SIMULTANEOUS ENGINEERING OF DEFENSE PRODUCTS AND PROCESSES

Report of the Defense Science Board
Task Force on Concurrent Engineering

October 1990

OFFICE OF THE UNDER SECRETARY OF DEFENSE FOR

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OFFICE OF THE SECRETARY OF DEFENSE
WASHINGTON, D.C. 20301-3140

DEFENSE SCIENCE
BOARD

July 9, 1990

MEMORANDUM FOR CHAIRMAN, DEFENSE SCIENCE BOARD

SUBJECT: **Defense Science Board Concurrent Engineering Task Force**

We are pleased to transmit the final report of the Defense Science Board Task Force on Concurrent Engineering and two proposed implementing memoranda (attached).

The study was based on a review of product development and production in leading DoD and commercial industry, recent related studies, and expert opinion on the in-practice nature of the Defense engineering and acquisition processes. Undersecretary Betti suggested the Task Force concentrate on actions that DoD can take to implement the subject engineering practices and the Task Force has done so. The Task Force found the following:

- The practices generally referred to as "concurrent engineering," "simultaneous engineering," etc. would, if applied broadly to Defense products and processes, yield large savings in production and life-cycle costs, decreases in schedule, and increases in quality. This, in turn, improves the probability of achieving operational advantages.

- The label applied to the practices is unimportant. The label "concurrent engineering" is in widespread use, but is often confused with "concurrency" of design and production. The report, therefore, uses no label. Furthermore, regardless of label, the practices are the engineering or product development implementation of Total Quality Management.

- The essence of the practices is the simultaneous, integrated engineering of products and their associated manufacturing and logistics processes. By making the product design robust in manufacturing and the product, itself, robust in use, quality is designed in and built in. The integration of product and process focus starts at the generation of requirements and continues through the life of the product.

- There is an increasing recognition of integrated product/process engineering in DoD industry, but its implementation is sparse and incomplete. Some DoD acquisition organizations have also recognized the benefits of the approach and are beginning to consider how to accelerate its use in the DoD industrial base.

- The funding, organizational, business practice, and educational barriers to accelerating industry's use of these practices are significant, but not insurmountable.

- Some barriers can be addressed immediately by clarifying R&D resource allocation, technology base funding, and the acquisition milestone expectations or exit criteria.

- Other barriers, including organizational and contracting issues, the integration of cost, schedule, and performance considerations within early system requirements, establishment of self-benchmarking processes, and education of the acquisition work force, will take longer.

- There are technical issues being faced by those trying to implement concurrent engineering, particularly in large projects. These issues include the difficulties of integrating computer-based engineering tools and methods in an evolvable, seamless way yet with adequate performance, and, for some products, difficulties in developing tools to assist design teams in manufacturing, reliability, and maintenance analysis and development. The Task Force recognized the depth and extent of these issues, but concentrated on direct DoD management actions rather than technological issues. One recommended action includes attention to 6.1, 6.2, and IR&D funding to help address technical issues.

The proposed implementing memoranda contain immediate actions and longer range thrusts.

There are three recommendations of the Task Force to DoD and one to industry. The DoD recommendations are:

1. Modify acquisition expectations so that the goals at each acquisition milestone, especially the early phases, would be based on a balance of product and manufacturing and logistics process engineering results. Provide OSD guidance to clarify the allowability of process research and development within 6.1, 6.2, 6.3, and 6.4 funds and IR&D in order to accommodate simultaneous product/process engineering.

2. Encourage the Services and OSD to evolve organizations and practices to accelerate the educated and widespread use of simultaneous product/process engineering. In particular, the Task Force strongly recommends that the Defense Science Board Task Force on Acquisition Streamlining consider the detailed suggestions set out in the report as being critical to meeting its objective of halving acquisition time:

3. Update DoD 4245.7-M, the Transition-from-Development-to-Production Templates, to incorporate the simultaneous integration aspects and focus on robustness applied in simultaneous engineering. The Transition Initiative education program should be used as an approach to educate the acquisition work force on best practices including simultaneous product/process engineering and its business implications.

The industry recommendation is to **implement integrated, simultaneous product/process engineering now.** The report outlines steps that have been demonstrated to achieve the required changes.

OFFICE OF THE SECRETARY OF DEFENSE
WASHINGTON, D.C. 20301-3140

DEFENSE SCIENCE
BOARD

12 OCT 1990

MEMORANDUM FOR SECRETARY OF DEFENSE
DEPUTY SECRETARY OF DEFENSE

SUBJECT: Final Report of the Defense Science Board Task Force on Concurrent Engineering

Attached is the final report of the Defense Science Board Task Force on Concurrent Engineering cochaired by Mr. Travis Engen and Dr. Don P. Clausing. The Task Force addressed the application of concurrent or simultaneous engineering pracitices of world-class manufacturing companies to the DoD. They concluded that widespread adoption of such practices would enable the acquisition of high quality systems on time, within cost, and with the advances in performance required to maintain military superiority.

The underlying concept of simultaneous engineering practices is that development of manufacturing capabilities and logistics products is done in close concert with the detailed design of the product. The Task Force found that simultaneous engineering practices are in limited use in DoD acquisitions. The Task Force recommends that the DoD: clarify the allowability and promote the funding of work on manufacturing and logistics design much earlier in the program development cycle; define producibility expectations to be achieved during each acquisition phase; and update the Transition-from-Development-to-Production Templates. These actions should be started at once. Longer term recommendations addressing requirements formulation, organizational structure, and contracting should be taken up by the Defense Science Board Task Force on Acquisition Streamlining.

I concur with the Task Force's findings and recommendations.

John Foster

John S. Foster, Jr.
Chairman

Attachment

The Task Force believes very strongly in the approaches studied and in the recommendations. The widespread use of simultaneous product/process engineering in DoD acquisitions will significantly improve operational capabilities even in a declining budget. Because of the importance of simultaneous engineering approaches and their potential payoff for the DoD, the Task Force worked hard to make the main body of the report short and to the point, yet accessible to those unfamiliar with the topic. We urge you to review the report and recommend the rapid implementation of the DoD recommendations.

Finally, the Task Force members and advisors were from many backgrounds and work settings. Without exception, each contributed to the understanding of simultaneous product/process engineering and the development of our findings and recommendations. We are very grateful for their support.

Travis Engen
CETF Co-chair

Don Clausing
CETF Co-chair

Case Study	Cost	Schedule	Quality
McDonnell Douglas	60% savings on bid for reactor and missile projects.	Significant savings (reduction from 45 weeks to 8 hours) in one phase of high-speed vehicle preliminary design; 18 month saving on TAV-8B design.	Scrap reduced 58%, rework cost reduced 29%, and nonconformances reduced 38%; weld defects per unit decreased 70%; 68% fewer changes on reactor; 68% fewer drawing changes on TAV-8B.
Boeing Ballistic Systems Division	Reduced labor rates by $28/hour; savings 30% below bid.	Part and materials lead-time reduced by 30%; one part of design analysis reduced by over 90%.	Floor inspection ratio decreased by over 2/3; material shortages reduced from 12% to 0; 99% defect-free operation.
AT&T	Cost of repair for new circuit pack production cut at least 40%.	Total process time reduced to 46% of baseline for 5ESS.	Defects reduced by 30% to 87%.
Deere & Company	30% actual savings in development cost for construction equipment.	60% savings in development time.	Number of inspectors reduced by 2/3.
Hewlett-Packard Instrument Division	Manufacturing costs reduced 42%.	Reduced development cycle time 35%.	Product field failure rate reduced 60%. Scrap and rework reduced 75%.
IBM	Product direct assembly labor hours reduced 45%.	Significant reduction in length of PMT design cycle. 40% reduction in electronic design cycle.	Fewer engineering changes. Guaranteed producibility and testability.

Table 1: Cost, Schedule, and Quality Benefits.

EXECUTIVE SUMMARY

Simultaneous product/process engineering is a commonsense approach to the problem of bringing a product from recognition of need to field operation. It has been known for some time under various labels, but it is only sparsely practiced in Defense industry. The basic principle is to iterate and integrate the design of a product and the design of its manufacturing and logistics processes with specific focus on achieving lowest product cost, shortest schedule, and robust quality. The approach works by tying product and process designs together, preventing problems rather than depending on problem detection and correction. In its review of leading industry practices, the Task Force finds that simultaneous, integrated product/process approaches significantly increase the probability of bringing mature products to the field at reasonable cost and within predictably shorter schedules while at the same time achieving required advances in performance. Table 1 summarizes some of the results reported in a recent study on the use of simultaneous, integrated engineering approaches among leading U.S. companies. The Task Force has concluded that substantial benefits would accrue to the DoD if the typical Defense sequential engineering approach were changed to a simultaneous, integrated product/process engineering approach. Further, methods and technologies are available and emerging that enhance the simultaneous engineering of products and their processes, particularly for complex, high-performance products. For large projects, implementers of simultaneous engineering face difficult technical issues, particularly in the area of information integration. It is important that DoD and its industrial base both insert these tools and methods into practice and continue their development in order to address technical issues more effectively.

Accelerating the widespread Defense use of simultaneous product/process engineering will require changes in DoD and industry acquisition practices and organizations. Specifically, the Task Force recommends that the DoD:

1. Modify acquisition expectations so that the goals at each acquisition milestone, especially the early phases, would be based on a balance of product *and* manufacturing and logistics process engineering results. Provide OSD guidance to clarify the allowability of process research and development within 6.1, 6.2, 6.3, and 6.4 funds and IR&D in order to accommodate simultaneous product/process engineering.

2. Encourage the Services and OSD to evolve organizations and practices to accelerate the educated and widespread use of simultaneous product/process engineering. In particular, the Task Force strongly recommends that the Defense

4. Encourage a process that will lead to the use of world-class tools to improve product/process integration and to provide technically sound bases for engineering robust products.

Science Board Task Force on Acquisition Streamlining consider the following suggestions that are critical to meeting its objective of halving acquisition time:

- — Establish team organizations and relationships within DoD institutional structures that will support simultaneous product/process engineering. This will tend to decrease the use of advocacy organizations that tend to fragment the engineering effort.
- — Modify government business practices that are barriers to industry implementation of simultaneous product/process engineering. This includes modification of contracting practices that tend to fragment the engineering effort.
- — Integrate design-to-cost with consideration of performance and schedule to encourage broad product and process trade-offs. When warranties are used, identify them prior to the design phase.
- — Establish acquisition process self-benchmarking to provide a baseline and focus for process improvements.

3. Update DoD 4245.7-M, the Transition-from-Development-to-Production Templates, to incorporate the simultaneous integration aspects and focus on robustness applied in simultaneous engineering. The Transition Initiative education program should be used as an approach to educate the acquisition workforce on best practices including simultaneous product/process engineering and its business implications.

The Task Force finds that Defense industry is capable of carrying out a simultaneous product/process engineering process and should accelerate its implementations. DoD leadership is encouraged to challenge industrial associations and other private sector groups to initiate activities complementary to those undertaken by DoD. The Task Force suggests that industry use approaches based on a two-pronged, integrated strategy. The first three suggestions can be implemented in one year. The fourth suggestion should be started now but will take more time.

1. Integrate organizations, processes, and activities based on simultaneous product/process engineering principles, eliminating stovepiping and "over-the-wall" transactions through the use of multifunctional product development teams.
2. Establish active top management leadership toward integration.
3. Rethink how company organizations reach an understanding of end-user and customer needs.

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1. INTRODUCTION

Overview and Recommendation Summary Simultaneous product/process engineering is a commonsense approach to the problem of bringing a product from recognition of need to field operation. It has been known for some time under various labels, but it is only sparsely practiced in Defense industry. The basic principle is to iterate and integrate the design of a product and the design of its manufacturing and logistics processes with specific focus on achieving lowest product cost, shortest schedule, and robust quality. The approach works by tying product and process designs together, preventing problems rather than depending on problem detection and correction. In its review of leading industry practices, the Task Force finds that simultaneous, integrated product/process approaches significantly increase the probability of bringing mature products to the field at reasonable cost and within predictably shorter schedules while at the same time achieving required advances in performance. Table 1 summarizes some of the results reported in a recent study on the use of simultaneous, integrated engineering approaches among leading U.S. companies.[1] The Task Force has concluded that substantial benefits would accrue to the DoD if the typical Defense sequential engineering approach were changed to a simultaneous, integrated product/process engineering approach. Further, methods and technologies are available and emerging that enhance the simultaneous engineering of products and their processes, particularly for complex, high-performance products. For large projects, implementers of simultaneous engineering face difficult technical issues, particularly in the area of information integration. It is important that DoD and its industrial base both insert these tools and methods into practice and continue their development in order to address technical issues more effectively..

Accelerating the widespread Defense use of simultaneous product/process engineering will require changes in DoD and industry acquisition practices and organizations. Specifically, the Task Force recommends[2] that the DoD:

1. Modify acquisition expectations so that the goals at each acquisition milestone, especially the early phases, would be based on a balance of product *and* manufacturing and logistics process engineering results. Provide OSD guidance to clarify the allowability of process research and development within 6.1, 6.2, 6.3, and 6.4 funds and IR&D in order to accommodate simultaneous product/process engineering.

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1. The report that contains these results is summarized in Appendix C.
2. These recommendations are detailed in Section 3.

Case Study	Cost	Schedule	Quality
McDonnell Douglas	60% savings on bid for reactor and missile projects.	Significant savings (reduction from 45 weeks to 8 hours) in one phase of high-speed vehicle preliminary design; 18 month saving on TAV-8B design.	Scrap reduced 58%, rework cost reduced 29%, and nonconformances reduced 38%; weld defects per unit decreased 70%; 68% fewer changes on reactor; 68% fewer drawing changes on TAV-8B.
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Table 1: Cost, Schedule, and Quality Benefits.

2. Encourage the Services and OSD to evolve organizations and practices to accelerate the educated and widespread use of simultaneous product/process engineering. In particular, the Task Force strongly recommends that the Defense Science Board Task Force on Acquisition Streamlining consider the following suggestions that are critical to meeting its objective of halving acquisition time.

   — Establish team organizations and relationships within DoD institutional structures that will support simultaneous product/process engineering. This will tend to decrease the use of advocacy organizations that tend to fragment the engineering effort.

   — Modify government business practices that are barriers to industry implementation of simultaneous product/process engineering. This includes modification of contracting practices that tend to fragment the engineering effort.

   — Integrate design-to-cost with consideration of performance and schedule to encourage broad product and process trade-offs. When warranties are used, identify them prior to the design phase.

   — Establish acquisition process self-benchmarking to provide a baseline and focus for process improvements.

3. Update DoD 4245.7-M, Transition-from-Development-to-Production Templates, to incorporate the simultaneous integration aspects and focus on robustness applied in simultaneous engineering. The Transition Initiative education program should be used as an approach to educate the acquisition workforce on best practices including simultaneous product/process engineering and its business implications.

The Task Force finds that Defense industry is capable of carrying out a simultaneous product/process engineering process and should accelerate its implementations. DoD leadership is encouraged to challenge industrial associations and other private sector groups to initiate activities complementary to those undertaken by DoD. Some approaches to industry implementation are suggested in Section 4.

Scope and Approach This report summarizes the findings of the Defense Science Board (DSB) Concurrent Engineering Task Force (CETF) that were developed from March 1989 to April 1990.[3] [4] The Task Force study was concerned with the improvement

3. The CETF was initiated in March 1989 as the first task force of the Defense Manufacturing Board (DMB). The DMB and several task forces were merged into the DSB in January 1990.

4. A list of Task Force members and advisors is contained in Appendix A. The CETF Terms Of Reference are contained in Appendix B.

of the product engineering process (in a broad sense: bringing a product from need recognition to mature operation) in terms of quality, cost, and schedule via product/process integration. The Undersecretary of Defense for Acquisition stated in October 1989 that the CETF should concentrate on recommendations for action rather than analysis of benefits because the benefits are known as the result of previous studies.[5] The Task Force also considered, to some extent, the processes that surround product development (in particular, the Defense Acquisition Process), but only as they directly affect product design and development. Since the CETF found that the acquisition and product engineering processes' performance are interdependent, this report contains some high-level recommendations that should be examined in follow-on work on acquisition process restructuring.

The findings and recommendations are based on analysis of previous studies, visits and interviews with successful practitioners of integrated approaches to product and process engineering,[6] and expert opinion on the in-practice nature of both the Defense Acquisition Process[7] and the engineering and production of defense products.

Integrated approaches to engineering for both high-quality products and their production and logistics, all as part of product conceptualization, design, and development, have proven highly beneficial. These approaches are known by various names including *simultaneous engineering*, *concurrent engineering*, *concurrent design*, and *life-cycle engineering*. One approach is to use the Transition-From-Development-to-Production Templates[8] as a strong basis. Simultaneous, integrated product/process engineering, because of its focus on robust quality, is the application of Total Quality Management to the product and process development activity.[9] The label for this improved form of product and process development is less important than the actual practice. The Task Force has found that the label under which it was chartered, "concurrent engineering," has received widespread use but unfortunately is often mistaken for "concurrency" of development and production.[10] The use and benefits of the best practices recommended in this report should not be delayed by confusion created by labels. Each organization can determine the label that is best suited to its traditions and activities.

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5. For example, *The Role of Concurrent Engineering in Weapons System Acquisition*, Institute for Defense Analyses, Alexandria, VA, IDA Report R-338, NTIS AD-A203 615, December 1988.
6. Appendix D summarizes industry's view of Industry-DoD interaction derived from these interviews.
7. Appendix E discusses current DoD process issues.
8. Defense Science Board, *Solving the Risk Equation in Transitioning from Development to Production*, May 1983, currently available as DoD Publication 4245.7-M. The current formulation of the Templates needs to be evolved to include greater attention to process integration and robustness.
9. A discussion of the relationship between product/process integration and the Transition-From-Development-to-Production templates and total quality management appears in Section 2.
10. Congressional Budget Office, *Concurrent Weapons Development and Production*, August 1988.

