability.

There are five basic functions of an engineering environment framework to support concurrent engineering:

- tool integration—the ability to operate, efficiently and uniformly, tools with different data and hardware requirements;
- data exchange—the ability to translate and to communicate data among different hosts and tools not only within the the environment but also between the environment and external systems;

- engineering and manufacturing management and control—the facilities to monitor the design and manufacturing process and to impose automatic and manual controls on accessing and modifying data;
- information management—the facilities to describe and to control globally available environment data including the creation and manipulation of data, the imposition of data validity and constraint checking, version and configuration management, concurrent transaction control, and backup and archive management; and
- environment administration—the tools and specifications for managing the data dictionary, tools, workstations, user profiles, and control rules.

2.3.5.2 Description of Engineering Designs and Characteristics

Some participants in this study assert that a necessary requirement for concurrent engineering is the ability to represent the object being designed in an accurate, unambiguous language. In addition, moving from total reliance on design drawings to electronic representations that can be accessed by many team members is an important advance in design technology that allows teams to be more productive and provides an opportunity for concurrent, integrated execution of different design tasks. Other participants point to the existence of successful concurrent engineering efforts of many kinds when no such language was available and infer that a common unambiguous representation of the design object is not necessary.¹¹ Through the CALS initiatives, DoD participates in the effort to develop such a representation and foster its implementation.

There exists now a national effort to develop such a specification.¹² There is a national voluntary group, supported by the CALS initiative, whose goal is to develop Product Data Exchange Specification (PDES). An industrial cooperative, PDES Inc, has formed to accelerate implementation of the technology.

The PDES endeavor supports industrial automation in its broadest sense. The resulting standards would deal with the entire range of product data and are intended to represent the U.S. position internationally in the quest for a single standard for product data. The term *product data* denotes the totality of data elements which completely defines a product for all applications over the product's expected life cycle. The data include not only the geometry but tolerances, material properties, surface finishes, and other attributes and features that completely define a component part or an assembly of parts.

11. The authors believe that such a representation or family of representations is desirable.

12. Howard Bloom of the National Institute of Standards and Technology contributed to this section.

PDES must provide the capability of exchanging data among the multiple computing systems that will be involved in the product life. There is a particular necessity for archived models that will be interpreted at a future date by an unknown system. Industry has found that the ability to exchange product data among a variety of different vendor computer systems is critical to its external relationships with contractors and customers.

It is important to understand that the conceptual schema of the PDES model, while built to support application areas, is supposed to be independent of both the physical implementation and the applications making use of the information. The PDES model is referred to as the Integrated Product Data Model (IPDM).

2.3.6 Continuous Improvement

In addition to taking major steps to redefine the design process to make it more consistent with the ideas of concurrent engineering, there is a need to recognize that most processes are just too complicated for managers or engineers to specify exactly *a priori*. Most processes will either have latent errors or will develop them as the environment changes. The concept of continuous improvement is intended to deal with this situation.

Under a continuous improvement plan, the workers who carry out the process together with management are encouraged to understand it and to think of ways that it might be improved. Most suggestions result in only minor improvements, but collectively their impact can be significant.

A substantial effort is required to prepare workers and managers to adopt a continuous improvement philosophy. Among the companies visited, a training expenditure of one-half percent of gross sales was average. Such training is customary for companies that are starting a total quality management effort. Nash [Nash89] provides a catalog of training and education sources for concurrent engineering that includes several sources for training in continuous improvement methods.

In addition to continuous improvement of the development and production processes, considerable effort has been devoted to improvement of the product. Not normally viewed as concurrent engineering, *value engineering* is a program that supports product improvement. Using the same techniques that are applied during concurrent engineering, albeit often after an item has entered production, value engineering has been credited [Shaw89 p. 26] with over \$2 billion in savings within the defense community. Function analysis [Snod86] is one of the principal tools used in value engineering. The functions of a product are analyzed, classified, assigned priorities, and assigned a position either on or supporting a critical path. Alternatives can be evaluated in light of their ability to satisfy critical path functions at better cost. Within DOD, *value engineering*

supports the generation, evaluation, and implementation of value-engineering change proposals whose goal is provide the customer with an improved product while sharing the benefits between the supplier and customer.

2.3.6.1 Statistical Tools

The quality movement and the statistical community have developed a collection of methods, some simple and others complex, for promoting continuous process improvement. The "seven old tools" or Ishikawa's [Ishi82] seven tools are particularly simple, graphic devices intended for use by factory workers. They have also proven useful for professionals and are included in AT&T's PQMI [Acke87] workbook. Evolutionary operation [Box57] is a technique for using a process as a continual source of experimental data for improving it in an evolutionary manner. Box [Box89] stresses the importance of combining an informed observer with a significant event to learn from the observed behavior of processes, including the evidence of bugs and errors.

2.3.7 Robust Product Design

Since 1981, the concept of robust design has been gaining wider acceptance within U.S. industry. Among the workshop participants there was recognition that a Japanese engineer, Genichi Taguchi, can be credited [Phad89] with developing the key elements of this idea.

2.3.7.1 Taguchi's Contribution

The principal contributions of Taguchi include reexamination of the role of specifications, emphasis on using controlled experiments, recognition that products are built in factories under environmentally "noisy"¹³ conditions, attention to designing products to operate consistently under varying conditions (including aging), and re-emphasis on the need to improve quality while lowering costs. He is credited with the idea that producing products which are merely within specification is not adequate. His formulation of the concept of a quadratic "loss function" has sparked renewed interest in ways of reducing variability.