Description of Simultaneous Product/Process Engineering Integrating the design of products and processes reduces production and life-cycle costs, reduces the time from concept to maturity, and increases product quality. It accomplishes these goals by preventing downstream problems through the design of products and processes that fit together well. The commonsense notion of products and processes fitting together has been formally and scientifically captured in the idea of *robustness*. The fundamental objective at every stage of development from concept exploration on is to try to assure the robustness of the key characteristics of the design and the product during all the downstream stages of design, production, use, and logistics. A product is robust to the extent it can exhibit its desired characteristics even in the face of uncontrolled variation in the surrounding process. This idea can be applied equally to the manufacturing, operation, and logistics processes, and rests on a sound statistical basis.[11]

Robustness is accomplished by taking an integrated view of product and process design so that interactions and sensitivity to important uncontrollable factors can be predicted and dealt with early. As a problem-prevention technique, this concept goes far beyond the approach of having separate producibility, operability, and maintainability analyses as is typically the case today. In fact, the typical approach today has the effect of fragmenting the engineering process and wasting energy and resources, rather than integrating and truly affecting the design of the product early enough to benefit cost and schedule. As stated in the recent Technology Assessment Team (TAT) Report on Japanese Manufacturing Technology:

> The Japanese have made impressive gains in productivity by coupling concurrent design with continuous improvements in the manufacturing process, implementation of the latest manufacturing technologies, and operating concepts emphasizing flow-through manufacturing. Concurrent design emphasizes the links among product design, fabrication, assembly, test, and logistics. In practice, this means combining the most important design issues during the early phases of product design where they can have the most influence.[12]

A problem-prevention posture is essential so that downstream problems are preempted

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11. For a more technical description of robustness, see Appendix L.

12. *Findings of the U.S. Department of Defense Technology Assessment Team on Japanese Manufacturing Technology*, June, 1989, pp. 15-29. Further results reported here include: required parts reduced by 20%, sub-assembly times reduced by 35%, assembly times reduced by 28%; five Ford projects report required parts 26-70%, costs predicted to fall 31-98%; Sony hardware component fabrication cycle reduction of 80%; Japanese automobile, fork-lift, and engine labor at about 50% of U.S. labor levels; and initial factory rework/repair requirements on consumer electronics at 0.5-1% of produced units versus 8-10% of comparable U.S. production. The report attributes these results primarily to product/process integration approaches.

rather than detected and corrected. Problem detection and correction will always be necessary; however, no matter how well organized they are, detection and correction cannot lead to systemic schedule, cost, and quality improvement because they are not addressed until after development has been largely completed.

Product/process integration drastically reduces the time to maturity[13] by focusing due effort on manufacturing and logistics issues early on and throughout development. The sequential process greatly extends time to maturity in five ways: (1) delayed starts for downstream activities, waiting for earlier activities to be completed and the information to be transferred, (2) information weakly understood by downstream, receiving organizations because they did not participate in the decision-making, (3) lack of commitment in downstream, receiving organizations to decisions in which they did not participate, (4) suboptimized, parochial trade-offs, which must be redone when other considerations are brought to bear, and (5) chaotic mistake corrections, caused by lack of robustness, which cause build-test-fix iterations to be inefficient and excessive in number. The integration of product and process engineering directly overcomes the first four problems. An early emphasis on robust quality, using world-class tools and methods, overcomes the fifth problem. After making these improvements, new technology can be brought to initial operating capability much quicker and with greater maturity.

By reducing the time to maturity, there is less reason to push the expectations of future technology improvements as much. Thus, by using less risky technology, cost can be more accurately estimated and contained. Decreasing (not eliminating) the technology push allows performance expectations to be much more accurately established and achieved.

Increasing numbers of commercial companies are adopting integrated approaches in order to remain internationally competitive. For example, Ford, Xerox, and Motorola have all made major changes to adopt techniques leading to product/process integration. These companies have demonstrated significant improvements in competitiveness and profits by adopting simultaneous product/process engineering approaches.

The degree of implementation varies depending on how far along each company is with respect to a few factors.[14] A very fundamental measure of progress is the degree to which the company and its engineers recognize the central importance of robustness. This recognition can vary from vague comprehension to true team focus on driving down development and production cost and schedule through making product and process

13. *Time to maturity* is defined as the time from concept exploration to the production of mature products.
14. For a more complete discussion, see Appendix G.

designs robust with respect to each other. At the same time, the team can increase the end performance and availability of the system through attention to robustness in end use. Part of the focus on robustness is the realization that there are disciplined approaches to it and that robustness is founded on sound mathematical and scientific bases. A second factor is the degree of integration of the engineering specialties. At one end of this dimension are efforts that are done in parallel but with little communication. At the other end there are the truly unified team approaches. The integrated team still has specialty engineers but as a group performs as if with one mind, that is with a coherent, end-to-end view of the whole product and all its surrounding processes. A third factor is the use of world-class tools and methods to support the focus on robustness.[15] These include formal approaches, some of which have been known for decades but are just now being inserted into Defense industrial practice.[16] Other world-class tools include judicious use of computers for process planning, simulation, and analysis as well as "art-to-part" integrated engineering information systems and feature-based information systems that are tied to manufacturing information. Emerging tools include use of expert systems that can help analyze or detail designs with respect to downstream process effects. Truly advanced companies have proceeded beyond adopting existing tools and methods by engaging the workforce in the invention of improved approaches.

At the same time that commercial industry has made progress and DoD industry is getting started, some of the Service Acquisition Commands are beginning to recognize the benefits of simultaneous product/process engineering and to consider how they might facilitate industrial implementation of integrated approaches to product and process engineering. The Air Force Aeronautical Systems Integrated Product Development process is an example approach.[17]

Although progress is being made in bringing process issues upstream to be integrated with product design, much more needs to be done before this is a demonstrated capability in American companies. DoD and DoD industry must take the lead in the shift to product/process integration in order to reduce weapons development time, reduce weapons costs, and improve weapons quality. International commercial practices have shown that efficient, integrated product and process engineering can be done successfully. Success in the United States will require implementation by DoD industry aided and assisted by DoD actions. Specific recommendations are described in Sections 3 and 4.

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15. See Appendix F and IDA Report R-338, *op. cit.*, Appendices B and C.
16. Available formal approaches include use of quality function deployment and other advanced systems engineering methods, statistical models of parameter design, design of experiments, Pareto analysis, normal plots, etc.
17. The Air Force Aeronautical Systems Division Integrated Product Development process is described in Appendix H.

Technological Implementation Issues This study has concentrated on DoD business-practice issues, but industrial implementors of simultaneous engineering, particularly for large projects, face some unusual technological issues as well. For example, many companies find that the requirement for an integrated engineering process can lead to a need for integration of a wide variety of engineering synthesis and analysis tools around an integrated information base. Tool integration and integrated information management are difficult to implement when starting afresh and are even more difficult if the integration occurs on an existing base with its own attendant technical and cultural issues.

Further, in product domains where engineering and tooling are changing rapidly, many perceive a need for the integrated information system to be easily evolvable and accepting of products acquired in an open marketplace. One way to achieve that kind of evolvability is with a common, open system architecture for integrated information systems. However, there may be unacceptable system performance costs if one maximizes openness and integration simultaneously. Thus, there is a set of ill-understood engineering trade-offs between broad engineering process performance improvement (through openness and integration) and narrower engineering performance improvement (through integration alone). Even though there are multi-enterprise, DoD-level issues surrounding this technical problem that deserve attention, some companies implementing concurrent engineering are trying to implement their own solutions now. Because of the extent, potential benefits, and difficulty of these efforts, and because of the relationship between integrated information technology and the DoD CALS issue of government receipt of integrated technical data, the DoD should participate in the development of integrated information systems and common, open system architectures. This is one suggested focus area for 6.1-6.3 funding as recommended in Section 3.

Another technical issue is in the development and application of engineering methods and tools to provide timely and accurate information to designers. There are requirements for many such methods and tools having to do with analysis, simulation, and synthesis in various engineering disciplines. Some of these tools and methods are generic, for example, methods that tie design-parameter selection and optimization to downstream product and process quality characteristics. Others are specific to particular product types, for example, manufacturing cost predictors for electronic circuit boards. For methods and tools that exist, but are not in widespread use, there is a typical technology transfer challenge. For new tools and methods, there is a research and development challenge. In all these cases, DoD technology-base projects should pursue the related simultaneous engineering tooling issues.

Outline of Remaining Sections Section 2 provides background information for the report, including an historical perspective and the relationship of product/process integration to other efforts; in particular, the relationships to the Transition-From-Development-to-Production Templates, Total Quality Management, and the Computer-aided Acquisition and Logistics Support initiatives are discussed. Recommendations for integrating product and process engineering in DoD projects are provided in Sections 3 and 4. Recommended DoD actions are given in Section 3, and recommended industry actions are in Section 4.

2. BACKGROUND

This section provides relevant background information, including an historical perspective and a description of related efforts.

Historical Perspective[18] World War II was a triumph of manufacturing in which the U.S. won by out-producing the enemy and overwhelming him with its quantity of weapons and logistical support. Then, with the adoption of the "qualitative superiority" policy in the mid-1950's, manufacturing as a key element of weapons systems acquisition was implicitly de-emphasized. Coincidentally, and for different reasons, this de-emphasis of manufacturing in the defense sector was mirrored by a similar change in attitude toward manufacturing in the civil sector. The de-emphasis of manufacturing also coincided with a decrease in attention to the connection between design and manufacturing. This in turn greatly complicated production activities and increased production and life-cycle costs while reducing quality.

For the last 20 years, in keeping with the decreased emphasis on manufacturing and design, both defense and civil sector research in the U.S. has focused primarily on device or product technology to the neglect of process innovation. Often, where process innovation has occurred in the lab, the U.S. has been poor at transferring the innovation to practice. As a consequence, we have created very sophisticated weapons systems from advanced device technologies but have been increasingly frustrated by an inability to rapidly and efficiently produce these weapons systems with the reliability and maintainability required to sustain the desired operational advantage. Many industries in other countries (e.g., Japan) believe that manufacturing and product design and development coordinated with manufacturing are as important as product innovation or marketing in obtaining market share and have increasingly emphasized manufacturing design and process research and development.

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18. Some of this perspective is paraphrased from *Industrial Insights on the DoD Concurrent Engineering Program*, The Pymatuning Group, Inc., Arlington, VA, October 1988.

Because of these events, many commercial companies faced a competitive shock in the 1970's and 1980's. Deputy Secretary of Defense Atwood described the automotive industry reaction:

> ...The next focus was on the basic design of the product.... the best way to attack quality was to get back into the engineering design of the products. For the first time, the total product was looked at simultaneously by both manufacturing and design engineers. The products were redesigned for simplicity and producibility while keeping quality clearly in mind.
>
> Donald I. Atwood
> DoD Procurement Conference
> Williamsburg, Va., November 1, 1989

Industry managers in the U.S. believe that the Defense Industrial Base could produce just as efficiently as its foreign, commercial counterparts if modern structural factor changes and manufacturing innovation were emphasized by its primary customer, DoD, rather than the current emphasis on crippling documentation and on prohibitions to process innovation. It is admitted that the DoD is not entirely at fault here, and if the Defense Industrial Base were allowed to operate effectively, industrial leaders believe that the current budget reality would lead DoD industries to become more efficient. DoD industries are beginning to recognize that such efficiency can be achieved by adopting approaches such as those recommended in this report. Thus, DoD could acquire systems with both technical superiority to convey decisive operational advantage and with high reliability so they work when needed, and with corresponding improvement in the "tooth-to-tail" ratio.

DoD will have to act to accelerate the broad integration of product and process engineering in its industrial base. DoD must act to confirm its intent to buy intelligently on the basis of the process improvements that product/process integration can provide, and it must act to remove systemic and individual barriers.

This is an instance where, for different reasons, DoD and industry interests lead to a common conclusion. To delay is to lose ground and to lose money. Increased DoD use of integrated approaches could reverse the pattern of cost overruns, schedule stretchouts, and unacceptable field performance as it has in commercial industry. This report recommends actions for DoD in order to accelerate the integration of product and process engineering.

Related Efforts Much of what is proposed in this report is not new. Even though the focus on integration is not typical of recent history, many past studies touch on issues raised here. Among the studies of the overall product development process (as differentiated from the acquisition process), two studies that are particularly important to the

present report are the Transition-From-Development-to-Production Templates and the IDA Study on Concurrent Engineering. Other efforts with important relationships are the Total Quality Management (TQM) and Computer-aided Acquisition and Logistics Support (CALS) initiatives.

Relationship to Transition-From-Development-to-Production Templates The first important related effort is based on the 1983 Defense Science Board study that resulted in the issuance of DoD Directive 4245.7, DoD publication 4245.7-M *Transition from Development to Production—Solving the Risk Equation*, and the continuing transition initiative.[19] This effort identified reasons for the difficulty defense systems programs encountered in the transition from the engineering design phase to the production phase. The DSB study identified forty-seven risk areas and provided corresponding outlines for reducing risk in the form of critical-path "templates". These templates are intended to ensure that fundamental engineering principles are applied in the development and production of defense systems, support equipment, and modifications.

Many of the companies and some of the individuals who participated in the 1983 DSB study also participated in the DSB concurrent engineering study. Thus, many fundamental principles are shared including the importance of problem prevention. For example, in the templates titled "Design Process," "Computer-Aided Manufacturing (CAM)," "Factory Improvements," and "Logistics Support Analysis," various aspects of product/process integration are called out. Both formation of multifunctional teams and design producibility and logistics analyses are recommended during the design phase.

The current study should be viewed as a follow-up that supports the issues raised in the templates. This report concentrates on changes to DoD organization and practice that would enhance the use of the templates in areas of common interest. It also suggests that the templates be enlarged in the areas of integrated product and manufacturing process design and consideration of robustness based on recent successful industry practices. The recommendations included in the present report are not substitutes for the use of the templates, but rather suggest future DoD actions to specifically focus on and strengthen simultaneous, integrated engineering activities. These recommendations are entirely consistent with the templates initiative and should be used as a basis for evolving them.

Relationship to IDA Report on Concurrent Engineering[20] The second study[21] important to the current report was carried out by the Institute for Defense Analyses

19. Defense Science Board, *Solving the Risk Equation in Transitioning from Development to Production*, May 1983, currently available as DoD Publication 4245.7-M.

20. A summary of the IDA Study is in Appendix C.

21. *The Role of Concurrent Engineering in Weapons System Acquisition*, Institute for Defense Analyses, Alexandria, VA, IDA Report R-338, NTIS AD-A203 615, December 1988.

(IDA) in 1988, with follow-ons that continue to date. The IDA study used a task force of about one hundred industry, government, and academic representatives to investigate the potential applicability and benefits of concurrent engineering to DoD weapons system development and production. Table 1 referred to earlier is taken from that report. The IDA Report was the first effort that explained the various sophisticated approaches industry has been using in its attempts at integrating product and process engineering. It was based on twelve case studies of successful, if partial, implementations. It also provided a broad definition that went far beyond the idea of simply putting a group of engineers in the same room and expecting them to cooperate. The report presented what many feel is a compelling management-level argument for DoD and its industries to integrate product and process engineering.

The Defense Manufacturing Board (DMB) unanimously endorsed the IDA Report, but the Report made very high-level, broad recommendations. The DMB created the present task force to follow up by providing actionable recommendations for the DoD.

Relationship to Total Quality Management (TQM) Over the past two years, DoD top management has acted to emphasize the importance of a focus on quality in DoD acquisitions. Product/process integration is a critical factor in TQM. The TQM point of view is that quality, in the sense of user satisfaction in a broad range of operating conditions, can be used as an integrating focus in product engineering. The TQM initiative is by definition pervasive in scope whereas the current report is quite focused. The Concurrent Engineering Task Force views the simultaneous product/process engineering approaches it is recommending as TQM applied to the engineering aspects of fielding a product.

Relationship to Computer-aided Acquisition and Logistics Support (CALS) CALS strives to provide broad information management support for process improvement. It has for several years contained a focus area on design integration that has evolved to concurrent engineering. The CALS/Concurrent Engineering Industry Steering Group has about 400 volunteers who are actively interested in concurrent engineering and, in particular, computer information integration. CALS supports the Product Data Exchange Specification (PDES) effort that seeks to produce an integrated representation of product data that could be worked on by various specialists with minimum translation. In this connection, CALS is pursuing the issue of multi-enterprise integration in order to facilitate process improvements such as simultaneous, integrated engineering among a team of contractors and subcontractors with efficient and timely delivery of information to the DoD. The success of these efforts would significantly enhance the practice of simultaneous product/process engineering.

Other Related Efforts[22] [23] [24] [25] [26] [27] There have been many studies of the defense industrial base and of the effects of the acquisition process on the schedule and cost of DoD systems. The industrial base studies focus on the ability of industry to respond to surge and mobilization requirements, the economics of the industrial base, and the effects of various government policies on industry and, hence, on the defense posture of the nation. The acquisition process studies concentrate on ways of establishing competition in defense acquisitions, on ways of ensuring that progress is being made in programs, on budgeting issues, on the utility of actual or proposed regulations, and on the general business structure of the DoD. Table 2 summarizes relevant points from five of these past studies.

22. The relevant points in these five studies are detailed in Appendix M.
23. Defense Science Board, *1977 Summer Study on the Acquisition Cycle*, March 1978, p. 47. Recall that "concurrent engineering" is often used to describe the sort of product/process integration proposed in this report.
24. Defense Science Board, *1985 Summer Study on Practical Functional Performance Requirements*, March 1986, p. 1.
25. Tyson, Karen, *et al.*, *Acquiring Major Systems: Cost and Schedule Trends and Acquisition Initiative Effectiveness*, Institute for Defense Analyses Paper P-2201, March 1989.
26. Defense Science Board, *1989 Summer Study on the Use of Commercial Components in Military Equipment*, June 1989.
27. Defense Science Board, *1988 Summer Study on the Defense Industrial and Technology Base*, Volume I, October 1988.