Robust product design starts with a concept that quality can be viewed as a loss to society associated with a product. The loss is assumed to be a continuous function of one or more quality characteristics (measurable characteristics of a product e.g. temperature, hardness, dimension, etc.). Robust product design seeks to find ideal target values for quality characteristics so that the loss function will be minimized. If such a target value can be found, then not only will the loss be minimized when the that target is achieved, but

13. Sources of variation in manufacturing, use, and age that cannot be controlled with economically practical methods are called noise factors.

also the expected loss can be calculated when that target is not achieved. Taguchi asserts that the loss increases as the square of the displacement from the target value when quality characteristics varies from the target value. Using this concept, it no longer suffices to produce items that are "within specification." Taguchi recommends use of statistically designed experiments to help designers find the parameter settings that will result in a product whose important characteristic is consistently close to the ideal target despite the presence of manufacturing variations or the effects of age. Moreover, he recommends that these values be selected using the least expensive materials.

The design steps involved are system design, parameter design, and tolerance design. System design is used to find the best technology for a product. Parameter design finds the parameter values which optimize the product loss. It reduces the effects of variability. Tolerance design selects the tolerances that must be used in manufacturing to assure minimum loss after the product is manufactured and is being used by the customer. It reduces the causes of variability in a product.

The benefits of Taguchi's approach have been demonstrated in automobile manufacturing, electronic component production, computer operating systems, engine design, optimization of integrated circuit chip bonding process, ultrasonic weld process optimization, and design of disc brake systems. The study team heard reports of many applications of this technique and the results have been impressive.

2.3.7.2 Design of Experiment

Design of experiment did not originate with Taguchi, but his works have sparked renewed discussion and application of this technique. Experimental design was invented and developed in England by Fisher and his colleagues in the 1920s. In the 1930s Fisher's ideas were also introduced into industry. At that time, The Industrial and Agricultural Section of the Royal Statistical Society was inaugurated in London and papers from industry on applications to manufacture of glass, light bulbs, textiles, etc., were presented and discussed. This led to new statistical methods: fractional designs were first used by Tippet in 1933 to improve a spinning machine and variance component analysis was developed by Daniels in 1935 to reduce variation in textiles.

During World War II the need for designs which could screen large numbers of factors led to the introduction of fractional factorial designs and other orthogonal arrays respectively by D. J. Finney (a student of Fisher) and by Plackett and Burman, two statisticians working in Britain's Ministry of Defense. In 1947, orthogonal arrays were named and further developed by C. R. Rao. Further notable work on these designs were performed in this country by Kempthorne, Sieden, Addelman, Box, Hunter, and others.

These designs have been widely applied in industry and many successful industrial examples are described in papers and books dating from the 1950s and, in particular, by a highly respected engineer and statistician, Cuthbert Daniel. Daniel also invented a very simple but important and effective way of analyzing the designs using normal probability plots.

In the early 1950s, Box, who was then working for the Imperial Chemical Industries, developed new techniques called response surface methods for the improvement and optimization of industrial processes experimentally. Initially when systems may be far from optimum conditions, fractional factorial designs and other orthogonal arrays were used to estimate a path of steepest ascent to increased response. Once the maximum was approached, second degree approximations were used with new types of designs, introduced by Box and Hunter and others, to estimate the necessary coefficients. Further analysis was used to study ridge systems which might allow simultaneous maximization of more than one response (e.g., maximum yield with minimum impurity). Response surface methods are routinely used by such companies as 3M, DuPont, General Electric, Allied Signal, and Dow Chemical to improve and optimize their processes, and many successful industrial applications have been described in numerous papers and books published over the last 30 years.¹⁴

In some industries, particularly the chemical industry, there is a tradition extending over several decades concerning the use of statistical methods including design of experiment. In other industries, statistical methods have only recently been rediscovered. There is a possible correlation between use of different design-of-experiment methods and the type of industry using a particular method.

Taguchi introduced some variations to the statistical techniques used during the later phases of robust design. Evaluation of the benefits and limitations of these particular variations is a subject of continuing research [NIST89].

Among the companies contacted, the use of robust design has been credited with some of the most spectacular cost savings, ranging up to 80 percent in some cases. In other cases [Winn88 p. 59], robust design techniques are credited with preventing the early termination of entire product lines. Seven companies reported success with robust design techniques.

14. We are indebted to Dr. George Box, Center for Quality and Productivity Improvement, University of Wisconsin-Madison, for contributing the information in this section.

2.3.7.3 Competitive Benchmarks

Competitive benchmarking is not, strictly speaking, a concurrent engineering technique. Competitive benchmarking is a technique applied by several companies to evaluate the quality of their product and process designs. Typically, competitors' products are purchased, evaluated for performance, and disassembled to evaluate the effectiveness of the design techniques and production process used to make the item. The company performing the analysis gains knowledge about the state of practice in their industry and they establish various benchmarks that can be used to evaluate the quality of their own products.

There may be different variations of the process, but it is widely practiced. Three companies mentioned it as an element of their normal product development. If a company has a rule that new designs must be the best in the class or world class, then competitive benchmarking is one method for establishing quantitative measures for achieving that goal.

2.3.8 Breakthroughs

Whether or not a company chooses to apply concurrent engineering, they will always be vulnerable to finding their products obsolete if a competitor achieves a breakthrough in product or process technology. Companies have traditionally relied on research and development, internal and academic, for new product and process ideas. Some directed the research into areas that were thought to be most important and others supported research in areas that were broadly defined.

Juran [Jura88 5.20, 22.12] discusses the relationship of a quality improvement program and the ability to set objectives for breakthroughs. He also provides a sequence of events that are associated with breakthroughs.

One company visited during this study has adopted a formal planning method to identify critical areas and focus attention on those areas so as to achieve breakthroughs. They do not limit breakthroughs to the fruits of research, but also target marketing, financial, and management functions. This company adopted a planning process called *Hoshin Kanri*, and they practice it extensively.

Other companies might be performing a similar process under the label of strategic planning. However, the adoption of a well-defined procedure for such planning at all levels of a corporation seems likely to produce additional benefits. Only two companies described formal strategic planning processes.