Related Study	Issue	CETF Report
1977 DSB Acquisition Cycle	"concurrency" defined; eventually interpreted as overlapped design and production	"concurrent engineering" fundamentally differs; seeks product, production, support *design* maturity prior to production
1985 DSB Practical Functional Performance Requirements	iterative requirements analysis needed	agree
	continuous trade-off performance, cost, utility needed	agree but adds support cost
	recommends DoD Directive 5000.1 revision for above	agree
	CEO authority to program management needed	part of team program organization
	continuous involvement of CINCs in trade-offs	actual users must be continuously involved
	schedule adherence should have highest priority	calls for balance of objectives: integrate schedule, cost, and performance trade-offs
	appears to address only development cost	addresses development, unit production, and life-cycle costs
1989 IDA Acquisition Initiative Effectiveness	finds design-to-cost ineffective if applied late but effective if applied early	calls for *integrated* use of cost requirement
1986, 1989 DSB Commercial Components	calls for specification focus on needs not design details	agree; recommends integrated, high-level requirements
1988 DSB Industrial and Technology Base	suggests more "goal-oriented businesslike arrangement" between DoD and industry with longer term view	calls for increased DoD-industry teamwork from requirements through development
		provides explicit approach to longer-term view dealing with downstream issues early through integrated productprocess design
	calls for new industrial management philosophies	calls for top DoD and industrial management leadership with explicit recommended strategic goals and tactics

Table 2: Summary of Related Study Issues

3. RECOMMENDED DOD ACTIONS

Only industry can implement simultaneous product/process engineering. However, the DoD can take steps now to promote, allow, and facilitate simultaneous, integrated product and process engineering in the development of weapons systems. Contractors will react strongly if the promotion indicates permanent commitment at the highest level. They will pursue the benefits for themselves and for their customers by falling in line with an initiative that has top-level DoD support and involvement. However, promotion is not enough. *DoD must take steps to accelerate integration* particularly (a) modification of timing for and expectations of review and audit of product and process packages and (b) clarification of resource allocation strategies. DoD should encourage the Services and OSD to (a) modify certain business practices, (b) establish internal and external team relationships, (c) integrate design objectives, and (d) institute process self-benchmarking. In order to effect these recommendations consistently, DoD and the Services will need to educate the acquisition workforce. These recommendations are all based on the fact that, in order to reach its cost, schedule, and quality goals, DoD needs to adopt practices that lead to products that are robust in the various downstream processes of manufacture, test, operation, and logistics. To encourage processes that engender this robustness, the DoD should change its expectations in the various phases of the acquisition process.

In order to accomplish the integration of product and process engineering, encouraging the defense industrial community is only part of the battle. The DoD must also engage its own personnel. Those involved in weapons systems acquisition and development must understand the concepts, tools, and goals of product/process integration and must be able to actively participate in the development effort. *The acquisition workforce must know enough about integrated product/process engineering to apply its concepts with judgement rather than by rote.*

The highest levels of DoD should promote product/process engineering integration. Top DoD management should take opportunities to challenge industry associations and other private sector groups to initiate activities complementary to those undertaken by DoD. This effort must be sustained across changes of management personnel in OSD and the Services. All companies studied insisted top management must lead the introduction of product and process engineering integration. DoD and its contractor community will respond to those initiatives which have strong, visible support by top Defense officials. There is, however, skepticism about the willingness of DoD to sustain such effort long enough to make a significant difference. The contractor community will recognize actions that tend to create a sustainable policy and will react accordingly.

Recommendations

Three recommended DoD actions are described below. The first recommendation is required to accelerate industry implementation. The second recommendation is necessary to sustain the change of the development process. Finally, the third recommendation on workforce training is needed to decrease variability in the application of the underlying concepts. Each recommendation is preceded by a description of the problems addressed and followed by the predicted consequences of executing the recommendation.

Problem The current DoD acquisition process tends to institutionalize a sequential approach to product and process engineering. One fundamental issue addressed by simultaneous, integrated product and process engineering is the timing in which elements of product and process engineering occur. In typical sequential product engineering, problems arise because manufacturing, operation, and logistics processes are designed after the product has been designed. This approach leads to time consuming redesign efforts, expensive manufacturing, and immature and inefficient logistics processes. Associated with the current institutional expectations of a sequential process, many program and funding managers do not allocate R&D funding to address manufacturing and logistics process design and development issues (beyond "-illity" analyses) because they feel that regulations prohibit such activities. Thus, it is unlikely that industry will propose a simultaneous, integrated engineering process, even when industry has the requisite tools and knowledge. In addition, DoD technology base programs are largely product-focused, with very little development of process technology. With the exception of part of the Computer-aided Acquisition and Logistics System program (CALS) and the DARPA Initiative on Concurrent Engineering (DICE), virtually no funds are earmarked for generic technical and methodological support for engineering process integration. Finally, current interpretation of Internal R&D (IR&D) rules tends to preclude process research and development even though this is not precluded by legislation.

DoD Recommendation 1.
Modify acquisition timing and expectations and clarify R&D resource allocation.

DoD must change its expectations in the acquisition process to promote integration of process and product engineering early and throughout the acquisition process. The requirements for each phase of system acquisition should be expanded to include the simultaneous preparation of product, process, and logistics packages. These packages should be reviewed by the Defense Acquisition Board, and appropriate integrated (product,

process, logistics) exit criteria should be established for the succeeding phase of development. Future DoD acquisition policy directives should describe the specific milestone expectations (program goals or exit criteria) consistent with simultaneous, integrated product/process engineering. Appendix I describes expectations the Task Force considers important.

OSD should provide guidance that (1) would clarify the allowability of using program R&D funds, during the concept definition and feasibility phases, for manufacturing and logistics process design and manufacturing process feasibility demonstration; (2) would allow detailed manufacturing and logistics process designs to be completed and proven during the development phase; (3) would encourage a significant share of applied research (6.2) and advanced development (6.3) funds to be devoted to process technology, including integration of the engineering process itself; and (4) would encourage a significant share of corporate IR&D funds to be devoted to the integration of product and process engineering.[28]

Consequences Since DoD will require production and logistics packages at each milestone, there is a greater opportunity for the DoD to be aware of and to judge the trade-offs between these process designs and the design of the product. Industry will be strongly motivated to satisfy integrated product/process exit criteria. This motivation in turn will result in DoD systems having reduced time to maturity, lower costs, and greater robustness.

By issuing guidance on resource allocation, OSD will clarify the misperception that currently exists about the use of R&D funding for process design efforts. Thus, programs will be able to address problems early on before they appear in production. This action can be taken at once.

Problem There are several systemic barriers to sustaining the recommended shift in the broad engineering process. Current DoD and industry organizational structures reflect and encourage the fragmentation of engineering activity. Specialty organizations within the DoD communicate with similar organizations within contractors. This structure decreases the efficiency of the engineering effort through fragmentation, tends to prevent interfunctional and interdisciplinary trade-offs, and ends up drawing resources away from the desired end results. To eliminate this phenomenon (sometimes called "stovepiping"), two levels of DoD integration must occur: within Service acquisition organizations and between the DoD and its contractors.

28. Further explanation of these ideas is in Appendix J.

Present contract structures (SOW, specifications, CDRLs) encourage and legitimize highly separate, single-purpose, functional organizations ("stovepipes"). These organizations impose separate, functional requirements that impede the use of a multi-functional development team to conduct a development program. Comparison and trade-off of requirements between specific functional constraints is also made much more difficult.

Current DoD practice places primary emphasis on product performance and device technology with little regard for cost and unpredictable effects on schedule. As a result, DoD has created very sophisticated weapons systems from advanced device technologies but has been increasingly frustrated by an inability to rapidly and efficiently produce these systems with the reliability and maintainability required to sustain a desired operational advantage. Warranties are sometimes used in an attempt to contain life-cycle costs, but they are often introduced after the design is complete. This late introduction does not have the desired effect because life-cycle cost drivers are usually designed into the product.

There is little historical basis for accurately judging the effectiveness of DoD acquisition processes. In commercial industry, the implementation of *self-benchmarking* elevated the awareness of management as to the real state of their companies' processes, and provided a data-driven basis for improvement.[29]

DoD Recommendation 2. Modify Organizations and Practices

DoD top management should encourage the Services and OSD to evolve organizations and business practices to accelerate the educated and widespread use of simultaneous product/process engineering. The Task Force strongly recommends that the Defense Science Board Task Force on Acquisition Streamlining consider the following four suggestions that are critical to meeting the objective of halving acquisition time.

a. Establish team relationships.

Instead of organizational structures and behavior that institutionalize a fragmented engineering process, DoD units should organize to support simultaneous, integrated engineering practices. OSD should encourage

29. For example, when Xerox discovered that Japanese competitors were able to produce products, export them to the U.S., distribute them, and sell them for less than Xerox's unit production cost, and when Xerox benchmarked its processes against analogous ones elsewhere to discover why, that was the beginning of Xerox's well-known turn-around.

the Services to determine how they can best organize to meet the objectives of simultaneous product/process engineering.[30]

Possible Approaches (1) Service acquisition organizations should incorporate the multifunctional product/process development team concept in ways appropriate to each organization. The role of specialty functional organizations can change to support and increase the effectiveness of individual specialty engineers. These individuals then could be assigned and individually empowered within program teams. Industrial experience shows that team leadership must be absolutely committed to and knowledgeable about fostering team behavior. Otherwise, specialists will not be able to be effective and there will be a reversion to powerful stovepipes. (2) The DoD should improve communications and direct involvement with the contractors during concept definition, design, and qualification testing. The DoD could facilitate an integrated product/process development team concept for the acquisition process. To this end, one successful approach to consider is collocation of fully empowered program personnel at prime contractor sites.[31] (3) One obstacle to effective team integration within both government and industry is the limited number of manufacturing and logistics engineers and their difficulty in being heard in the design process. Increased numbers of manufacturing and logistics engineers need to be trained and equipped to be effective in true team situations. Each Service should address its personnel policies in this regard.

Consequences Although industry can integrate product and process engineering under the current DoD organizational structure, establishing team relationships will make industry's implementations much more efficient and effective. An integrated team on the DoD side will tend to encourage a similar organization on the contractor side. An important side effect of this suggestion and the following associated one would be to decrease the number of organizational advocates. *It is not the intent of the Task Force to suggest the creation of a new bureaucracy surrounding simultaneous engineering.*

b. Modify business practices.

OSD should encourage the Services to modify business practices that are barriers to industry implementation of simultaneous, integrated product and process engineering. The Services should consider accelerating the use of performance-based contract requirements to promote a more integrated engineering process. USD(A) should encourage and accelerate

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30. One example approach to such an organization is being attempted by the Air Force Aeronautical Systems Division as described in Appendix H.

31. This was done successfully in the T-800 engine program. It also is often done in the development of logistics systems where it is recognized that detailed requirements may not be adequately captured in a requirements document.

specification streamlining with a view toward more integrated engineering. The DoD should allow alternate proposals for a product meeting mission requirements, eliminating barriers created by process specifications and regulations.[32] [33]

Consequences By eliminating detailed, fragmented, overspecified requirements in favor of performance-based contracts and both streamlined and tailored specifications, DoD and its contractors will have increased flexibility to make effective trade-offs. Increasing the scope of trade-offs through integration tends to prevent downstream problems, thus directly reducing cost and schedule while increasing quality.

c. Integrate design-to-cost, performance, and schedule.

DoD should modify the front end of the product engineering process to explicitly require the introduction of unit product cost, logistics cost, and development time as critical, early system requirements. It should also allow performance vs. production cost, logistics cost, and development schedule trade-offs during the concept definition and feasibility phases. DoD should encourage the development of robust engineering and production processes, that is, processes that are relatively less sensitive to the technical risks being undertaken in the product design. Even though design-to-cost may be harder for unprecedented systems, the potential value of the approach is greater than for precedented systems and certainly should be applied. When the DoD uses warranties in an attempt to contain life-cycle costs, the items to be warranted should be identified prior to design.[34]

Consequences By integrating cost, performance, and schedule, the design process can be robust against the risks being undertaken. There are several recent examples where the presence of an aggressive and firmly held design-to-cost goal provided significant integration of design, manufacturing, quality, and logistics support functions at the first stages of the product engineering process (e.g., F-16, AIWS). If the DoD establishes cost objectives that are as significant as performance requirements, a mechanism will be created to encourage functional integration and foster cost/performance trade analyses at concept exploration and throughout the program.

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32. Further explanation of this concept is in Appendix J. An example reorganization effort is described in Appendix H.

33. The DSB study on Practical Functional Requirements, *op. cit.*, had recommendations focused on the flexibility to execute trade-offs of greater scope. As in the present report, this flexibility was to be derived from integrated, higher-level requirements.

34. This suggestion follows the lead of the DSB study on Practical Functional Requirements, *op. cit.*, which also addressed the value of cost, performance, schedule trade-offs.

d. Establish acquisition processes self-benchmarking.

Each major acquisition command should establish a self-benchmarking process to track the performance and quality of its own acquisition processes, and to measure the effectiveness of product/process integration. Benchmarking requires comparison with analogous processes in other organizations. The purpose of benchmarking is for each organization to evaluate *its own* progress, not for higher level organizations to measure their subordinates or for DoD to benchmark industry. Each organization should establish its own relevant metrics of interest.

Consequences In order to track progress in integrating product and process engineering, each organization must establish a means for measuring the performance of its important processes. Competitive benchmarking enables an organization to use its own data to identify the areas that need to be improved and, thus, to focus its resources where they will have the greatest effect. Competitive benchmark comparisons are made with other organizations that execute comparable processes with the best results.[35] This view to the outside tends to result in greater improvement than simply comparing against an organization's own past experience. The experience of commercial industry is that this action will lead to integration and simplification of processes and organizational structures. *It is very important, however, that this not be established as or become a way for others to compare subsidiary organizations.*

Problem There is great variation in the approaches DoD elements use to plan and manage the process of bringing products from concept to the field. All known successful implementations of integrated product and process development have required an education and training effort to reduce variation in the existing approach and to provide knowledge of advanced tools and methods. Two steps are required. The first step is to establish a base of knowledge about integrated, simultaneous approaches, their goals, and disciplined implementations. The second, relatively more difficult, step is to educate the workforce about world-class tools.

DoD Recommendation 3. Educate the acquisition workforce.

DoD should educate the acquisition force in integrated product and process engineering and its tools and methods. The program should begin

35. For example, Xerox's warehousing operation compared itself against a world-class warehousing process at a mail-order clothing company. It took the world's best as a baseline against which to improve as opposed to its own past performance.

with the orientation of source selection personnel. Appropriate training should be scheduled to support initiation of new acquisition programs. The education program within the Transition-From-Development-to-Production Templates initiative is outstanding and should be leveraged for deeper and more widespread education.[36] This education program should be enhanced to include generic training on integrated engineering and robustness, and some specific technical training in the use of related world-class tools, methods, and technologies. Members and advisors from this Task Force are available to work with the office responsible for the Templates to evolve the Templates with integrated product and process engineering, robustness, and world-class support tools in mind.

Consequences Once top level management has made its commitment obvious and continuous, reorienting the source selection force will encourage industry to change its product development process. Eventual widespread education of the acquisition workforce will result in a greater ability for government personnel to work in teams both among themselves and with industry people. It will also increase the ability of acquisition workers to recognize what is feasible by using integrated approaches.

4. RECOMMENDED INDUSTRY ACTIONS

This section consists of a single recommendation to DoD industry management:

Initiate or accelerate a simultaneous, integrated product and process engineering process.

There are no fundamental legislative or regulatory barriers to this approach. Several contractors have found that it is possible to implement product/process integration on DoD weapons systems under the current DoD acquisition process.[37] Certain DoD regulations appear to constrain the completeness of industrial implementations, but the effect of these regulations often can be overcome by educating the DoD customer. In any case, *the potential competitive benefits of product/process integration make it imprudent to delay industrial implementation*. Industry must make a major change to the product development cycle in order to remain competitive and be profitable. Integration of product and process engineering is a proper and effective way of doing business to achieve the desired results. The industrial implementation philosophy should emphasize satisfaction as

36. The Templates education program is described in Appendix K.

37. See, for example, the Boeing case study in IDA Report R-338, *op. cit.*; the Martin-Marietta example on pages 8-14 of the *Proceedings of the 1st AIAA/ADPA/NSIA National Total Quality Management Symposium*, Denver, CO, November 1989, and pages 436-441 of the supplement to this symposium; and Appendix D. These companies did not have any widely recognized labels like "concurrent" or "simultaneous" engineering on what they set out to do, nor did they have a predetermined focus on integration. Nevertheless, they all ended up integrating product and process engineering.

perceived by the customer (using the "voice of the customer") and should focus all activities on quality, cost, and schedule as equals in the development cycle. Quality, here, means the extent to which a product satisfies the expectations and needs of its users in operational environments over a period of time; thus, in the sense used here, quality encompasses performance.

In support of this single industry recommendation, four implementation suggestions to industry are stated below as broad themes. The Task Force does *not* intend that DoD tell industry how to implement improvements to the product engineering process. The Task Force recognizes that industrial implementations vary depending on the nature of each company's products and its current organization and culture. The approaches from which these suggestions are derived have been proved in practice in leading, successful industrial implementations.

It is often stated that the integration of product and process engineering is a very major change, and therefore must require a long time. This statement is too pessimistic. While it is true that it can easily take five years to *complete* the transition to world-class status, major partial benefits can be achieved in one year. The implementation can be conveniently thought of as having two tracks: quick-start actions and world-class actions.[38] The quick-start actions are primarily changes in management practices and processes, and can be completed in one year. Industry Implementation Suggestions 1, 2, and 3 outline these improvements. The actions to reach world-class status consist of the implementation of powerful development tools (operational practices), which take roughly five years to implement. These two tracks can best be implemented when integrated together. After implementation, continuous improvement will provide continuous competitiveness.

Industry Implementation Suggestion 1. Accomplish integration.

> Establish long-term and short-term enterprise goals, strategies, and planning to accomplish integration of company organizations, processes, and activities on the basis of product/process integration principles and employee involvement principles. Integration should be based on the use of multifunctional product development teams and avoidance of "stovepipe" phenomena. A particular emphasis should be placed on vendor involvement since vendors typically provide 50-80% of a weapons system.

Just as international competition led commercial industry to integrated approaches, a tightening DoD budget and the continuing need for an adequate level of

38. The two-track implementation process is described in more detail in Appendix N.

defense imply a requirement for increased efficiency in the DoD industrial base. Integration must take place in all aspects of business and product relationships with the customer, including multifunctional product development teams and integration of suppliers into the teams. "Over-the-wall" transactions must be eliminated. In order to make a product robust within its encompassing processes, integration must be maintained through all phases of a product life cycle.

Industry Implementation Suggestion 2. Establish top management leadership.

Active top management leadership toward integration is essential because company survival and competitiveness depend on successful implementation of integrated product and process engineering.

Experience indicates that company-wide process improvement requires top management involvement. One approach top management has used to get action is competitive benchmarking. *Competitive benchmarking* of all products, processes and activities within the company is an effective method of gaining broad participation as it provides all employees with goals to achieve by means of participation in process improvement.

Industry Implementation Suggestion 3. Understand the voice of the customer.

Top management should rethink how its organizations reach an understanding of end-user and customer needs.

A clear understanding and establishment of product performance characteristics based on the voice of the customer is mandatory to achieve earliest delivery, lowest life cycle cost, and maximum availability to the user. Simultaneous, integrated product and process engineering provides the environment and organizational structure to allow up-front communications and the participation of all elements of the business enterprise who participate in or are the recipients of the design process of the product.

Industry Implementation Suggestion 4. Implement world-class tools.

Effective and efficient use of tools and methods is essential to achieve world-class levels of simultaneous, integrated product/process engineering.[39]

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39. For a discussion of the benefits of various tools and methods, see Appendix F.

World-class tools, such as Quality Function Deployment,[40] Taguchi's concept of robust design,[41] statistically well-designed experiments,[42] and Pugh's concept selection process,[43] can be used to improve robustness, achieve better development efficiency, and enable integration. Computer tools, including integrated information bases, design analyzers, and product and process simulations, allow systematic deployment of information to minimize mistakes, and can perform effective cost/performance trade-offs among product and process features. The combination of approaches, such as using statistical design of experiments to drive simulated or analytical design-space searches, can provide tremendous leverage.

The implementation of this suggestion takes longer than the others. For example, education in tools and methods must be planned and implemented on a broad scale. Information integration requires people who understand information technology thoroughly and have a global view of the enterprise and how it evolves. In general, a better process for transferring new tools and methods from labs into the workplace needs to be implemented. The benefits of this suggestion can take five years to show large results. Implementation of this suggestion, however, engenders a new way of dealing with product development problems throughout the workforce and provides a basis for sustained improvement. The total benefits of integrated approaches and complete international competitiveness can only be achieved through the implementation of state-of-the-art tools and methods integrated into a well-defined simultaneous engineering process.

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40. Hauser, J. R. and Clausing, D., "The House of Quality," *Harvard Business Review*, pp. 63-73, May-June 1988; or King, B., *Better Designs in Half the Time: Implementing QFD Quality Function Deployment in America*, GOAL/QPC, Methuen, MA, 1987.

41. Phadke, M. S., *Quality Engineering Using Robust Design*, Prentice-Hall, Englewood Cliffs, NJ, 1989.

42. Box, G. et. al., *Statistics for Experiments*, John Wiley & Sons, New York, 1978.

43. Pugh, S., "Concept Selection — A Method that Works," *Proceedings I.C.E.D. WDK 5 Paper M3/16*, pp. 497-506, Rome, March 1981.

APPENDIX A

Membership of the Defense Science Board (DSB)
Concurrent Engineering Task Force (CETF)

Chairmen

Dr. Don P. Clausing
Bernard M. Gordon Adjunct Professor of
Engineering Innovation and Practice
Massachusetts Institute of Technology
Building 35, Room 237
77 Massachusetts Avenue
Cambridge, MA 02139

Mr. D. Travis Engen
Senior Vice President, ITT
President & Chief Executive
ITT Defense, Inc.
1000 Wilson Boulevard
Arlington, VA 22209

Members

Dr. Charles Bernstein
Vice President for Analysis
Northrop Corporation
1840 Century Park East
Los Angeles, CA 90067

Mr. William P. Brown
President
McDonnell Douglas Helicopter Co.
Bldg. 510 A380
5000 East McDowell Road
Mesa, AZ 85205

Mr. Stephen Burdt
Deputy for Program Evaluation
HQDA (SARD-ZE)
The Pentagon, Room 2E673
Washington, DC 20310-0103

Mr. Gordon England
Vice President for Engineering
General Dynamics Land
Systems Division
38500 Mound Road
Sterling Heights, MI 48310-3268

Dr. Jacques Gansler
Senior Vice President and Director
The Analytic Sciences Corporation
1101 Wilson Boulevard
Suite 1500
Arlington, VA 22209

Mr. Richard Godfrey
Vice President and General Manager
TRW Military Electronics and
Avionics Division (MEAD)
1 Rancho Carmel
Building RC1, Room 3039
San Diego, CA 92128

Dr. John Halpin
Air Force Systems Command
Aeronautical Systems Division
Wright-Patterson AFB, OH 45433-6503

Dr. Robert Henderson
Director
South Carolina Research Authority
P. O. Box 12025
Columbia, SC 29211

Mr. Frank Kendall
ODDRE
The Pentagon, Room 3D1044
Washington, DC 20301

Dr. Norma Loeser
Professor of Business Administration
George Washington University
2707 Thyme Drive
Edgewater, MD 21037

LTG John Loh
Commanding General U. S. Air Force
Aeronautical Systems Division
Wright-Patterson AFB, OH 45433-6503

Mr. Frederick J. Michel
Consultant
8409 Felton Lane
Alexandria, VA 22308

Dr. Robert Schell
Chief Operating Officer
Hi-Shear Industries, Inc.
204 Edison Way
Reno, NV 89502

Mr. Russell Shorey
Consultant
4390 Eaton Place
Alexandria, VA 22310

Dr. Jerome Smith
Vice President
Anti-Armor Weapon Systems/
Missile Systems
Martin-Marietta Corporation
P. O. Box 555837
Orlando, FL 32855-5837

Dr. Allan Somoroff
Director for System Acquisition
Naval Air System Command
Code: AIR-51
Washington, DC 20361

MG Billy Thomas
Commander
Communications-Electronics Command
Army Materiel Command
Ft. Monmouth, NJ 07703-5000

Mr. W. J. Willoughby
Director for Reliability, Maintainability,
& Quality Assurance
Department of the Navy
CP5, Bldg. 5, Room 348
Washington, DC 20360

Executive Secretary

Mr. Timothy Neel
WSIG Office OASD (P&L)

Advisors

Capt. Lloyd Abbot
OASN (S&L) RM&QA

MG E. P. Barry
USAF/ASD

Mr. Ted Goranson
SAIC

Dr. Gary Denman
USAF/WRDC

Col. Larry Griffin
USAF Logistics Command

Dr. William Kessler
USAF/WRDC

Mr. Noel Longuemare
Westinghouse

Mr. Colin MacDonnell
USA/CECOM

Mr. Michael McGrath
OASD (P&L)

Mr. Vern Menker
USAF/ASD

Mr. Martin Meth
OASD (P&L)

Mr. Gerald Shumaker
USAF/WRDC

Mr. John Strakosch
Grumman

BG Richard Wharton
ODDRE (TWP)

IDA Advisors

Dr. Robert Winner

Mr. Stephen Welke

Mr. William Akin

Dr. James Pennell

Mr. Harold Bertrand

Ms. Janice Holt

Ms. Edna Jordan

APPENDIX B

Terms of Reference for the Defense Science Board (DSB) Concurrent Engineering Task Force (CETF)

This appendix contains the Terms of Reference for the Task Force on Concurrent Engineering, dated 30 March 1989, and a letter requesting the addition of specific government representatives to the Task Force membership, dated 28 December 1989.

THE UNDER SECRETARY OF DEFENSE
WASHINGTON, DC 20301

ACQUISITION

30 MAR 1999

MEMORANDUM FOR CHAIRMAN, DEFENSE MANUFACTURING BOARD

SUBJECT: Terms of Reference--Task Force on Concurrent Engineering

You are requested to organize a task force to recommend a Department of Defense (DoD) and industry strategy to accelerate the implementation of concurrent engineering in DoD research and development and acquisition programs.

Recent DoD and industry studies have identified examples where high quality systems have been developed in half the time at reduced cost by using concurrent engineering techniques. The issue is how to achieve these benefits on a broad scale as quickly as possible. The task force should examine options for achieving widespread practice of these improved processes, and should recommend an overall strategy for DoD implementation. The scope of the deliberations should include: training and education, management practices, engineering practices, manufacturing practices, acquisition practices and incentives, funding procedures, the technology base, weapon system pilot programs, manufacturing technology, and quality improvement.

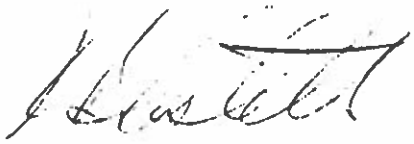
The task force, as a minimum, should address the following questions:

- What is the degree to which concurrent engineering is practiced in DoD industry today?
- Within DoD industry, what are the impediments to increasing the successful practice of concurrent engineering?
- Given appropriate DoD action, what action is required by DoD industry to overcome internal impediments?
- From the DoD industry perspective, what are the most important DoD inhibitors to efficient industry implementation of concurrent engineering?
- What specific DoD actions would have the most leverage in terms of accelerating the implementation of concurrent engineering in DoD industry?

The task force should develop recommendations which address the following areas:

- An overall DoD/industry strategy to achieve the most rapid and appropriate employment of concurrent engineering.
- Key technology base actions required to support wide spread concurrent engineering implementation.
- Key DoD actions required to encourage industry to implement concurrent engineering.
- Key DoD industry actions to support DoD efforts to implement concurrent engineering.

You are requested to provide a first phase task force report within six months and a final report within twelve months. Future actions will be determined after the final report has been evaluated. The Deputy Under Secretary of Defense for Industrial and International Programs is the sponsor. COL Larry Griffin is the executive secretary.



THE UNDER SECRETARY OF DEFENSE
WASHINGTON, DC 20301

ACQUISITION

28 DEC 1989

MEMORANDUM FOR SECRETARIES OF THE MILITARY DEPARTMENTS
DIRECTOR, DEFENSE RESEARCH AND ENGINEERING

SUBJECT: Defense Manufacturing Board's Concurrent Engineering Task Force

On March 30, 1989, the USD(A) requested the Defense Manufacturing Board (DMB) to develop a Department of Defense (DoD) and industry strategy to accelerate implementation of concurrent engineering in DoD research, development and acquisition programs (attachment 1).

The Concurrent Engineering Task Force (CETF) was formed as a result of that request. The CETF has completed a review of recent DoD and industry efforts that serve as examples where high quality systems have been developed by using concurrent engineering techniques. The Task Force will be examining options for achieving wide spread use of concurrent engineering techniques and will recommend an overall strategy for DoD implementation in their final report due April 1, 1990.

During a DMB/CETF briefing on October 25, 1989, the Task Force Chairman suggested that senior Military Service acquisition officials be invited to participate as full members of the Task Force. These officials would represent individual service/Organization interests and provide guidance and expertise during the development of the concurrent engineering implementation strategy. To facilitate the timely completion of Task Force objectives, the addition of senior Service/DoD Acquisition Officials to the membership of the CETF is appropriate and desirable.

Specifically, the DMB would like to invite MG Billy Thomas and Mr. Steve Burdt, USA; Mr. W. J. Willoughby and Dr. Allan Soromoff, USN; LTG John Loh and Dr. John Halpin,USAF; Mr. Frank Kendall,DDR&E to be members of the CETF until the Task Force final report is completed. All invitees have indicated informally that they are interested in participating and are able to make the commitment through the remaining life of the Task Force. The Task Force Co-Chairman, Mr. Travis Engen of ITT and the Executive Secretary of the Task Force, Mr. Tim Neel, are available to brief the CETF mission

and objectives as required. We would like to have the new CETF members on board not later than December 29, 1989.

Request your recommendations and/or concurrence be coordinated with the DMB Executive Director, Mr. Charles Kimzey at 697-0957.

Robert C. McCormack

Robert C. McCormack
Deputy Under Secretary

Attachment

APPENDIX C

Concurrent Engineering: Practices and Prospects

James P. Pennell
Robert I. Winner
Harold E. Bertrand
Marko M. G. Slusarczuk

Institute for Defense Analyses
1801 North Beauregard St.
Alexandria, VA 22311
(703) 845-2000

ABSTRACT

This paper summarizes a 1988 investigation of concurrent engineering and its role in weapons system acquisition. Concurrent engineering has recently been promoted in the automotive, computer and electronics, and aerospace industries as a response to competitive pressures. Viewed as a more systematic approach to creating high quality products and bringing them to market at lower cost and in significantly less time, it also attracted the attention of the Department of Defense. In 1988, the Institute for Defense Analyses (IDA) was asked to investigate concurrent engineering and to identify any advantages that could be expected from applying it to weapons system acquisition.

We describe the investigation, present highlights of the evidence, and set forth the principal findings and recommendations. This paper includes the definition of concurrent engineering developed during the study. We offer a sample of reported benefits that include 60 percent reduction in product development time, elimination of two thirds of the inspectors in one factory, and several million dollars annual savings in chemical and soldering processes. We outline the methods and technologies of concurrent engineering—the process management ideas, the computer support, and the problem-solving techniques. We provide a conceptual framework to describe the continuing research needed in this area.

1. INTRODUCTION[1]

The President's Blue Ribbon Commission on Defense Management (The Packard Commission) noted that weapons systems take too long to develop, cost too much to produce, and often do not perform as promised or expected.[2] Similar problems in automobile and electronics industries resulted in a crippling loss of market share by United States producers to offshore competition. Surviving companies in affected industries responded to competitive pressures by modifying their management, engineering, production, and customer support processes. Many of the modifications included a more systematic method of concurrently designing both the product and the downstream processes for producing and supporting it. This systematic approach is the fundamental theme of *concurrent engineering*.

In 1988, IDA, at the direction of the Undersecretary of Defense for Acquisition, examined concurrent engineering and

1. *The work reported in this article was conducted as part of the Institute for Defense Analyses Project T-B5-602 under Contract No. MDA 903 84 C 0031 for the Department of Defense and first appeared in IDA Report R-338, "The Role of Concurrent Engineering in Weapons System Acquisition." The publication of this paper does not indicate endorsement by the Department of Defense or the Institute for Defense Analyses, nor should the contents be construed as reflecting the official positions of those organizations.*

2. *A Quest For Excellence*, Final Report to the President by the President's Blue Ribbon Commission on Defense Management, June 1986, p. xxii.

presented recommendations to the Department of Defense. Our recommendations, along with findings of independent groups, helped to point out the need for new guidance concerning acquisition. On March 9, 1989, Dr. Costello, Under Secretary of Defense (Acquisition), provided interim program acquisition guidance for the Secretaries of the Military Departments and their Service Acquisition Executives concerning concurrent engineering and its role in the acquisition process. The interim guidance builds on existing DoD policy to articulate a top level approach to integrating the engineering processes that support DoD acquisition.

2. APPROACH

In response to initial reports from several companies, the Under Secretary of Defense for Acquisition (USD(A)) directed that the Institute for Defense Analyses (IDA) investigate concurrent engineering and its possible application to weapons system acquisition. An IDA study team was formed and the team, in coordination with representatives[3] from industry, academia, and government, collected information about concurrent engineering. The information gathering consisted of literature reviews, site visits, and workshops. The IDA study team followed the progress of another group that presented insights from a cross section of industrial officials regarding concurrent engineering, particularly senior management's perception of barriers and incentives to implementation. [Davi88]

A report of the initial IDA investigation was provided to the Department of Defense in December 1988. [Winn88] The report describes concurrent engineering in terms of success stories. It includes case studies of companies that simultaneously improved quality, decreased cost, and reduced development time through the application of concurrent engineering.

3. DEFINITION

Participants at the first IDA concurrent engineering workshop discussed concurrent engineering as it is practiced in several U.S. companies and developed the following definition to describe the practice.

> Concurrent engineering is 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.

Concurrent engineering is characterized by a focus on the customer's requirements and priorities, a conviction that quality is the result of improving a process, and a philosophy that improvement of the processes of design, production, and support are never-ending responsibilities of the entire enterprise.

3. The authors acknowledge the contribution of individuals from the following companies: Aerojet Ordnance, Allied Signal, AT&T, Boeing, John Deere, Ford, Grumman, Hewlett-Packard, Honeywell, IBM, ITT, McDonnell Douglas, Northrop, and Texas Instruments. We are also grateful for the contributions of members of the faculties of Carnegie Mellon University, MIT, University of Wisconsin-Madison, Princeton, University of Chicago, Brigham Young University, Harvard Business School, New Jersey Institute of Technology, Auburn University, and Rensselaer Polytechnic Institute. Scientists and engineers from Charles Stark Draper Laboratories, The National Science Foundation, The National Center for Manufacturing Sciences, the American Supplier Institute, the American Statistical Association, the National Institute for Standards and Technology, and many government scientists and managers also helped. Although the contributions of the many participants has been substantial, the names of their institutions should not be construed as an endorsement of this paper or its contents.