2.4 FRAMEWORK

The authors believe that the problem-oriented view of methods and tools provides a useful framework for considering when to use them. The preceding discussion, however, is only intended to be an introduction. For sources of further discussion of the individual tools, the reader is referred to *An Annotated Reading List for Concurrent Engineering* [Pen89].

Table 1 provides a summary of the problem-oriented framework for methods and tools.

Table 1. Framework of Methods and Tools

USE	METHOD OR TOOL	REMARKS
Determine Customer Wants		
	Multifunction Teams	At least manufacturing and design, (manufacturing is design's customer) usually more, often 8-12 people who work on a component
	Customer Surveys	Traditional marketing approach
	Send Engineers to the Customer	e.g., USAF Blue-two
	Supportability Awareness Training	Without genuine support this may not be taken seriously
	QFD	QFD charts are only the final part of this effort, the thought process and interaction of different groups are more significant. The charts only record the result.
	In-House Techniques	Sending engineers to the factory, factory workers to the distributors, giving products to employees for evaluation. Place people in a new role.
Establish Process Control		
Define the Process		
	PQMI	An AT&T approach described in [Acke87]
	Flow Charts	Widely used to describe tasks, but creative efforts are difficult to capture.
	Brain Storming	Supports many QFD efforts
	Computer-Aided Modeling	Particularly useful when different functional groups can access a common computer-based product and process description even when different evaluation or synthesis tools are used.
	Operational Definitions	See Deming
	DoD 4245.7	"Best practices," they should support the concurrent engineering concept if they are not misinterpreted as mandating a strictly sequential development.
	NAVSO P-6071	See best practices
	R&M 2000	An Air Force program that clearly stresses the importance of reliability and maintainability for new weapons systems.

USE	METHOD OR TOOL	REMARKS
Measure Process Characteristics	None	
Control the Process	SPC	Statistical process control, well-known in manufacturing, but also applicable in service tasks including engineering and design
	Pareto Diagrams	A simple histogram to show what problems should be attacked first.
	Cause and Effect Diagrams	Sometimes called the fishbone or Ishikawa diagrams—a kind of tree with effect at the root and causes as the branches and leaves.
	PERT Diagrams	A directed graph showing the relationship of tasks in a schedule. Tasks are usually the nodes and arcs show precedence relations.
	Reactive, Preventive, Progressive, and Dynamic Control	Hayes et.al., describe increasing levels of control that equate to increased levels of quality and greater advantage for the practicing company. Dynamic control provides the greatest competitive advantage.
	CUSUM	A technique, related to SPC, but especially good for detecting gradual shifts in the mean.
	EWMA	A technique for predicting trends and evaluating the accuracy of the prediction. Possible use with feed-forward.
	On-Line Process Control	[Tagu86 p 83] describes three forms: diagnosis and adjustment, prediction and correction, and measurement and action.
Improve the Process	Multifunction Teams	Discussed above.
	Design Evaluation Tools	Computer-based and checklists
	CATV	Timing simulations for circuit designs
	Logic Analyzers	For electronic circuit designs
	Fault Simulators	Used for circuit design verification
	Thermal Analysis Tools	Predict hot spots that usually indicate points of low reliability

USE	METHOD OR TOOL	REMARKS
	Design for Assembly	See Boothroyd and Dewhurst, 23
	Fault Tree Analysis	Both a traditional aerospace validation technique and one of the so-called seven new or management tools of Japanese management.
	Failure Mode Effects Analysis	Used to identify critical failure modes, traditionally used to help design more robust or safer products.
	LSSD	A set of design rules introduced by IBM, when followed the designs have certain nice features for testing.
	BILBO	A circuit design technique to simplify testing.
	Standardization	Use of standard or approved parts speeds design and avoids surprises for purchasing and manufacturing.
	Environment Frameworks	A concept that promotes interoperability of design tools, databases, evaluation tools, and other computer software and hardware needed to support the entire enterprise
Continuous Improvement	Description Languages	Computer descriptions of products and processes.
	Value Engineering	Similar concept to concurrent engineering, except that is is often applied only after the product has been developed and is in production.
	Ishikawa's Seven Tools	Simple devices to help factory workers monitor and improve quality. They can be used in service and design sectors.
	Evolutionary Operation	Concept of measuring the effects of very small, controlled variation in process controls to see how process can evolve to produce better quality products.
Design Robust Products	Taguchi Concepts	Importance of reducing variation, within specification is not enough, during design anticipate variation or noise in manufacturing and operation of the product, use experiments to select optimum parameters.

USE	METHOD OR TOOL	REMARKS
	Design of Experiment	Technique for efficiently evaluating effects of changing multiple parameters simultaneously.
	Competitive Benchmarks	Evaluate the best features of competitors products, including an estimate of the cost to manufacture and operate the product so that targets for new products can be established.
Other Improvements	Breakthroughs	Discoveries in products or processes that give a company a significant market advantage.
	Hoshin Kanri	A technique for focusing energy on areas where breakthroughs are needed.

3. EVALUATION OF METHODS

Several people have asked for a ranking of the various tools or methods that have been associated with concurrent engineering or with TQM. Sometimes the person making the request wants to know where to start in their quality or productivity improvement effort. Other people are looking for a method of grading companies as to which ones are "better" at concurrent engineering.

During the original workshops, an attempt was made to develop information that would support such a ranking. For the reasons outlined in this section, the attempt was not successful and neither were our efforts during this study. Following the suggestion of the NIST workshop, the authors associated the methods with the problems being solved and also reported such associations of methods with classes of benefits as could be supported by the available evidence.

3.1 THE PROBLEM OF RANKING METHODS

Although Winner [Winn88 p. 129] developed a framework for concurrent engineering and the preceding section presented a problem-oriented framework for methods and tools, the relative novelty of studying concurrent engineering has not provided an accumulation of data necessary for complete analysis in this field. For example, based on the data available, a final ranking of tools or methods cannot be completed now for two reasons. First, the list of potential methods is not stable and, second, there is no generally accepted criterion for measuring the benefits associated with individual techniques.