The integrated, concurrent design of the product and processes is the key to concurrent engineering. Figure 1 compares a sequential approach to product development, as shown at the top of the figure, with a concurrent approach in the lower half. In the sequential method, information flows are intended to be in one direction, from left to right as shown by the arrows. In the concurrent approach, information flows are bi-directional and decisions are based on consideration of downstream as well as upstream inputs. The companies studied in this report found that achieving this sharing of information required both organizational and technological change.

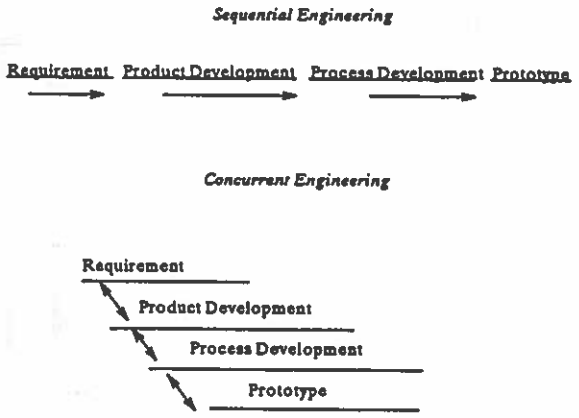


Figure 1. A Comparison of Sequential and Concurrent Engineering

The philosophy of concurrent engineering is not new. The terms "system engineering", "simultaneous engineering", and "producibility engineering" have been used to describe similar approaches. In fact, a number of authors have described similar techniques and hundreds of companies have applied them successfully. [Haye88] Nevertheless, many companies have *not* adopted concurrent engineering because of the "fundamental, wrenching, far-reaching transformations that are required throughout the enterprise."[4]

Where changes were made, concern for *survival* in the face of increased competition (particularly from Japanese manufacturers) often provided the necessary incentive for companies to improve the quality of their products and increase the efficiency of their product development processes. As the pressure to improve quality and efficiency increased, newly developed computer-based design and analysis tools gave specialists from different engineering disciplines the freedom of working with the same description of the design to evaluate the effects of particular design features. The companies that have been successful in concurrent engineering have embraced the philosophy of continuing improvement, and they are using new tools as well as traditional techniques to implement this business philosophy.

Although the study team found examples of companies that are moving in the direction of concurrent engineering, it found no company claiming to have developed "the one best way." The people affected by the changes say that progress has been difficult, that mistakes have been made, and that enthusiastic advocacy and support by top management have been essential. None of the companies said that concurrent engineering, in isolation, is capable of producing the type of improvements needed to remain competitive. Concurrent engineering is part of an integrated corporate competitiveness plan that emphasizes concepts such as those described by Deming.

4. Robert H. Hayes, Steven C. Wheelwright, and Kim B. Clark, *Dynamic Manufacturing*, The Free Press, New York (1988), p. 344.

[Demi86]

Nevertheless, they are pleased with their accomplishments and they are actively looking for additional improvements.

4. METHODS AND TECHNIQUES

The study team identified three complementary classes of activities that support concurrent engineering:

- engineering process initiatives such as the formation of multidisciplinary teams;
- computer-based support initiatives such as improvement of computer-based design tools, including giving the user an environment that integrates separately developed software; and
- use of formal methods including application of special purpose tools for design and production support.

Engineering process initiatives are management actions to improve the organization and the procedures used to develop a product. Involvement of representatives of manufacturing early in the design process is a minimal step in this direction. Most case studies show that companies form teams which include marketing, production, engineering, support, purchasing, and other specialists.[5] Team members are selected for their ability to contribute to the design effort by early identification of potential problems and by timely initiation of actions to avoid bottlenecks. The ability to work effectively as a member of a team is critical. Using multidisciplinary teams is not equivalent to forming committees where members often delay decision making; instead design teams get faster action through early identification and solution of problems.

Leadership at the highest corporate and government levels driving continuous quality and productivity improvement is a prerequisite for the success of the changes associated with these initiatives. Changes to the status quo, especially the cultural changes required for concurrent engineering, are not likely to be successful or to endure without top management leadership and support.

Most of the companies visited during this study have also undertaken substantial education efforts in team skills and related problem solving techniques.[6] Other management initiatives include the following:

- emphasizing attention to customer needs and quality improvement,
- improving horizontal integration of the organization,
- promoting employee involvement in generating new ideas for improvement,
- requiring engineering comparisons of proposed products and competitive offerings, and
- establishing closer relationships with suppliers to include supplier involvement during conceptual design phase.

Computer-based support initiatives cover a range of computer-aided

5. Where companies form long-term partnerships with their principal suppliers, they often include representatives of the suppliers on the design team beginning with the conceptual design.

6. Boeing, Deere, IBM, ITT, McDonnell Douglas, Northrop, and Texas Instruments. Sources of education include local colleges and universities, special purpose institutes, consultants, and in-house education programs.

tools, database systems, special purpose computer systems that improve design verification, and computer-based support of product design, production planning, and production. The companies differ in the sophistication of their systems, but those companies making advances in this area share a goal of using a single data object as a source for many engineering functions including design synthesis and verification as well as planning production processes. This use of a shared, common data object by specialists throughout an enterprise provides a mechanism for concurrently performing the product and process design tasks. Feature-based design and group technology are approaches to creating order and imposing regularity on the databases that support the design process.

A solid model of the object being designed is frequently used as the single data object that allows automated systems to be integrated. [Wolf87] Sometimes, several companies participating in a development team share access to the same computer representation of a solid model. Mechanical design, tooling, machining, and assembly need accurate solid models.

Computer tools that evaluate the behavior of potential designs are used extensively. Among companies doing electronic design, simulation is a critical tool. Aircraft companies use finite element models (FEM) and computational fluid dynamics (CFD) to support design.

Computer tools not only assist in the validation of proposed designs, they can also be used in synthesizing the design itself. Rule-based systems are sometimes used in design synthesis. In attempting to provide rule-based design systems, several companies[7] are developing practical applications of expert systems.

Formal methods[8] are difficult to categorize. They include techniques that date to the 1930s and more recent approaches. Statistical process control (SPC)[9], design of experiments, design-for-assembly (developed by Boothroyd Dewhurst Inc. [Dewh85]), value engineering and quality function deployment (QFD) are just a few of the formal methods discussed during the study.

In this group we include computer-based statistical tools for data analysis in support of both SPC and design of experiment. We also consider fundamental engineering philosophies such as the robust engineering principles as proposed by Taguchi to belong in this class. Quality function deployment (QFD), and the techniques used by Pugh are likewise seen as formal methods. [Pugh81] Other methods that have been useful in problem solving include Ishikawa's [Ishi85] seven tools,[10] response surface methods, group technology, exploratory data analysis, and fault-tree analysis.

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7. Litton Amecom, McDonnell Douglas Astronautics, Deere, IBM, AT&T, Texas Instrument, ITT, Northrop, and Hughes all mentioned some initiative in expert system or rule-based design.
8. See [Winn88], Appendix B for further discussion of the formal methods.
9. Statistical process control is sometimes considered to be applicable only to manufacturing processes and not to design or service activities. There is abundant evidence that SPC provides direct benefits for improving a wide range of processes and that it provides indirect benefits to the design process when it is used in manufacturing. The indirect benefits result from feedback of more reliable information about manufacturing process capabilities and limitations. This information is used to design products with characteristics that match a company's ability to produce them.
10. The tools are histograms, cause-and-effect diagrams, check sheets, Pareto diagrams, graphs, control charts, and scatter diagrams.

Formal methods are used for different purposes, but they are all designed to help people understand the behavior of processes, products, mechanisms, and so forth, which otherwise could not be understood as thoroughly. If used properly, the methods and tools are a tremendous aid in design, production, and engineering, yielding sharply reduced life cycle costs, shortened design cycles, and improved quality.

The apparent diversity of the formal methods sometimes masks the more important process that takes place when they are used properly. This underlying process is the scientific approach to problem solving. For a company to be successful using the approach, its employees must develop the habit of identifying problems and solving them so as to improve the company's processes. Once problems are identified and analyzed, the choice of a particular formal method will depend on the situation. Box [Box89] discusses the paramount importance of recognizing that problems represent opportunities to gather information to improve a process. The following paragraphs are provided as a brief introduction to formalized methods.

An SPC standard was developed for the War Department in December 1940 by the American Standards Association. It is a technique for using statistical sampling methods to determine the regularity of a process. The original standard was updated and now the use of SPC is described in a 1985 ANSI standard [ANSI85].

Design of experiments (experimental design) was invented and developed in England in the 1920s by Fisher. It has been used in agriculture, medicine, and biology. In manufacturing, design of experiments provides tools for designing and conducting experiments in an efficient way so that optimum values for product and process parameters can be identified.

Design-for-assembly software is commercially available to help designers evaluate the benefits of using fewer parts, better fasteners, and more efficient assembly techniques. One product was developed by Boothroyd Dewhurst, Inc. [Dewh85] and has been licensed by approximately 300 companies in the United States and Europe. Many dramatic product improvements have been reported through its use, particularly in the automobile and consumer products industries.

Pugh is a proponent of encouraging creativity during the conceptual design stage and using unbiased evaluation criteria to develop the strongest concepts.

Robust design[11] has come to be associated with Taguchi. His engineering innovations and statistical methods, however, can be addressed separately. He has introduced several new and very important quality engineering ideas. He stresses the importance of closeness-to-target rather than within-specification objectives. He recommends using statistical design to formulate a product or process that operates on target with smallest variance, is insensitive to environmental disturbances and manufacturing variances, and has the lowest possible cost.[12]

Robust design is achieved through system design, parameter design, and tolerance design. System design is a search for the best available technology, parameter design selects optimum levels for design parameters, and tolerance design establishes the manufacturing tolerances. [Tagu86] Parameter design and tolerance design make use of planned

experiments. Although there is general agreement that the principles of robust engineering are an important contribution, the question of the selection of statistical methods for conducting the experiments and analyzing the results remains open within the scientific community.[13] The terms "Taguchi Experiments", "Taguchi Methods", and "Design of Experiments" are sometimes used interchangeably by practitioners. We use the term that was applied by the person who performed the experiment.

We did not conduct a survey of which methods are most widely used in the United States. A recent article [Kusa88] from Japan describes the statistical methods mentioned in the presentation to a quality circle conference. The most widely used methods were the Ishikawa tools, design of experiment, and tree analysis (QFD).

One theme that emerged from the discussion of methods and technologies, particularly from the discussion of formal methods, is that there is merit in diversity. Participants were in agreement that no one set of tools can be expected to serve the needs of all users, even within the same company. A consensus emerged that solutions should be problem centered, not tool centered.

4.1 Common Characteristics

We observed several common characteristics in the companies that successfully deployed concurrent engineering:

- Upper management supported the initial change and continued to support its implementation.
- Changes were usually substitutions for previous practices, not just additional procedures.
- The members of the organization perceived a need to change. Usually there was a crisis to be overcome. Often the motivation seemed to center around retaining or regaining market share.
- Companies formed teams for product development. Teams included representatives with different expertise, such as design, manufacturing, quality assurance, purchasing, marketing, field service, and computer-aided design support.
- Changes included relaxing policies that inhibited design changes and providing greater authority

11. The terms robust design, robust engineering, and robust product design refer to an engineering philosophy that seeks to reduce variability of some important characteristic of a product in the presence of variability in the manufacturing and use environments. It does not, unless specifically noted, refer to the robustness of an experimental design or of the inferences that can be drawn from an experiment.
12. George E. P. Box, Discussion Section, *Journal of Quality Technology*, Vol. 17, No. 4, (October 1985) p. 189.
13. For an example of such discussions see: Raghu N. Kacker, "Off-Line Quality Control, Parameter Design and the Taguchi Method," *Journal of Quality Technology*, Vol. 17, No. 4, (October 1985), pp. 176-209; Myron Tribus and Geza Szonyi, "The Taguchi Methodology: An Alternative View" (December 1987); Romon V. Leon, Anne C. Shoemaker, and Raghu N. Kacker, "Performance Measures Independent of Adjustment: An Explanation and Extension of Taguchi's Signal-to-Noise Ratios," *Technometrics*, Vol. 29, No. 3 (August 1987), pp. 253-285; George Box, "Signal-to-Noise Ratios, Performance Criteria, and Transformations," *Technometrics*, Vol. 30, No. 1 (February 1988), pp. 1-40; Ikuro Kusaba, "Statistical Methods in Japanese Quality Control," *Societás Quálitátis*, Vol. 2, No. 2 (May/June 1988), Union of Japanese Scientists and Engineers; and Genichi Taguchi and Madhav Phadke, "Quality Engineering Through Design Optimization," *Conference Record*, IEEE GLOBECOM 1984 Conference, Atlanta, Georgia, IEEE, pp. 1106-1113.

and responsibility to members of design teams. Companies practicing concurrent engineering have become more flexible in product design, in manufacturing, and in support.

- Companies either started or continued an existing program of education for employees at all levels.
- Employees developed an attitude of ownership toward the processes in which they were involved.
- Companies used pilot projects to identify problems that were associated with implementing new concurrent engineering techniques and to demonstrate their benefits.
- Companies made a commitment to continued improvement. None of the companies said it was prepared to freeze the latest process as the ultimate solution to design and production.

4.2 Misconceptions

To dispel some misconceptions about concurrent engineering, we list what concurrent engineering *is not*.

First, it is *not* a magic formula for success. The best system cannot compensate for a lack of talent. The companies studied have hired and trained engineers who are able to identify important design parameters, and who are capable of creating solutions to problems. At least one of the companies said that a significant part of their success was the fact that people worked harder. Concurrent engineering is an approach for improving the efficiency of good people who work hard; it provides no guarantees of success.

Second, concurrent engineering is *not* the arbitrary elimination of a phase of the existing, sequential, feed-forward engineering process. For example, it is not the simple, but artificial, elimination of a test-and-fix phase or of full-scale engineering development. Concurrent engineering does not eliminate any engineering function. In concurrent engineering, all downstream processes are co-designed toward a more all-encompassing, cost-effective optimum design.

Third, concurrent engineering is *not* simultaneous or overlapped design and production.[14] Concurrent engineering entails the simultaneous design of the product and of the downstream processes. It does not entail the simultaneous design of the product and the *execution* of the production process, that is, beginning high rate production of an item that has not completed its test, evaluation, and fix phase. On the contrary, concurrent engineering emphasizes completion of all design efforts prior to production initiation.

Winner[15] provides a more complete list of the misconceptions concerning concurrent engineering that were encountered during the initial study phase.

We intentionally avoided creating a template or checklist that could provide some metric of concurrent engineering. Such an approach would offer a temptation to people who are looking for an easy fix. We did not find a foolproof recipe for

14. At least one spokesperson for manufacturing engineers points out that "design" continues throughout a product's life, so that even in high volume production, the design of the production process and the design of the product improvements must be coordinated. Nevertheless, we continue to hold that concurrent engineering does not imply beginning production of a product before its *initial development* has reached a stage where the design has been validated.

15. See [Winn 88] pp. 21-23.

success in using concurrent engineering. We believe, however, that companies which focus on the customer's requirements and priorities, are convinced that quality is the result of improving a process, and hold a philosophy that improvement of the processes of design, production, and support are never-ending responsibilities of the entire enterprise will find themselves practicing something closely related to concurrent engineering.

5. BENEFITS

During the study, we found evidence that application of concurrent engineering methods, as described in the case studies, achieved improved quality, lower cost, and shorter development cycles.

The next three subsections present reported[16] benefits by category: quality, cost, and schedule.

5.1 Quality Improvements

Several of the companies visited during the study reported that their decision to use concurrent engineering procedures can be traced to corporate quality improvement programs. When these companies pursued a vigorous quality program to improve their competitive capabilities, they often found that concurrent engineering was a natural part of such a program.

We observed a trend among U.S. companies toward accepting the view of quality that the Japanese learned from such American pioneers as Sarasohn, Deming, and Juran. Corporations are sending senior executives to Japan and to U.S. quality seminars and courses (that are often based on Japanese extensions to the quality tools originally provided to them by American advisors).

Executives of U.S. companies are learning that improving quality does not have to drive prices up, but that if quality is improved through attention to the system (or process) then costs often go down. The cost savings result from reductions in scrap and rework (the elimination of the so-called "hidden factory"), reduced warranty costs, elimination of inspections, and the resulting improvement in production efficiency. The view of quality as a driver for competitiveness improvements is gaining wider acceptance.

The companies we visited usually associate *quality* of their design with fewer engineering changes as the product enters high volume production and use. They use reduction of scrap and rework as a measure of the quality of their production processes. Some companies that have adopted more strenuous efforts to reduce their process variability use other measures of quality such as Taguchi's loss function.

Examples[17] of reported quality improvements are listed below:

- Aerojet Ordnance salvaged 400,000 pyrotechnic pellets that would have been discarded because of insufficient burn times. The pellets could be used because Aerojet redesigned the loading parameters on the basis of Taguchi experiments. They improved the consistency of tracer rounds as measured by μ/σ (mean/standard deviation) by a factor of 5. Their support on one munitions program was instrumental in

16. The data presented by the companies were accepted at face value.

17. A more complete discussion of these cases can be found in Appendix A of [Winn 88].

identifying correct design parameter values so that yield was improved from approximately 20 percent to 100 percent, a 400 percent improvement.

- AT&T achieved a fourfold reduction in variability in a polysilicon deposition process for very large scale integrated (VLSI) circuits (1.75 micron design rules) and achieved nearly two orders of magnitude reduction in surface defects by using Taguchi methods.
- AT&T reduced defects in the 5ESS™ programmed digital switch up to 87 percent through a coordinated quality improvement program that included product and process redesign.
- Deere reduced the number of inspectors by two thirds by emphasizing process control and by linking design and manufacturing processes.

Other reported quality improvements associated with the use of concurrent engineering are described by Winner[18].

5.2 Cost Reductions

Reports of cost reduction include the following classes of cost savings:

- Reduced bid in company proposals.

  McDonnell Douglas had a 60 percent reduction in life-cycle cost and 40 percent reduction in production cost on a short range missile proposal. Boeing reduced bid on mobile missile launcher and is realizing costs 30 to 40 percent below bid.