3.1.1 Changing Lists

During this study, the authors considered four different lists of methods and finally concluded that none of them could be considered as final. The diversity is illustrated below. The IDA report [Winn88 p. 112,114] describes thirteen methods and techniques associated with concurrent engineering. It then cites a list of 26 methods and techniques generated during one workshop and finally mentions a list of 23 methods that were reported at a 1987 Japanese conference. Figure 3 shows the list of methods that were identified during the 1988 IDA workshops as having some association with concurrent engineering.

1. Quality Function Deployment
2. Threat Analysis
3. Technology research and transfer
4. System Design, Parameter Design, and Tolerance Design (Taguchi Method)
5. Testing Methods
6. Problem History Feedback
7. Design for Simplicity
8. Design for Assembly
9. Rule-Based Design
10. Simulation (Soft Mock-up)
11. Common Parts Database with Reliability, Maintainability, and Producibility Information
12. Pugh Concept Development
13. Fault Tree Analysis (FTA)
14. Failure Mode Effects Analysis (FMEA)
15. On-line Quality Control
16. Design of Experiments
17. Response Surface Methods
18. Evolutionary Operations (EVOPS)
19. Exploratory Data Analysis
20. Statistical Graphics
21. Group Technology
22. Value Engineering
23. Measurement Methods
24. Operational Definitions
25. Ishikawa's Seven Tools (Graphs, Histograms, Cause-and-Effect Diagrams, Check Sheets, Pareto Diagrams, Control Charts, Scatter Diagrams)
26. Foolproofing

Figure 3. Tools and Techniques to Support Concurrent Engineering

After attempts to develop a consistent ranking of the importance of these tools, participants determined that such a ranking would be misleading. Each of these techniques serves a different purpose; each is a different tool to be used during product development. Saying that one tool is more important than another makes no more sense than saying that a saw is more important than a hammer for a carpenter. Just as a good carpenter uses a variety of tools, so an engineering team uses a variety of methods and tools. In many domains, familiarity with some minimal set of tools is seen as entry-level qualification and experts are the individuals who understand a wide variety of methods and can apply the correct approach to the problem at hand.

In Section 2 of this paper, forty-four different methods or tools are mentioned. IDA is not alone in noting fluctuation in the lists of methods and tools. A speaker at a company workshop who has been a frequent visitor to Japan reports a similar phenomena in that country—on each visit he saw a different list of tools and methods.

The authors' experience derived from visiting different companies or participating in different workshops is that no list of methods used in concurrent engineering or in TQM should ever be considered complete. Therefore, the authors believe that a complete ranking of such tools or methods is neither feasible nor desirable.

3.1.2 Confounded Causes and Effects

The difficulty of developing a complete list notwithstanding, the problem of assigning specific benefits to the use of individual methods based on available data remains intractable. During the concurrent engineering task, IDA collected data from a number of companies. Because the data were not the result of preplanned experiments, they could not be used to support strong conclusions about correlations of tools with benefits. The data do not support a statistical regression analysis because potential variables were not originally controlled and benefits were not measured using consistent metrics. Nevertheless, where benefits could be assigned the role of response variables, anecdotal association of benefits with different methods was developed. The benefits were classified according to whether they were quality improvements, cost reductions, or shortened schedules. The next section contains associations of different methods with benefits of each type.

The difficulty of providing cause-effect relationships concerning concurrent engineering (or TQM) is not limited to the IDA study. In general, the companies practicing either approach have not developed a rigorous mapping of benefits to the use of individual initiatives. In fact, when questioned about this idea, there was some indication that such a mapping was intentionally avoided. One company (that had been contacted during the first phase of the study and was later revisited) identified more than 80 internal

improvement actions, but said they were unable to show how much each of the actions contributed to their overall improvement. Their approach did not include a program for corporate-wide standardization on the individual elements of their improvement initiatives. They said that individual divisions were free to interpret for themselves how to implement the various ideas.

During this study, collective attempts to develop cause-effect relationships for tools and methods were also unsuccessful. In September 1988, participants at an IDA workshop attempted to apply QFD to the problem of ranking the various methods and tools of concurrent engineering. The effort failed because the members could not come to agreement on how the different problems which were being addressed should be ordered. In fact, when a company is faced with one problem, that particular problem becomes the most important one at that moment. After realizing that agreement on an ordering was not achievable, the members agreed to disagree on how the methods and tools should be ranked.

If experiments were to be planned with a goal of establishing correlations among different methods and specific benefits, then the experimental effort would be expensive and time consuming. Suppose one were interested in evaluating the primary effects and just the two-factor interactions for 11 methods where a given method was either used or not used. Using typical statistical techniques[Box78 p.407] one might chose a resolution V fractional factorial design requiring 128 separate experiments. To be realistic, each experiment would involve the complete development of a product. If other factors were to remain under reasonable control, e.g., technology, qualifications of the workers, etc., then the experiments would be performed within the same company using the same product line. After the experiments were completed, one would not be certain that the conclusions would be valid in other situations. The delay and expense of producing such results does not appear warranted in light of a considerable body of anecdotal evidence suggesting that certain classes of tools have been applied with success in solving certain types of problems. In the opinion of the authors and industry participants, the decision of which tools to apply is, best left to the people responsible for identifying and solving the particular problems.

Similar opinions were developed at a recent workshop [NIST89] on quality and productivity. Its final report recommended against premature comparisons of the benefits of different tools or methods. Instead, they recommended [NIST89] concentrating on identifying which problems should be solved first and looking for the tool most likely to be of use in solving that problem.

3.2 ASSOCIATION OF METHODS WITH IMPROVEMENTS

In this section we present such associations of general classes of methods and benefits (quality, cost, and schedule improvements) as could be established with the available data.

3.2.1 Quality Improvements

A review of the original case studies together with subsequent visits to several companies provided a count of the number of times each of the factors listed above was mentioned as contributing to improved quality. These frequencies are presented in Figure 4. The categories of engineering process initiatives, technology support, and formal methods were introduced in [Winn88] and represent a very rough grouping of methods and tools according to whether they were developed by management (including management consultants), by computer or technology support groups (including CAD vendors), or by the quality department (including statistician consultants).

Figure 4 shows that the most frequently cited tools were from the first two classes. Although there is a temptation to associate effectiveness of methods with number of times their use is mentioned, there is insufficient data to support that conclusion. One aerospace company said that they would not be able to develop such a correlation because they could not separate the interactions among different factors.

One electronics company provided a detailed breakout showing correlation among *quality* improvement initiatives and benefits achieved. They completed 19 documented quality improvement projects during a two-year period. The distribution of benefits was approximately even among quality, cost, and schedule improvements. In addition to cost improvements, they noted six categories¹⁵ of other benefits, three of which are related to quality (improve customer satisfaction, improve conformance to customer requirements, and reduce customer confusion).

Eight of the 19 projects involved development and use of better computer tools. Of these, all provided better customer satisfaction, two improved conformance to customer requirements, and two helped to reduce customer confusion.

Figure 5 shows that, within this company, the computer-based quality improvement projects (QIP) were customer focused.

15. The six categories are: improve customer satisfaction, conform to customer requirements, decrease critical path interval, reduce customer confusion, increase productivity, and decrease off critical path interval.

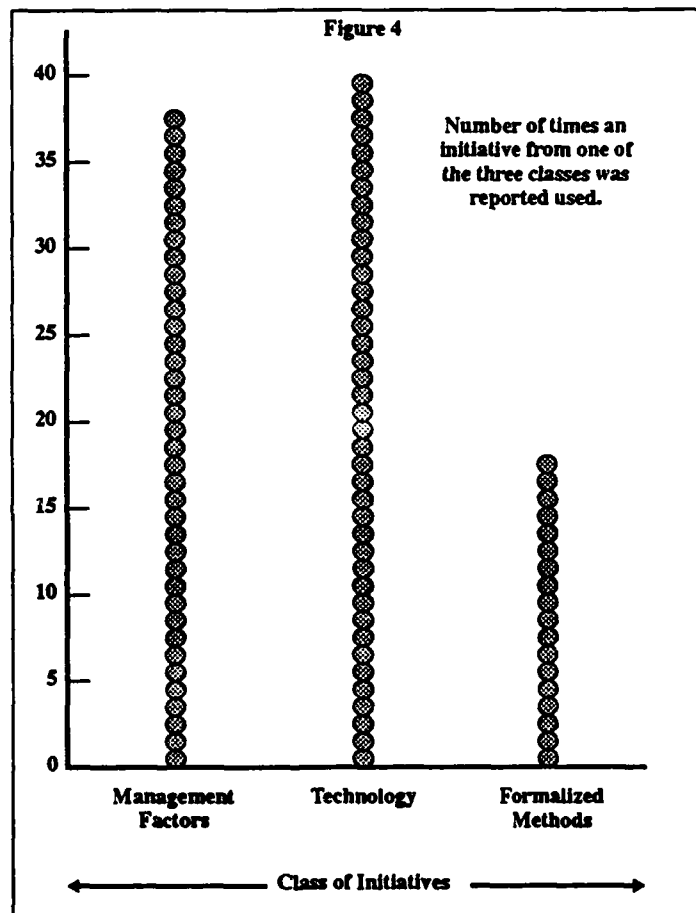


Figure 4. Use of Various Classes of Methods

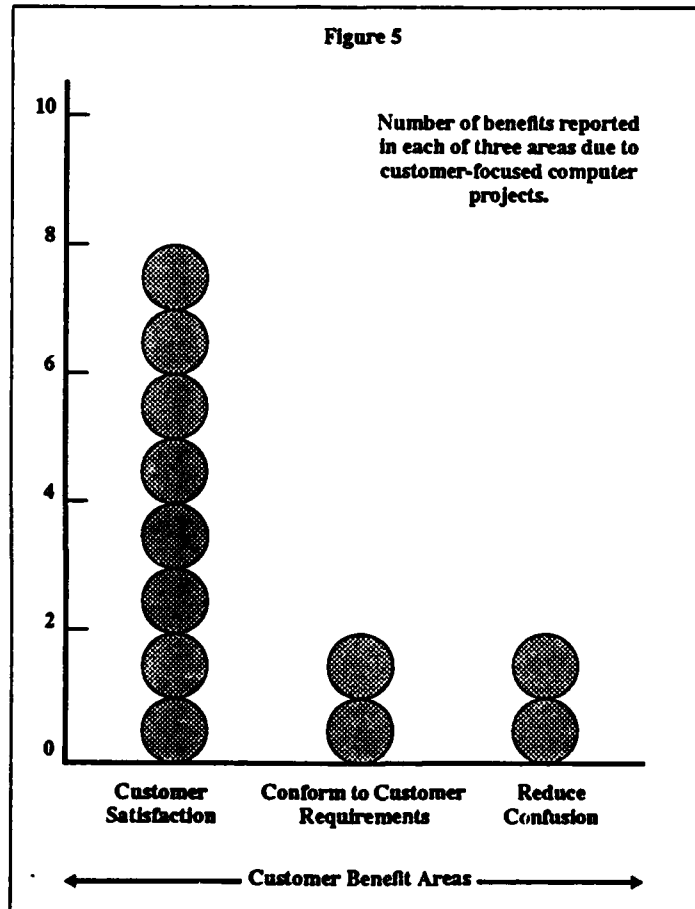


Figure 5. Results of Computer-Based Initiatives

Figure 6 shows that of the eleven projects involving management initiatives, eight reduced customer confusion, seven provided improved customer satisfaction, and four improved conformance to customer requirements. For this organization, customer focus had become important among both the technical staff and management.