- Reduced costs in the design phase.

  AT&T and IBM reduced the number of design iterations and made extensive use of computer-aided design verification during design saving money and time. Deere reduced product development cost 30 percent.

- Reduced costs during fabrication, manufacture, and assembly.

  IBM reduced direct labor costs in system assembly by 50 percent. ITT saved 25 percent in ferrite core bonding production costs. Allied Signal saved more than $3,000,000 annually in a bulk chemical process as a result of experimental design.

- Costs reduced by parts reduction and inventory control.

  Boeing reduced parts lead time by 30 percent. AT&T reduced parts by one third on surface mount technology (SMT) packs and reduced costs to one ninth. AT&T Denver Works decreased in-process inventory 64 percent. Deere reduced the number of parts to fabricated and stocked by 60 to 70 percent. Hewlett-Packard Instruments Division recognized inventory reductions of 62 percent and a productivity increase of 250 percent.

- Costs reduced by reducing scrap and rework.

  Deere reduced scrap and rework costs by 60 percent. Using a Taguchi experiment, ITT saved $400,000 by reducing rejects on

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™ 5ESS is a trademark of AT&T

18. See [Winn 88] pp. 23-26.

one product. ITT saved $1,100,000 annually by improving a soldering process based on a Taguchi experiment.

5.3 Decreased Development Time

There were many reports of shortened development cycles. Experienced engineers pointed out that even significantly improved methods will not eliminate all the bottlenecks and long lead-time items found in some large, complex products such as weapons systems. Nevertheless, the reported savings indicate that substantial improvements were achieved. Samples are listed below:

- AT&T reduced the total process time for the 5ESS Programmed Digital Switch by 46 percent in 3 years.
- Deere reduced product development time for construction equipment by 60 percent.
- ITT reduced the design cycle for an electronic countermeasures system by 33 percent, and its transition-to-production time by 22 percent. Time to produce a certain cable harness was reduced by 10 percent.

Winner[19] presents additional reports of reduced development times associated with the use of concurrent engineering.

5.4 Interactions

We found it useful to classify the methods and tools associated with concurrent engineering into three categories and to describe payoffs in terms of quality, cost, and schedule improvements. These classifications are not intended to imply independence. In fact, interactions among the approaches are common. We found that companies typically employ some combination of approaches and they experience some mix of benefits. Some of these interactions are discussed below.

- *Multifunction teams.* The proximity and interaction of personnel from the different disciplines have a major positive effect by itself. Assignment of decision responsibility to the team allows big improvement in problem resolution which improves product and process development times.
- *Systems engineering.* Analysis of design features and their relation to observed reliability and producibility is a prerequisite to cross training personnel so that they achieve a systems perspective. The analyses and training are essential to quantitative predictions of producibility and reliability. Computer support has proven useful in performing these analyses without delaying the design process.
- *Computer support.* A parts database is valuable in conceptual design in terms of evaluating options. Product definition and shared common product design databases are enabling forces for a variety of concurrent engineering functions. Feasibility analysis, simulations, integration management, design release, and transfer to automated production processes all support decision making throughout the engineering process.
- *Complexity management.* The level of program integration and complexity affects the leverage of concurrent engineering methods and techniques. For complex systems, systems integration must

19. See [Winn 88] p. 27.

address both management and design systems. Product and process simulations are important at the systems level. At the component level, process and product optimization to achieve robust design may be of more immediate value.

- *Integration.* At the component level, concurrent engineering can be implemented by integrating the design system with a flexible manufacturing cell because the design and manufacturing systems employ features with known variability. This integration ensures that cost, performance, and quality objectives are met.

6. PITFALLS

The benefits cited in this report are encouraging, but they have not been achieved easily. One employee who is familiar with the success story of one of the companies encountered in this study related some of the mistakes and lessons learned in their implementation of concurrent engineering.

" . . . really impressive savings (hundreds of millions of dollars) remain largely unrecognized because they result only from improvements of the larger 'systems' over which only top management has control. These larger systems include policies of the company; training that people receive; actions of management; policies for purchasing parts; barriers between departments, between divisions, etc.; emphasis on short-term thinking and profits; policies for never-ending improvement; the way employees are evaluated; fostering of teamwork; and so forth. To date, most top managers have failed to comprehend, or at least execute, their critical responsibility. Their verbal 'support' is simply not sufficient."

He continues:

"Our corporation's lack of leadership for concurrent engineering has resulted in an effort without any clear direction or guidance both within many divisions and between the divisions. This fosters the widespread perception that concurrent engineering is a fad that will eventually go away . . . .

"Most divisions placed too much emphasis on the techniques of concurrent engineering (SPC, QFD, Design of Experiments, etc.) and not enough emphasis on the critical management philosophy underlying the application of the techniques. This partly explains the lack of top management understanding and involvement. Top management views concurrent engineering as something the lower levels learn and apply . . . ."

Sometimes the customer's acquisition strategy is a barrier. In one case, the customer elected to serve as system integrator and to have the program office control communication between the engineering and manufacturing groups. The contract required the engineering and manufacturing branches of the company to maintain separate relationships with the program office. For example, when the engineering branch is funded to design improvements or modifications for the weapon system, the output of this activity is an engineering change proposal (ECP) that constitutes a full technical change of the technical data package. Depending on the nature and scope of the ECP, the resulting manufacturing is accomplished by the same company or else by another vendor. Final assembly is accomplished by the manufacturing division of the first company.

This contracting method separates engineering from manufacturing and, when coupled with a fixed price

production contract, has several disadvantages for concurrent engineering. First, to reduce cost, improve quality, and reduce scrap, the company is limited to production process changes. Engineering changes can only be made if significant cost reductions can be demonstrated, at which time a value engineering change proposal (VECP) is processed by the engineering branch and submitted to the program manager for approval. The result is that engineering changes in production are limited to recurring cost reduction items where the cost savings outweigh the implementation costs on a three-year payback. Second, some engineering changes are designed by competing engineering houses, so that the production organization and processes are unknown to the designers. Thus, continuous improvement is stifled and production is decoupled from design. In this case, the program office, while intending to serve as an integrator, was actually a barrier between different divisions of the same company.

A third problem is the expectation of instant success—an immediate reduction in costs with no investment. Because more people participate in earlier stages of design, the initial expenses of a development project may increase. Several companies report that concurrent engineering extends the early design effort so the early design functions may take more time and cost more. This experience was not shared by all practitioners. Even where encountered, its effect was compensated by the savings when the initial production was started. In each reported case, concurrent engineering resulted in a shorter overall development cycle.

6.1 Issues

Members of the working groups raised several issues about concurrent engineering. Some[20] of the issues are listed below:

Avoid overregulation. Assuming that concurrent engineering is a good philosophy for product development, how can DoD encourage its use without imposing a particular solution? Senior DoD executives can, by including discussions of total quality management and concurrent engineering as part of their continuing dialogue with industry executives, show their interest and support for improving the development process. Beyond demonstrating an interest, a statement of DoD policy on concurrent engineering, without being overly restrictive, is needed.

Simplify the acquisition process while encouraging use of concurrent engineering. Both industry and government participants expressed a belief that creation of additional new programs or publication of more regulations without eliminating or modifying current practices is not the best way to improve the acquisition process. They expressed a strong preference for consolidation, simplification, and coordination of existing standards and regulations, including updating the "templates" to include concurrent engineering methods.

Improve the customer-supplier relationships in the DoD acquisition process. This issue remains open. The benefits of establishing closer relationships with suppliers are well known among followers of Deming and practitioners of just-in-time manufacturing. At the same time, the benefits of competition cannot

20. For a more extensive list of issues see [Winn 88] pp. 33-35, 46-48, 110, and 125.

be overlooked and support for competitive policies is very strong in the Congress.

Can DoD managers evaluate a company's claims about concurrent engineering without imposing a solution? Workshop participants from the defense industrial base expressed concern about their company's continued ability to compete for DoD contracts. They are ready to make the changes that they believe are needed to become more competitive, but they do not want to start an internal improvement program, only to find that DoD will later impose some slightly different program. Neither did they want to implement some improvement whose benefits will not be understood by proposal evaluators.

7. PRINCIPAL FINDINGS

The study team reached the ten findings listed below.

7.1 Concurrent Engineering Works.

The methods and techniques of concurrent engineering have been used to raise the quality, lower the cost, decrease the deployment time, and increase the adherence to desired functionality of a variety of products.

Concurrent engineering has been used for applications that range from simple components to complex systems. The success of concurrent engineering over this variety of applications as well as the study team's understanding of how and why concurrent engineering works leads to the second finding.

7.2 Concurrent Engineering Has Worked for DoD.

Concurrent engineering has been used in the DoD acquisition process and its use was reported to have helped provide weapons systems in less time, at lower cost, and with higher quality.

Concurrent engineering methods are being used in weapons system projects at demonstration/validation, full-scale development, and in production. Nine[21] of the companies contacted during this study provided information that they are using concurrent engineering on weapons system programs. They are convinced that further progress toward a fuller implementation of concurrent engineering is possible, not only in their companies, but throughout the DoD contracting environment.

7.3 Adopting Concurrent Engineering Will Not Be Easy.

There are systemic and individual inhibitors to the use of concurrent engineering in weapons system acquisitions.

The inhibitors to using concurrent engineering are found in the contractors' organizations and practices as well as in DoD's practices and policies. Capital investment decisions,[22] poor horizontal communication, local optimizations, and misunderstanding of the importance of quality are some of the barriers that must be overcome by contractors. Unrealistic cost and schedule constraints, excessive reliance on specifications and standards, and contract language that assumes an adversarial relationship between the customer and the developer are examples of government barriers to using concurrent

21. The companies involved in weapons system development and production were Aerojet Ordnance, Bell Helicopter, Boeing Aircraft (Ballistic Systems Division), General Dynamics, Grumman Aircraft, McDonnell Douglas, Northrop, ITT Avionics, and Texas Instruments.

22. Robert H. Hayes, Steven C. Wheelwright, and Kim B. Clark, *Dynamic Manufacturing*, The Free Press, New York (1988), pp. 61-90.

engineering.[23]

7.4 There Is an Opportunity for Change.

The circumstances are right for DoD to encourage the further deployment of concurrent engineering in weapons system acquisitions.

This follows from an observation that commercial industry and, to some extent, defense industry have already begun to demonstrate success using concurrent engineering. Basic methods of concurrent engineering exist and are in use and technological support exists. Also, the need for developing weapons systems in less time at lower cost and with the assurance that they will operate satisfactorily when they are fielded is heightened by budget realities.

7.5 Avoid Past Mistakes.

Industry experts believe that if concurrent engineering becomes a slogan or a new area of specialization instead of a systematic approach applied across engineering disciplines, then the deployment effort will be counterproductive.

A broad vision is needed, one which can lead to continuous, sustained improvement in the engineering processes applied to all DoD weapons systems.

7.6 Continue Research and Development.

Continued effort is needed to develop the methods and technology necessary for advances in concurrent engineering.

The need for continued improvement in solid modeling, process-planning techniques and computer support, finite element modelling, simulation, integration of computer-based tools, and standardization of product description semantics was stated at many of the sites visited. The Computer-aided Acquisition Logistic Support (CALS) initiative has encouraged cooperative efforts by industry to develop unified databases and integrated design tools, but the results are not yet ready for deployment in an open market. Many companies are capturing lessons learned in the rule and knowledge bases that support their design environments.

7.7 Help Is Needed.

Several companies reported that funding for IR&D projects intended to provide an infrastructure for concurrent engineering is no longer available.

Companies that implemented elements of concurrent engineering did so either because they were faced with a crisis or else they were companies with a tradition of continuous improvement for whom concurrent engineering is another stage in the process. For companies in the first category, the crisis provided motivation, but changing the way people worked was a challenging task. Companies in the second group have established programs for encouraging people to re-examine their work continually to find improvements.

7.8 Top-level Support Is Essential.

Implementation of concurrent engineering requires top-down commitment across different company functions.

Because several years may pass before company-wide benefits are apparent, senior management support is essential to prevent premature termination of new business approaches. Early success with pilot projects helps promote

23. For further discussion of barriers see *Industrial Insights on the DoD Concurrent Engineering Program,* The Pymatuning Group, Inc. (October 1988).

acceptance of new methods and top-down support may be needed to ensure that pilot projects are carefully selected and adequately supported.

In each case described to us, a company implemented changes by first trying new methods on pilot projects. The pilot projects serve to identify elements of a new plan that need improvement and they demonstrate benefits of using new techniques. They also served to develop the initial cadre of corporate members skilled in the new methods. This observation is consistent with published reports of key elements for effecting change.

7.9 Pilot Projects Can Be Helpful.

Pilot projects have been useful in demonstrating the benefits of concurrent engineering.

With respect to technology, the study team considered whether there were domains that should be avoided.

7.10 Concurrent Engineering Is a Robust Approach.

In this study, concurrent engineering was found to be useful in a range of applications that differed in terms of the maturity and type of technology used in the product and the production process.

There are some methods, for example, that are particularly well suited to applications where the technology is poorly understood or hard to control. An example of this is the application of design of experiments to the design and production of traveling wave tubes at ITT.

8. RECOMMENDATIONS

The IDA report [Winn88] contained seven recommendations for the Department of Defense.

- **Recommendation 1**

That the Secretary of Defense and OSD's principal acquisition managers act to encourage the use of concurrent engineering in weapons system acquisitions.

- **Recommendation 2**

That DoD principal acquisition managers establish a policy to use concurrent engineering as an implementation mechanism for total quality management.

- **Recommendation 3**

That the Office of the Secretary of Defense (OSD) should encourage the establishment of pilot programs whose objectives are to demonstrate that concurrent engineering, when deployed in defense industries and applied to DoD procurements, has the potential to yield higher quality products at a lower cost and in a shorter period of time.

- **Recommendation 4**

That OSD, in encouraging the implementation of concurrent engineering, build upon the beneficial aspects of existing DoD, national, state, and private manufacturing improvement initiatives.

- **Recommendation 5**

That DoD implement an education and training effort that starts with the senior OSD acquisition managers and then progresses to the lower levels through the acquisition chain. Once started at the top, lower levels can be trained concurrently.

- **Recommendation 6**

That DoD encourage industry to develop and improve the methods and technologies specifically required to support the use of concurrent engineering in weapons system acquisition programs.

- **Recommendation 7**

That OSD acquisition managers should initiate a process to identify and analyze statutes, rules, regulations, directives, acquisition procedures, and management practices that act as barriers or inhibitors to the adoption and use of concurrent engineering.

9. FUTURE RESEARCH

At one of the workshops, participants were asked to identify critical research topics to support concurrent engineering. Their response showed the need for a framework that could relate the goals, functions, and capabilities that must be in place for concurrent engineering to succeed. Such a framework was developed and is described[24] in the IDA report. It describes the technical building blocks that provide the capabilities which support the critical functions necessary to achieve the goals of improving quality while simultaneously reducing cost and schedule.

The building blocks are labeled as data, information frameworks, tools and models, manufacturing processes, and design processes. Each category is described below.

The first area, *data*, includes the kinds of information that needs to be brought to the design process for concurrent engineering. There is a requirement for a common information architecture so that information users (e.g., designers) and information suppliers (e.g., maintenance organizations) can have a common understanding of the meaning of the information.

The second group, *information frameworks*, consists of a structure of specifications and standards for establishing, storing, executing, and evolving information-based policies and tools. An information framework also has capabilities to organize, access, and evolve the data used by the policies and tools. Using a conventional or standardized framework that can be evolved and tailored allows for easier interaction among tools, among engineers, among teams, and among organizations. DoD has several information framework efforts underway. These include systems driven by the needs of airframe specialists, electronics specialists, logisticians, and software engineers. It is important that DoD integrate the vision of these efforts.

The third area, *tools and models*, deals with improving the tools directly required to support the engineer. The report discusses a broad array of empirical, simulation, and analytical models. These include process models, assembly and cost models, and manufacturing system models.

The fourth, *manufacturing processes*, addresses improvement efforts in integration of the design systems in manufacturing cells and systematic techniques for acquiring and analyzing data that describe the capabilities and capacities of the manufacturing systems. This includes matters related to flexible manufacturing cells, production process technologies, and design of experiments and other statistical methods.

The last category, *design processes*, includes work that needs to be done to improve understanding of the design process itself. This concerns the process of design synthesis by the individual and group and the psychological and sociological phenomena in the execution of a team design process.

24. See Appendix C of [Winn 88].

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APPENDIX D

Industry's View of Necessary DoD Actions for Effective Implementation of Concurrent Engineering

The overall goal of the CETF is to recommend actions to the USD(A) to facilitate and accelerate the use of concurrent engineering in mission critical systems[1] development, production, and support. This is a report on frank and anonymous discussions with representatives from six different industrial companies that have tried to implement concurrent engineering on DoD projects, plus members of the CALS/CE Industry Steering Group and its working groups. They suggest the following objectives be implemented in order to achieve this goal. The objectives are divided roughly into two levels based on the authors' perception of priority and hierarchy. The objectives are *not* in priority order within each level.

1. FIRST-LEVEL OBJECTIVES

The objectives identified in this section are the most important and should be implemented immediately by the DoD:

1. Engage the bureaucracy
2. Educate and train the bureaucracy
3. Make concurrent engineering permanent and improving
4. Avoid stovepiping
5. Integrate the bureaucracy

A discussion of each of these objectives follows.

1.1 Engage the Bureaucracy

The DoD and Service bureaucracies must be engaged in the process of enabling and accelerating concurrent engineering, and the commitment of upper-level management must be continuously obvious. The first step toward gaining acceptance of

1. We take this to mean all weapons, command and control, and logistics systems.

concurrent engineering is to recognize the need to change the current way of doing business. Those interviewed feel that current DoD culture encourages program managers to establish projects with large numbers of people and lots of money, and to keep these projects going at all costs. The objectives of DoD projects are often unclear because there is a tendency to stretch out the schedule and to emphasize spending the budgeted money. This approach to conducting business is inherently inefficient and counterproductive to assuring our national security.

Once the DoD recognizes the need for change, top-level officials must use their influence to encourage the acquisition of quality products through concurrent engineering. It will not be possible to sell the DoD on concurrent engineering solely on the basis of financial or personnel benefits. The implementation of concurrent engineering is a process that takes at least two years before financial benefits are seen; improved quality can be used to reduce cost, but it must be done right. Traditional cost reducing methods usually do not result in higher quality, and frequently do not result in lower costs. Also, concurrent engineering will very likely eliminate some jobs; it is happening in industry, and it could happen in the DoD. The selling of concurrent engineering must be based on the success of past experience and a commitment that it will work in the future. Top-level officials must make this commitment continuously obvious.

1.2 Educate and Train the Bureaucracy

Education and training are two topics that every company agreed were essential to the success of concurrent engineering. Present and future decision makers and implementors must be educated in the concurrent engineering process; education is the key to changing their behavior. DoD customers cannot be expected to accept concurrent engineering if they do not understand it. "The team approach of concurrent engineering has to be sold to the DoD," and selling will only come through understanding (i.e., education).

Two real experiences illustrate the need for education. In one case, a customer spent three years and lots of money to become "quality certified." Certification was supposed to have resulted in a drastic reduction in DCAS quality inspectors. Instead, the DCAS presence did not change, and the number of "quality citations" nearly doubled. The DCAS inspectors were not included in the concurrent engineering learning process, and the result was resistance. (This is also an example where working-level backlash subverted top-level support for concurrent engineering.) No attempt has been made at this point to verify this story or find DCAS's view because doing so would necessitate

revealing the source company.

In another case, customer and DCAS personnel were put through the same concurrent engineering training as the contractor personnel (team building, development exercises, review process, etc.). The customer and DCAS personnel became convinced of the concurrent engineering approach and started to be supportive. The number of DCAS inspectors was significantly reduced, and the remaining inspectors increased their level of responsibility and participation. All of this was done within the current legislative/regulatory system and without support from the contractor's top-level management. In other words, this company feels that education can and should be started independent of bureaucratic involvement.

Both contractor and customer representatives must be part of the education process. However, DoD personnel should be the primary focus because industry is already signed up to concurrent engineering, and those companies that are not signed up will tend to mirror the DoD program offices.[2] The focus needs to be on "training quality managers, not managers of quality." Concurrent engineering is process-oriented, not product-oriented; people, processes, and organization should be the focus of concurrent engineering instead of automation and tools. The experience of every company interviewed for this paper is that it takes about two years for individuals to become educated in concurrent engineering from generality through detail.

1.3 Make Concurrent Engineering Permanent and Improving

The objective of sustained, measurable, continuous process improvement has been a constant in all the approaches to quality that have been encountered in the concurrent engineering studies. There is a concern expressed by the companies visited that concurrent engineering will be at most a transient concern of the DoD. Even though the companies visited are deciding for their own reasons to try to use concurrent engineering without much DoD encouragement, they are concerned that DoD customers' failure to understand what is being attempted will result in loss of business to competitors doing business as usual. On the other hand, companies are hopeful that if the DoD customers engage in a sustainable improvement process as called for in concurrent engineering, the business climate will change and they will have a competitive advantage that coincides with the national interest.

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2. *Industrial Insights on the DoD Concurrent Engineering Program*, The Pymatuning Group, Inc., October 1988.

The issue has two sides: creating permanence and avoiding increased complexity. An included question is: to what extent can DoD depend on education and training to cause the culture to shift sufficiently to initiate and sustain the improvement? Also, can the education and training process be executed sufficiently well without a visible process of making the acceptance of concurrent engineering permanent? In other words, will the DoD and Service bureaucracies accept the education and training in the first place unless they see the inevitability of change? The predominant opinion is that some visible set of actions by DoD top management is required to initiate and sustain this change and to set a course of improvement. At the Phoenix meeting of the DMB, Dr. Juran stated that in his decades of experience working on these issues, he has found that a mandate from the top is necessary. Attempting to institute change by the logic of the argument, regardless of the quality of the rhetoric, usually does not work. Once people have worked on the change and have begun to see that it works, they then accept the logical argument. This effect is magnified if the people have had to detail the implementation themselves and therefore develop a sense of ownership of the implemented solutions. Thus, actions to make the concurrent engineering improvement process permanent are required.

Several interviewees told stories of failure to maintain the required constancy of purpose. In addition, IDA Report R-338 (pp. 28-30) contains an anonymous story of failure of top management to convey the idea in a constant way across the several divisions of a large company. In all these cases, processes either reverted to traditional inefficiencies or a plateau of very limited success was reached and the company stayed there.

One case involved a change in government project manager at the flag level on a classified project. The previous program manager had been convinced to allow an integrated team approach to product and process development. Two-thirds of the way (5 years) through the project, the new manager required the fragmentation of the team based on security compartmentalization. The concurrent engineering approach involved too much information flow. The company estimates that this change resulted in a two-year delay in the project compared to what it would have accomplished continuing the concurrent engineering approach.

Another example is a follow-on to a case in the IDA Report. This is not a DoD example but nonetheless demonstrates that continuity of top management attention is important. In this instance, a company division had implemented the beginnings of concurrent engineering successfully. After one year, however, specialty engineers began reverting to their functional organizations and the concurrent engineering behavior began to give way to the older, entrenched, fractionated approach. The division president

reluctantly eliminated the specialty organizations so that the specialists "would have nowhere to go home to."

The question is: what mechanisms will make a DoD concurrent engineering process permanent so that the bureaus will see that top management is and always will be committed to this approach without using traditional bureaucratic approaches to the acquisition and exercise of power in order to effect change.

1.4 Avoid Stovepiping

There is a universal concern among interviewed companies that concurrent engineering will be "institutionalized" by creating new regulations, new standards, a new specialty bureaucracy, etc. If concurrent engineering is to succeed in the DoD, this institutionalization must not be allowed to happen. This has been a finding in both the IDA and Pymatuning Group reports on concurrent engineering with the reasons detailed in both. Since check-and-balance advocacy is antithetical to concurrent engineering, such institutionalization is one of the few things DoD could do that would actively stop the progress being made already. These concerns are based on previous experience with good ideas being executed by arguably well-intentioned people who use traditional bureaucratic approaches and cause more harm than good.

One particular result of bureaucratic institutionalization is that contractors react by the creation of mirror-image functional organizations to carry out the regulation enforced by the government specialty bureaus. This reaction in turn prevents integration of the engineering process.

On one program, the contractor spent some of its own money to demonstrate the benefits of a paperless connection with vendors as an integrating mechanism. A DoD specialty QA organization complained about the lack of drawings. The contractor asserts this complaint was due to job-security fears, incompetence, and being rule-driven. Now that the demonstration has succeeded, everyone takes credit for it. The underlying issue, however, is the power and proliferation of specialty organizations. If they were smaller and better integrated into a team product office, the probability of effective incompetence is (asserted to be) less.

The interviewees feel that DoD must avoid the creation of new regulations and standards on concurrent engineering processes from which waivers must be sought. One contractor cautions "not to get hung up on buzzwords," and is disturbed to see RFPs

calling out a concurrent engineering process. These kinds of concurrent engineering stipulations are disturbing because this contractor doubts the capability of the source selection evaluators to judge such processes now, and fears that this is the first step in the creation of a new bureaucracy.

One suggestion that emerged in the interviews is to require downstream risk identification and avoidance to be addressed in proposals with concurrent engineering cited as an example approach. The proposal would detail the risk avoidance approaches to be used so that an educated evaluator could determine whether or not the proposals are valid. This approach does not preempt the proposer's ability to determine for a particular product what the best approach might be given his environment. It becomes the job of the source selection authority and of the education establishment to ensure that product-class-specific, process-oriented source selection evaluators are educated to be able to make these kinds of judgements.

To sum up, the CETF has the problem of recommending a way of getting the accelerated improvement process started and making it permanent *without establishing a bureaucratic stovepipe*.

1.5 Integrate the Bureaucracy

Interviewed industry representatives feel that as stovepiping is eliminated, team organization and behavior on the DoD side must be promoted. Both program offices and contract mechanisms must be integrated to facilitate the use of concurrent engineering. This reorganization will encourage DoD industry to start dismantling the functional organizations that stand in the way of integrated product development.

Several companies mentioned that DoD contracts tend to fragment the engineering process via the work breakdown structures imposed. It was also mentioned that some DoD development program managers will not allow significant funds to be spent on advanced production or support process development, and further that this attitude is contractually enforceable.

Other companies, however, have implemented concurrent engineering in spite of the work breakdown structure. With sufficient effort, program offices can be educated into the ways of concurrent engineering and then will allow or encourage its use. The typical amount of time taken to cause this education to occur is at least two years and then is subject to chance. Nonetheless, one of the companies suggested that any attempt to

accelerate concurrent engineering through the revision of policies under control of the financial community were futile. They suggest that widespread implementation of concurrent engineering must precede rather than follow from such revision.

Several companies mentioned internal fragmentation problems that are not due to DoD behavior. One common problem is the engineering "caste system." The engineering community is divided into the designers, manufacturing engineers, and support engineers in that order. This breakout is reflected in people's pay, management's attitudes (sometimes), and their relations with each other. This system at once impedes concurrent engineering and is cured by it. It would appear, though, that the action on this problem is in the hands of industrial top management rather than government. (It is assumed here that government cost monitors will allow design, manufacturing, and support engineers of otherwise like capabilities and background to be paid the same.)

2. SECOND-LEVEL OBJECTIVES

The objectives identified in this section are not quite as urgent, but should be addressed by the DoD as concurrent engineering becomes accepted:

1. Improve the requirements process
2. Stabilize the requirements
3. Encourage cost/performance trade-offs
4. Establish pilot programs
5. Encourage support technology and method development

A discussion of each of these objectives follows.

2.1 Improve the Requirements Process

Clarity of requirements (including life-cycle requirements) prior to design is essential to producing a sound product. It was a consensus view from all of the industrial companies that the DoD does not communicate the right requirements early. They do not communicate the right requirements because of the lack of contractor/end-user interaction, and they do not communicate them early because of a lack of DoD/contractor cooperation. Legal restrictions prevent DoD/contractor cooperation in the development of requirements and the statement of work, and thus inhibit early-phase concurrent

engineering. These legal restrictions should be removed, and a new step should be added to the acquisition process wherein the qualified contractors (or a selected set of them) participate with the DoD in a detailed application of QFD (or the like) to establish firm requirements and to surface conflicting requirements. This step has been attempted by three contractors and the DoD on a major system.

Even if legal measures are taken to allow DoD/contractor cooperation, the DoD program manager is typically two or three levels removed from the *real* customer (e.g., infantry). As a result, the approval of overall requirements through the organizational levels automatically makes the requirements old, and there is no feedback from the actual user of a product. The DoD must eliminate the gap between representative end-users and contractors that is imposed by the current requirements and support processes. A potential recommendation is to encourage "blue two programs," where engineers go into the field to see the products they have designed. This kind of visit would give the engineer a first-hand understanding of the product and an opportunity to talk with end-users.

Another part of the requirements process that inhibits the use of concurrent engineering is the inclusion of unreasonable "how-to" requirements. How-to requirements dictate specific components or methods that must be part of a product. Although certain requirements must be specific for compatibility reasons, many how-to requirements are established without good reason. To be "reasonable", a how-to specification must be supported by a compelling argument. Otherwise, "form-fit-function" requirements should be used. Form-fit-function requirements specify overall product form-fit (e.g., length, weight) and behavior (e.g., can carry out a three-hour mission), which are much more conducive to the use of concurrent engineering.

2.2 Stabilize the Requirements

According to one contractor, "the proposal seldom ever is what you are going to implement — it is based on 'pseudo-requirements'!" Although an improved requirements process is necessary, its effect will be lost if the generated requirements are not stable. In keeping with current DoD culture, several interviewees felt that program offices seem to make requirements changes for their own sake to prolong the existence of their projects. This bureaucratic behavior, where "SPOs perpetuate SPOs," places more emphasis on spending money than on spending it wisely. A program manager has very little responsibility for the quality of a product ("it was the contractor's fault!"), but he must do a lot of explaining if he has not somehow spent *all* of his budgeted money.

Incentives/disincentives need to be developed to change this cultural attitude.

Contractors concerned with this issue suggest that requirements changes should be made only in response to a change in threat. While less than 5% requirements change would indicate a process under control, greater than 35% change is typical. In one major program, for example, the type-of-engine requirement changed; the size and weight requirements changed approximately 25%; and a major structural-type requirement change was introduced as late as the preliminary design review (PDR) milestone. These changes necessitated additional changes in all support equipment and all engineering analyses.

On the other hand, concurrent engineering implementation will result in a decreased development cycle, and a decreased development cycle will tend to stabilize the requirements. For example, one contractor pointed out a program in which integration and computerization of the technical information allowed rapid analysis and assessment of DoD-proposed requirements changes. This use of concurrent engineering had the effect of reducing the DoD's tendency to introduce requirements change. The contractor felt that it also increased the DoD's confidence, reversing DoD's rejection of this contractor for the subsequent procurement.

As a final note to the discussion of change, there have been instances where the DoD will not or cannot make changes in the requirements. The DoD/contractor adversary relationship leads to detailed, iron-clad contracts. These contracts discourage program managers from allowing requirements changes suggested by contractors. Instead, the program manager will grant a waiver, which decreases the quality of the overall product. Therefore, contractors are discouraged from using concurrent engineering to identify better alternatives.

2.3 Encourage Cost/Performance Trade-offs

The DoD has fostered an atmosphere where maximum performance is the ultimate goal, and cost is of little or no importance. The result is a number of state-of-the-art, highly complex systems that cannot be realistically tested or controlled. The DoD needs to shift its focus to encourage realistic uses of cost-performance trade-offs, including life cycle cost. (There was only short discussion on this point during the interviews.)

2.4 Establish Pilot Programs

A consensus among the companies interviewed was that concurrent engineering should be introduced into the DoD through pilot programs. Each of the Services should select a set of initial projects for implementing concurrent engineering. These selections should be made very carefully because "concurrent engineering cannot afford an early failure."

2.5 Encourage Support Technology and Method Development

In two of the current interviews, in a recent set of meetings of the Industry CALS/CE Steering Group, and in the workshops leading to IDA Report R-338, there were calls for concurrent engineering technology programs with implications of government funding. The justification for these requests is that concurrent engineering includes a requirement for sustained, continuous, measurable improvement, and that improved technology is viewed as part of how the United States can get ahead of the rest of the world in the execution of concurrent engineering. No one who has studied the subject carefully has stated to the authors that the problems our industries face are solvable purely by technology. It is reasonably well understood among those who support concurrent engineering that the primary problems are management-oriented. Nevertheless, many feel that supporting or facilitating technology and method development also has a significant role to play. One potential effect of a DoD technology program is to insert process thinking into the technology development community.

Many of the companies interviewed have been using technology, particularly information-integration technology, in support of their concurrent engineering efforts. They have been working on analytical tools for producibility, reliability, and maintainability analyses that can be integrated into the product design process. Others, particularly in electronics, have been working on design tools that are driven by rules from downstream processes. Some companies suggest that absent a standard way of representing product analysis information and a framework for evolving and sharing the information, it will be very difficult for the government to take full advantage of these tools after the product has been developed. Also, the sharing of information among large, distributed engineering teams would be greatly facilitated by such approaches. The CALS program (including the PDES projects) has undertaken to deal with these issues in progressively more ambitious phases. The concurrent engineering community should be supportive of this undertaking and should continue to place demands on the CALS program to ensure that the needs of concurrent engineering are met.

APPENDIX E

DoD Process Issues

Any concurrent engineering implementation process undertaken by the DoD must take into account factors important to DoD that are not typically of critical importance to commercial enterprises. This appendix describes differences critical to the recommended implementation. These differences are of three kinds. First, there are DoD practices or characteristics that should be eliminated to maximize the use and utility of concurrent engineering. Second, there are those that will be eliminated or whose effect will be decreased as a natural consequence of widespread adoption of concurrent engineering. Third, there are those that must be accommodated in DoD adoption of concurrent engineering. Any implementation strategy must carefully consider into which of these three classes each of the following factors falls.

1. Contracting versus Producing

Organizations implementing concurrent engineering are typically product producers. DoD, however, does not build products; it contracts to have products built. The contractor/DoD relationship is not a pure arms-length supplier/consumer relationship: DoD directly and indirectly affects contractor behavior and vice-versa. For example, DoD contracts can inhibit contractors from implementing concurrent engineering because of explicit contracting practices and because of the effect that government organization implicitly has on the organizations of industry contractors. The fact that this is not an arms-length relationship, however, also provides an opportunity for increased customer-supplier involvement in the design process. Unfortunately, this opportunity is not always exercised because of erroneous interpretation of the idea of separation of responsibilities.

2. Existing, Serial Acquisition Process

The DoD acquisition process begins with the approval of a project as a budget item (see DoD 5000.1 and 5000.2). This stage is called Milestone 0. The stage between Milestones 0 and 1 is called concept exploration. This step involves paper studies that explore various alternatives to carrying out the project.

At Milestone 1, the project has been defined and a number of cost analysis/effectiveness studies are performed. Current systems are compared with various wartime scenarios to determine cost effectiveness of the proposed project. A performance analysis is part of these studies, but there is no consideration of manufacturing analysis.

Prior to Milestone 2, analyses are performed to show that the proposed product is technologically feasible; this stage is called demonstration and validation (DEMVAL). No consideration is given at this step as to whether the product is producible or supportable. Once Milestone 2 is approved, one of the Carlucci study proposals stipulated that the DoD be virtually certain that it is taking the product to production. Notice that production is supposedly inevitable at this stage, yet production and support considerations have not been addressed; concurrent engineering addresses this problem by taking production and support considerations into account from the beginning (i.e., Milestone 0).