These numbers, the result of one company's quality improvement program, show that changes designed as part of a quality improvement program can produce benefits in cost, schedule, and quality. They also show that quality improvement uses tools from each of the three categories identified in [Winn88].

3.2.2 Cost Improvements

During the original IDA study, companies reported cost benefits from using concurrent engineering. These benefits were often expressed in terms of cost avoidance and were often higher than 30 percent. The savings were usually not attributed to particular tools, except in the case of some statistical tools.

The companies practicing "robust design methods" were an exception. They frequently cited specific cost savings and did so in terms of actual dollar savings. Sometimes savings were calculated using a theoretical "loss function" improvement, but often they were expressed in absolute terms.

Because of the disparities among methods for calculating cost improvements, assessing the incremental contribution of such methods to an overall cost was not possible with the available data.

The electronics company mentioned in the preceding section provided data about the cost of the various initiatives as well as the cost benefits associated with each QIP. Their cost benefits however were not calculated according to a consistent accounting rule, but were engineering estimates of the cost savings. Nevertheless, the ratio of benefits to cost of the initiative was approximately constant at 10:1 for QIPs from each of Winner's three classes of tools.

Two "rules of thumb" about cost improvements associated with concurrent engineering or TQM methods were offered during the study. One company claimed a \$4 improvement in profit for every \$1 improvement in quality indicators. Another reported an average \$10 benefit for every \$1 spent for quality improvements.

3.2.3 Schedule Improvements

No special methods were identified for reducing schedules, but schedule reduction was reported by almost every company contacted. There were thirty-nine benefits reported to be associated with the use of multifunction teams. Thirteen involved

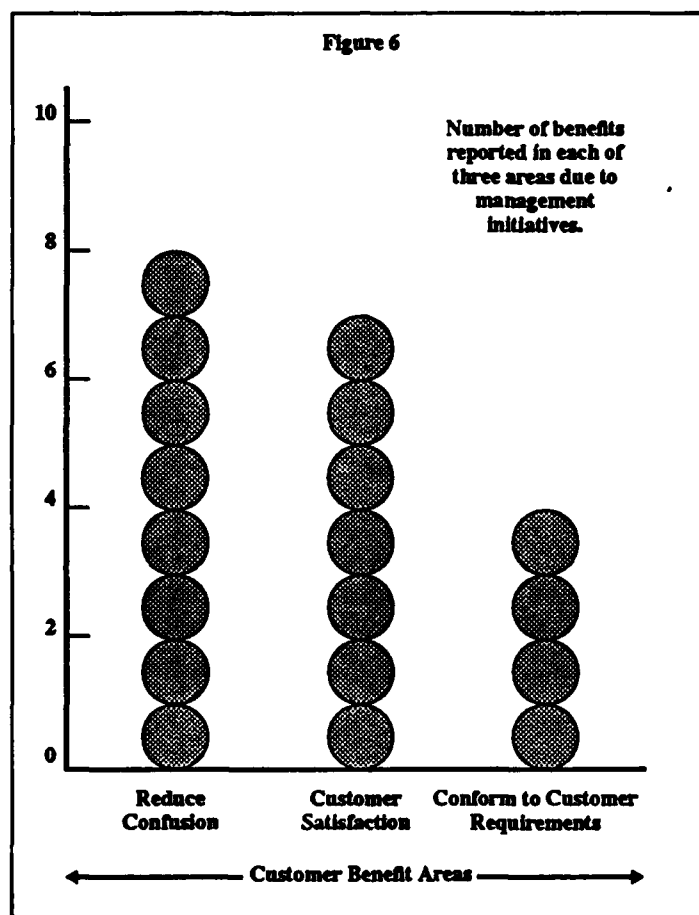


Figure 6. Results of Process Improvement Initiatives

schedule improvement and the average benefit was a fifty-seven percent improvement. However, for the same use of multifunction teams, fourteen benefits were cost reductions and twelve were quality improvements. The benefits of multifunction teams, therefore, are equally felt in cost, schedule, and quality improvements.

Other factors resulting in reduced time-to-market include the decision to reduce the number of prototype models to be produced, the decision to use parts and components from a standard database, the early participation of suppliers during concept definition, and better capture of the customer's requirements (e.g., through the use of QFD).

Automation, including selective use of computer-aided design tools, clearly contributes to decreased times for certain operations. Although not strictly a concurrent engineering element, it was reported by the companies visited as part of their process improvement efforts. These approaches are basically examples of using automation to speed-up an existing process, but schedule improvement was the most frequently cited benefit for the use of computer-aided engineering design and analysis tools.

Schedule improvements cited in [Winn88] include reports of orders of magnitude improvements for some particular process step (usually the result of using a better CAD tool) to more modest improvements in time-to-market for a full product. The later category ranged from 40 to 60 percent improvement compared to previous products of similar complexity developed before concurrent engineering was adopted. The reports of large improvements associated with CAD typically refer to reduction in the time to perform some discrete task within the development process and are not necessarily representative of overall improvement of the entire process.

Of the formalized methods that were mentioned by companies during this study, design for manufacture/design for assembly and design of experiment were mentioned most often as producing schedule improvements. In the judgement of the authors, the most important role for formalized methods is the improvement of quality. When quality, including the repeatability of the design processes, is improved, then both breakthrough and continuous improvements in the schedule are possible. Without improved quality, there can be no significant or sustained schedule improvement.

4. RECOMMENDATIONS

The various classes of activities that have been identified with concurrent engineering have been shown to produce multiple benefits. The association of methods with benefits is complex because single benefits result from the application of several methods and single methods result in multiple benefits. The importance, therefore, of any particular tool, or method, depends almost entirely on the situation existing when it is applied—what problem is being solved. Accordingly any attempt, at this time, to rank the tools in order of importance would necessarily be arbitrary and misleading. The Department of Defense would not benefit from such a list because it would seem to compare like items while not doing so.

It is tempting to look for some quantitative expression to model the concurrent engineering approach, but we have found no evidence to indicate that the search would be productive. The benefits to be derived from adopting concurrent engineering cannot as yet be expressed accurately in an equation where the methods and tools are the independent variables.

Although a strict ordering might not be useful and a simplistic cause-effect chart could be misleading, the subject of concurrent engineering has just recently gained wide attention. As with other subjects of recent attention, the initial examinations of the area may seem to produce data that seem to defy classification. Because the data are not clearly defined and relationships are not the subject of carefully drawn theories or even testable hypotheses, some observers might dismiss the concept of concurrent engineering entirely. The authors believe that such a dismissal would be a mistake. We are convinced that the companies we visited have found significantly better ways to develop their products.

More study is needed before comprehensive theorems or even reasonable axioms about concurrent engineering can be offered. Table 1 provided one framework, albeit only partially completed, for such future study. Winner [Winn88 p.129] offers another. Neither one suggests either a strict cause-effect relationship or a comparison that some tools are better than others. This observation leads to the first recommendation.

1. **Recommendation:** When continuing to conduct research in concurrent engineering or the associated tools and methods, choose a framework that relates them to the

problems to be solved. Instead of trying to find a best tool, try to understand how the different tools have worked, where they haven't worked, and how they can be improved. Understand the problems that have been encountered and suggest areas for research to develop new tools to solve them or to improve the tools that are already available.

The authors believe that in studying the tools, it will be useful to involve researchers from several disciplines. Learning why certain tools such as SPC or design of experiment have not been used might be more instructive than developing a quantitative model of how these tools work. For over 50 years people have known that the tools work, yet their use has been cyclic—widely used during the 1940s, infrequently used during the 1960s and 1970s, and being rediscovered in the 1980s.

Participants in this study reported that workshops were beneficial both for sharing information and for generating a body of case studies. Hearing participants describe how they solved various classes of problems using either new or traditional tools helped several companies develop their own concurrent engineering programs. The open discussion of how other organizations identified the problems is at least as important as learning how the problem was solved. Since the 1988 workshops, the authors have heard from several of the participants who reported that their companies have moved to adopt solutions that were presented during the workshops. Additionally, people said that contacts established during the workshops provided a network that could be used to exchange ideas about common problems. There is considerable support for continued workshops where further sharing of problems and solutions can take place.

Further, if a sufficient body of case studies is available, then qualitative analytic approaches might prove useful in promoting better product development techniques.

2. **Recommendation:** OSD, in conjunction with professional associations, should establish a regular series of workshops where participants can describe how they identified and solved problems to improve the quality of their products or productivity of their companies. These workshops could be jointly sponsored by TQM, value engineering, concurrent engineering, or other effort with goals of improving the weapons system acquisition process.

The Department of Defense faces a dilemma regarding concurrent engineering. On the one hand, it wants to encourage its suppliers to use the most efficient methods so as to provide products of the highest quality, according to realistic schedules, and within reasonable budgets. On the other hand, it does not want to impose any particular process on its suppliers as such efforts have been shown to be counter productive.

Some companies faced with a similar problem have achieved their desired goals by requiring their suppliers to apply for the Baldrige Prize or other quality award. The suppliers were given help initially, but they were responsible for developing their own programs. Several participants in this study suggested that OSD take a similar approach. The attractive aspects of the suggestion are that companies efforts to improve their quality would be evaluated by an independent agency (not associated with DoD) and, implicitly, that companies demonstrating superior quality would be rewarded accordingly. The dangers are that if applied by DoD it might generate another administrative bureaucracy and that unscrupulous companies would merely go through the motions of improving quality such as applying for an award merely to satisfy the DoD requirement.

- 3 **Recommendation:** If an effort is needed to improve the quality and productivity of the supplier base for DoD, and if DoD seeks to establish continuing associations with those companies that measure up to an externally specified quality standard, then OSD should evaluate the effectiveness of commercial organizations that have encouraged their suppliers to apply for a similar award (e.g., The Malcolm Baldrige National Quality Award). If several companies report demonstrable success from the approach, then OSD should undertake pilot projects to demonstrate the use of competition for quality awards as part of an acquisition improvement effort.

ACRONYMS

BILBO	Built-in Logic Block Observation
CAD	Computer-Aided Design
CALS	Computer-aided Acquisition and Logistics Support
CATV	Computer-aided Timing Verification
CUSUM	Cumulative Sum Charts
DFA	Design for Assembly
DoD	Department of Defense
EWMA	Exponentially Weighted Moving Average
FMEA	Failure Mode Effects Analysis
EVOPS	Evolutionary Operations
FTA	Fault Tree Analysis
IDA	Institute for Defense Analyses
IPDM	Integrated Product Data Model
LSSD	Level-Sensitive Scan Design
NIST	National Institute of Standards and Technology
OASD(P&L)	Office of the Assistant Secretary of Defense for Production and Logistics
OSD	Office of the Secretary of Defense
PDES	Product Data Exchange Specification
PQMI	Process Quality Management Improvement
QFD	Quality Function Deployment
QIP	Quality Improvement Project
SPC	Statistical Process Control
TQM	Total Quality Management
VOC	Voice of the Customer
WSIG	Weapons Support Improvement Group

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BIBLIOGRAPHY

- Acke87 Ackerman, Roger B. et al. 1987. *Process Quality, Management & Improvement Guidelines*. Indianapolis, IN: AT&T Bell Laboratories.
- ANSI85 ANSI and ASQC. 1985. ANSI Z1.1-1985/ASQC B1-1985, *Guide for Quality Control Charts*. ANSI Z1.2-1985/ASQC B2-1985, *Control Chart Method of Analyzing Data*. ANSI Z1.3-1985/ASQC B3-1985, *Control Chart Method of Controlling Quality During Production*. Milwaukee, WI: American Society for Quality Control
- Barn59 Barnard, G. A. 1959. Control Charts and Stochastic Processes. *Journal of the Royal Statistical Society Series B* 21: 239-271.
- Boot85 Boothroyd Dewhurst, Inc. 1985. *Design for Assembly Handbook*. Boothroyd Dewhurst, Inc., Wakefield.
- Box57 Box, George E. P. June 1957. Evolutionary Operation: A Method for Increasing Industrial Productivity. *Applied Statistics*
- Box78 Box, George E. P., William G. Hunter, and J. Stuart Hunter. 1978. *Statistics for Experimenters*. New York: John Wiley & Sons.
- Box89 Box, George E. P. February 1989. *When Murphy Speaks—Listen*. Madison, WI: Center for Quality and Productivity Improvement, University of Wisconsin, Madison. Report No. 34.
- Ches89 Cheslow Richard T. and J. Richard Nelson. October 1989. *The Executive Workshop on Cost/Performance Measurement*. Volume 2. Alexandria, VA: Institute for Defense Analyses. IDA Paper P-2321.
- Cros79 Crosby, Philip P. 1979. *Quality is Free—The Art of Making Quality Certain*. New York: New American Library.
- DARP87 DARPA. 1987. *Workshop on Concurrent Design, Key West, Florida, December 1-3, 1987*. Washington, D.C.: DARPA.
- Demi86 Deming, W. Edwards. 1986. *Out of the Crisis*. Boston, MA: The MIT Press.

- Fabr89 Fabrycky, Wolter J. 1989. Engineering and System Design: Opportunities for ISE Professionals. *1989 IIE Integrated Systems Conference & Society for Integrated Manufacturing Conference, November 12-15, 1989*. Atlanta, GA: Institute of Industrial Engineers.
- Haus88 Hauser, John R. and Don Clausing. May-June 1988. The House of Quality. *Harvard Business Review*: 63-73.
- Haye88 Hayes, Robert H., Steven C. Wheelwright, and Kim B. Clark. 1988. *Dynamic Manufacturing*. New York: The Free Press.
- Hunt86 Hunter, J. Stuart. October 1986. The Exponentially Weighted Moving Average. *Quality Technology* 18: 204-210.
- IIE89 Institute of Industrial Engineers (IIE). September 1989. F.Y.I. Drawing Higher Productivity. *Industrial Engineering* 21: 80.
- Ishi82 Ishikawa, Kaoru. 1982. *Guide to Quality Control*. White Plains, NY: Kraus.
- Jura88 Juran, J.M. 1988. *Quality Control Handbook*. Fourth Edition, New York: McGraw-Hill.
- King87 King, Bob. 1987. *Better Designs in Half the Time: Implementing QFD Quality Function Deployment in America*. Methuen, MA: GOAL/QPC.
- Linn86 Linn, Joseph L. and Robert I. Winner. July 1986. *The Department of Defense Requirements for Engineering Information Systems*. Volume I, *Operational Concepts*; Volume II, *Requirements*. Alexandria, VA: Institute for Defense Analyses. IDA Paper P-1953. DTIC accession numbers, AD-A176 153 and AD-A176 154.
- Merc87 Merchant, M. Eugene. March 11-12, 1987. *A Report to the National Science Foundation on Research Priorities for Proposed NSF Strategic Manufacturing Research Initiative*. Washington, D.C.: National Science Foundation.
- Nash89 Nash, Sarah H. November 1989. *Catalog of Training and Education Sources in Concurrent Engineering*. Alexandria, VA: Institute for Defense Analyses. Draft IDA Document D-666.
- Nevi89 Nevins, James L. et al. 1989. *Concurrent Design of Products and Processes: A Strategy for the Next Generation in Manufacturing*. New

York: McGraw-Hill.

- Newt86 Newton, A. R. and A. L. Sangiovanni-Vencentelli. April 1986. Computer-Aided Design for VLSI Circuits. *Computer* 19: 38-60.
- NIST89 National Institute of Standards and Technology (NIST). December 1989. *Report on DOD/NIST Workshop on Quality Technology and Statistical Methods for Defense Improvements*. Gaithersburg, MD: NIST.
- Page54 Page, E. S. 1985. Continuous Inspection Schemes. *Biometrika* 41: 100-115.
- Penn89 Pennell, James P. and Marko M. G. Slusarczuk. 1989. *An Annotated Reading List for Concurrent Engineering*. Alexandria, VA: Institute for Defense Analyses. IDA Document D-571. DTIC accession number, AD-A213 550.
- Phad89 Phadke, Madhav S. 1989. *Quality Engineering Using Robust Design*. Englewood Cliffs, NJ: Prentice-Hall.
- Seif88 Seifert, Laurence C. 1988. Design and Analyses of Integrated Electronics Manufacturing Systems. *Design and Analysis of Integrated Manufacturing Systems*: 12-33. Washington, D.C.: National Academy Press.
- Shaw89 Shaw, Steve. November 1989. Washington Report. *Aerospace Engineering* 9: 26.
- Snod86 Snodgrass, Thomas J. and Muthiah Kase. 1986. *Function Analysis: The Stepping Stones to Good Value*. Madison, Wisconsin: Board of Regents—University of Wisconsin System.
- Tagu86 Taguchi, Genichi. 1986. *Introduction to Quality Engineering*. Dearborn, MI: American Supplier Institute.
- Unit87 United States Air Force. October 1987. *USAF R&M 2000 Process*. Washington, D.C.: United States Air Force, Office of the Special Assistant for R&M.
- Whee86 Wheeler, Donald J. and David S. Chambers. 1986. *Understanding Statistical Process Control*. Knoxville, TN: Statistical Process Controls, Inc.
- Whit88 Whitney, Daniel E. July-August 1988. Manufacturing by Design. *Harvard Business Review* 66: 83-91.

Winn88 Winner, Robert I. et al. December 1988. *The Role of Concurrent Engineering in Weapons System Acquisition*. Alexandria, VA: Institute for Defense Analyses. DTIC accession number AD-A203 615.

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