Between Milestones 2 and 3 (FSD to LRP), a lab or prototype is built. FSD includes a production readiness review and transition-to-production templates. During FSD, the DoD and contractor are typically still negotiating product specifications and performance changes that are introduced at PDR and CDR; some people in the DoD feel that the customer is overly intrusive in this area. Notice that support processes are still not considered at this point.

Following FSD, the product is put through low-rate production and then high-rate production. Many design changes are expected even at low-rate production.

Funding Restrictions Many DoD regulations directly prohibit or inhibit the use of FSD dollars for considering production and support factors. These funding restrictions inhibit the implementation of concurrent engineering by discouraging the consideration of downstream factors early in the acquisition process. Three examples are shown below.

- Army Pamphlet 27-153: "Appropriations shall be applied only to the objects for which the appropriations were made except as otherwise provided by law . . . thus, appropriations may not be mixed or augmented by another appropriation"
- Army Regulation 37-1: "Applying funds to purposes other than those for which they were appropriated is a violation of 31 U.S.C. 1301(a)"
- Army Regulation 37-100-89: "All items and costs associated with maintaining the quantity sufficient to test for operations acceptability will be financed from other appropriations"

Regulatory Descriptions Imply Separation Between Design and Production Many DoD regulations also imply separation between design and production. These regulations inhibit the implementation of concurrent engineering by discouraging interaction between different specialty organizations involved in the acquisition process. One example is stated in DoD Regulation 5000.2, paragraph D3C: "Particular emphasis will be placed on the requirements for transitioning from development to production . . . a development baseline is established at Milestone 2 and a production baseline is established at Milestone 3"

3. Focus on Budgetary Considerations

Whereas successful implementors of concurrent engineering in commercial industry are often driven by market share, the DoD acquisition process is driven by budgetary and performance considerations. The DoD contracts for unique products that do not appear in the marketplace, and it reviews its contracts annually to make budgetary adjustments.

Most concurrent engineering implementations are based on a product development team that exists within a reasonably stable planning environment. The team is empowered by the planners to produce a product with go/no-go decisions based on understood criteria at planned milestone points. Budgets for product and process development are established and evolved. The political nature of DoD budget planning and its effects on the milestone decision process are significant differences from the like processes in commercial industry. The DoD "backs into" its unit cost after the budget is set because annual budget upheaval is now the rule rather than the exception. While it would be desirable to change this situation, the recommended concurrent engineering process is formulated independently of any such change. It is projected that a faster, more efficient development and production process will decrease the opportunity and motives for budget disruptions and their effects.

4. Focus on Performance Considerations

The DoD wants products that will give its forces a substantial performance advantage over its adversaries. Thus, in the DoD mission critical systems development process, there is a tendency to emphasize large improvements in performance almost to the exclusion of cost and schedule considerations. Reasons for this tendency include the fact that end-user commands are not responsible for the cost and delivery of the products.

Also, a predicted long schedule forces a riskier approach to performance targets. The expected long schedule causes immature technologies to be selected to avoid obsolescence at the time of initial operating capability.

The contracting and political mechanisms then make it difficult to compromise those targets until very late in the acquisition process, sometimes as late as full-rate production. The result is that the DoD acquires systems that are technological wonders of the world but at prohibitive cost and under an unpredictable schedule. This result, in turn, means that the operating commands may not be able to acquire enough systems, or they may not be able to acquire them soon enough to accomplish their missions.

There is an interlocking relationship between this issue and concurrent engineering. An environment in which performance is used as the sole driver on engineering is not conducive to approaches that tend to decrease cost and schedule. On the other hand, concurrent engineering has the effect of making the engineering process inherently more efficient. That means that performance targets that are important to users should be achievable more quickly unless they depend on ill-understood technologies.

5. Acquisition Process Makes it Difficult to Trade-off Performance

Because of the focus on performance described above, proposals for new systems are based on very large jumps in performance. These jumps are intended to provide a substantial advantage over potential adversaries and over the likely evolution of current systems. A performance advantage is planned to occur at the end of a long development cycle, say 15 years, and must be evolvable over the system life, say another 20-25 years. The cost of these systems is projected to be acceptable because of anticipated technology improvements that will lead to dramatic improvements in cost as a function of performance. In practice, the technology improvements that are applied in a production system do not lead to quite the projected cost-to-performance improvement. The DoD is then faced with a choice of adhering to performance projections or trading some performance for an acceptable cost. In either case, substantial performance increases are attainable; in the maximum performance case, however, performance and cost often are in the very steep part of the cost-to-performance curve. The tendency is to try to achieve the performance levels on which the system was sold in the first place, leading to dramatic cost overruns.[1]

1. This argument is detailed in Gansler, Jacques, *Affording Defense*, MIT Press, Cambridge, Mass., 1989, pp. 228-231.

Lowest Bidder Some companies argue that DoD evidences its attention to cost by its typical practice of awarding business to lowest-cost bidders. This practice rarely leads to the lowest unit-cost product or to the lowest life cycle cost. Even though lowest-bidder auctions are typical, DoD regulations, Congress,[2] occasional DoD use, and GAO recognize that quality can be combined with price in a source selection. Several cases indicate that quality and cost criteria in competitive selection can result in overall lower costs.[3] The relationship between supplier quality and end cost is particularly evident in the Japanese commercial experience, where supplier quality is used to drive down costs through reduction in waste effort.

6. Single Issue Advocacies: Stovepipes

During the last twenty years, DoD has developed an approach to problem prevention which can best be described as a checks-and-balances approach. For every area which conceivably might be of interest in a weapons system (e.g., reliability, safety, logistics, design requirements, software), there is an OSD and a Service organization that "advocates" for that area. These organizations exert influence over system acquisitions and designs by requiring the delivery of analytical reports on the contractors' attention to the specialty areas. They have their own engineering standards that are enforced contractually. These groups establish tight boundary conditions that have good intentions but often do not lead to the best overall results. Reasonably, the contractors organize in a mirror-image of the DoD organizations so that contractor people can communicate with the customers for their reports. The main flow of information is between government and contractor specialty organizations rather than across contractor specialty areas. This communication organization leads to the term "stovepipes" to describe the specialty organizations.

While many large commercial companies have specialty organizations, rarely do they have the power that the DoD stovepipes have. The effect of the stovepipes is to fragment the contractor effort and is, thus, antithetical to concurrent engineering.[4] There is a diversion of effort from the main task of product development, and the influence of the specialties on product design is low. This is a situation that concurrent engineering addresses head on, and the stovepipe organizations can be expected to impede actual

2. Public Law 98-369, Section 2753.

3. Gansler, *op. cit.*, pp. 184-185.

4. It has been reported that at design reviews there is often a complete turnover in both government and industry people when the discussion turns from the engineering design to the specialty areas such as reliability, maintenance, etc.

implementation.

Note, however, that concurrent engineering does not necessitate elimination of specialty organizations, but rather a change in their role.

Side Benefit of Eliminating Stovepipes DoD's current "checks and balances" management style, with lots of required output reports, is an inhibitor to concurrent engineering implementation. Many DoD problems surface as technical problems due to the lack of a process to deal with technical risk. Concurrent engineering adds engineering burden early in the acquisition process (instead of waiting until later when rework is much more expensive). To relieve this burden, it is essential to remove non-value-added checks and balances.

7. Dependency on Immature Technologies

One of the Milestone 0 criteria is that the proposed weapons system lead to a large jump in capability over current systems and over the projected adversary capability. This has led to a strategy of undertaking system developments that depend on very advanced, often immature technologies. This situation is amplified by the historical trend toward very long concept-to-maturity cycles: a very long cycle requires a farther out, less reliable projection of required capability. This in turn requires the undertaking of greater technological risk which has the effect of making the development cycle longer. The DoD is rightly concerned with its future needs. By projecting 15 years into the future, however, the DoD is counting on advances in technology that may not occur, and if they do, the technology may still be in its infant stages. Technologies that are not known to be producible remain in system designs through Milestones 1 and 2. This clearly is a key contributor to the schedule difficulties DoD experiences.

The dependency on immature technology in system developments is very different from the criteria for project initiation and continuation typical among commercial companies that have implemented concurrent engineering.

8. Poor Requirements Process

Identity of the Customer is Confused The identity of the "customer" in DoD is confused. The DoD program office is a buyer that also serves as an intermediary for the end-users. Program office personnel are concerned with contractual obligations,

spending *all* of their budgeted money, and to some extent with organizational survival. Program managers exercise little, or no, flexibility to trade-off preformance and cost.

The end-user community has many interests at different levels (e.g., commanders, operators, maintainers). Commanders tend to "ask for the world," never fully addressing the financial realities that ultimately result in fewer (possibly too few) units. Low production quantities are currently made up for by keeping old equipment. Operators and maintainers are often not significantly involved in the acquisition process.

Do Not Communicate the Right Requirements Early The DoD does not communicate the right requirements early because of the lack of contractor/end-user interaction. Legal restrictions prevent DoD/contractor cooperation in the development of requirements and the statement of work (SOW). Furthermore, field maintenance information is suspect because it is used for budgetary purposes by maintenance organizations. It is often impossible for designers to get any reliable field failure information in a timely fashion. DoD program managers are typically two or three levels removed from the *real* users (e.g., infantry). As a result, the approval of overall requirements through the organizational levels automatically makes the requirements old, and there is no feedback from the actual user of a product. In a concurrent engineering environment, it is desirable for designers to get detailed, feature-by-feature, maintenance information as well as having interactive communication with actual and potential end-users.

Requirements Unstable Since the DoD does not communicate the right requirements early, a proposal is seldom ever what is going to be implemented; the requirements are inherently unstable. Furthermore, in keeping with current DoD culture, program offices seem to make requirements changes for their own sake to prolong the existence of their projects. Some contractors and DoD officials state that design reviews, as currently implemented, are little more than excuses to introduce requirements changes.

DoD Assumes It Can Identify All Engineering Specs In Advance The DoD operates under the assumption that it *can* identify all of the (detailed) engineering standards and specifications that will be necessary for a particular project, even though DoD experience indicates the opposite. The DoD tends to overdetail its contracts, often including unreasonable "how-to" requirements. "How-to" requirements dictate specific components or methods that must be part of a product and its development. Although certain requirements must be specific for compatibility reasons, many "how-to" requirements are established without good reason.

By comparison, the DoD realizes that it cannot identify all of the logistics specifications that will be necessary for a particular project. So, logistics personnel are put on site to work with the contractor in addressing logistics issues as they arise. DoD logistics personnel have set a precedent showing that it is possible to establish DoD/contractor teams that can work together.

9. Lots of Design Changes Expected as Late as Full-rate Production

The acquisition process accepts long-term maturation after delivery. Logistics are not expected to be in place upon delivery, and reliability maturity is not required until 1-5 years after a product is first produced. In fact, most systems require block upgrades before they are considered mature from a performance viewpoint. Figure 1 describes the reliability and maintainability maturation process for several past or present DoD systems.

SYSTEM	IIIA DECISION	III DECISION	IIIA DEL	III DEL	R & M MATURITY
Project A	Month 0	Month 12	Month 24	Month 40	Month 79
Project B	Month 0	Month 27	Month 37	Month 57	Month 72
Project C	Month 0	Month 24	Month 15	Month 36	Month 47
Project D	Month 0	Month 35	Month 15	Month 43	Month 62
Project E	Month 0	Month 67	-	-	Month 93
Project F	Month 0	Month 34	Month 22	Month 55	Month 59
Project G	Month 0	-	Month 22	Month 58	Month 76

Figure 1: R & M Maturation in the Acquisition Process

10. Unusual Change Characteristics

The size of DoD, or even of one of the Services, is so large that incorporating change is inherently more difficult than in any commercial industry. Also, the relationship between the permanent civilian workforce and transient top management is unusual. The

relationships among OSD and the Services and Agencies further complicates matters. The DoD as a whole employs over 2 million people, 600,000 of whom report in some sense to the USD(A). Therefore, the amount of leverage that DoD management has is widely distributed relative to industry management. This dispersal of power may be necessary, but it means that incorporating change requires the support of a large number of enthusiastic management personnel.

APPENDIX F

Concurrent Engineering: Support Methods Used

ABSTRACT

This paper describes the relationship between concurrent engineering and some of the methods and techniques used by those who practice it. The paper was prepared to support the CETF report. Some of it was taken either modified or directly from a paper by James P. Pennell and William E. Akin entitled "Examination of Various Methods Used in Support of Concurrent Engineering."

1. INTRODUCTION

By definition, the practice of concurrent engineering, implies those people engineering the product will interact with those engineering the production and support processes. These tasks will take place at the same time with each group taking into account the work of the others, making trade-offs and optimizing the global engineering process over the product and all its downstream processes.

Concurrent engineering is basically an approach for integrating different activities, but it manifests itself in the application of certain tools and methods. Some of these methods are new but many are not. The use of these methods is not sufficient reason to conclude an organization is practicing concurrent engineering. However, successful implementations of concurrent engineering in U.S. industry report the use of many of the methods as bases for their programs.

This document seeks to present some of the methods found in U.S. industry today which support concurrent engineering efforts. Many of the methods have been modified in practice to address a particular need in concurrent engineering. Some are used in traditional ways. The following sections name the methods, describe their use and relate their value in the support of concurrent engineering.

2. TEAMWORK

Some people think teamwork is concurrent engineering. This is not true. One person could engineer a product and its processes concurrently. In the real world of large developments, that is not likely. It is more likely the engineering of the product and each of its processes would be done by different people skilled in the different disciplines. To perform concurrent engineering, those in each discipline must work at the same time with interaction and consideration, and with the common, global goal of optimizing the product and all its related processes.

The most common and most obvious way to provide the needed interaction and consideration among the disciplines is to form multi-disciplined teams. The team has the responsibility of engineering the entire life cycle of the product from concept development through production and lifetime support. Team members interact, trading-off among the disciplines to optimize the overall project, not their own area.

The formation of multi-disciplined teams is the dominant method used by industry to implement concurrent engineering by providing a vehicle for interaction and consideration. If an enterprise relies on a multi-disciplined team approach to concurrent engineering and effective means for integrated engineering are available, it is important to see that all disciplines which impact the project throughout its life cycle be represented. Many early attempts to form teams have omitted less obvious but very important members. Sometimes companies fail to educate the engineers in the tools that allow them to control the complexity of integrated design.

3. PROCESS PERSPECTIVE

A philosophy that sets concurrent engineering apart from traditional approaches is the emphasis on viewing activities from the global process perspective. The entire collection of activities needed to change an idea into a fielded, successful product is now viewed as a single process. This single process is managed and optimized based on global optimization criteria, not the optimization standards of the different functional subgroups.

Every person or group in an enterprise has one or more jobs. In the concurrent engineering environment jobs are described by their processes (including input and output) rather than purely by their products. Although each job will have identifiable

products, it is still described by describing its process.

In leading companies in the concurrent engineering community one can hear questions about a process such as: "What is my process?"; "How do I measure it?"; "How am I doing?"; "Who is the process owner?"; "Who is the process customer?"; etc. In these progressive companies the process perspective is the viewpoint of choice.

4. FORMAL MATHEMATICAL AND SCIENTIFIC METHODS

Controlling the complexity of large scale developments requires the use of sophisticated, but easy-to-use tools and methods. Processes have to be measurable and controllable to be optimized. Approaches to problem solving must be based on formal, scientific methods. Depending on the kind of product and the size of the company, U.S. companies either create or adopt such scientifically based approaches.

Some of the seemingly simple techniques are backed by complicated statistics and mathematics. Successful concurrent engineering methods are those which are based on sound, scientific principals but which are applied using straight forward, easy to understand techniques.

5. STATISTICAL PROCESS CONTROL (SPC)

To evaluate alternatives and make trade-offs among product and various process designs, engineers must have a quantitative understanding of the stability of important measurable parameters. It is necessary to understand the variability of a process in the presence of uncontrolled "noise" and to know the effect of changing controlled parameters on that variability.

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.

SPC 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.

During the IDA concurrent engineering study, process management and use of SPC were the most frequently mentioned tools. Many companies described how they used SPC or process management as part of their concurrent engineering programs.

6. QUALITY FUNCTION DEPLOYMENT (QFD)

There is a significant increase in the use of statistical and scientific methods by U.S. companies developing concurrent engineering programs. Trade-offs made to achieve a global optimization during a development should be based on best available information. First cuts are often made by informed or experienced minds focused on a problem. In large, complex developments companies find they need much more accurate information and more of it. They have turned to methods such as QFD to help provide it and to track important relationships.

QFD uses teamwork and creative "brainstorming" to identify customer demands and design parameters. The correlation between the demands and the design parameters is ranked and normalized. Such data are collected from concurrent engineering participants of all disciplines. 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.

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 other parameters listed for the columns. Entries where rows and columns intersect indicate how design parameters correlate with the process customer needs. Positive and negative correlations among the product features are given in a triangular table above the matrix.

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. It tends to surface conflicting requirements very early and tracks their resolution. It also tracks the relationship between process and product design decisions.

Although QFD appears to offer substantial benefits in the design of complex systems such as military systems, the application of QFD to such tasks has not been publicly reported. There is one example military system in which three competing contractors and the program office have participated in a QFD exercise. Individual contractors in this project have also been using QFD for competitive advantage. It is too early, however, to assess the outcome. Opinion on QFD is not universally consistent. At least one executive of a leading aerospace company characterizes QFD as a grossly simplified application of the principles of system engineering.

The application of QFD in concurrent engineering provides a scientific approach to the collection and evaluation of information on which the multi-disciplined teams can make trade-off decisions. Measures are provided whereby parameters can be compared and ranked.

7. ROBUST PRODUCT DESIGN

Since 1980, the concept of robust design has been gaining wider acceptance within U.S. industry. Japanese engineer, Genichi Taguchi, is credited with developing some of the key elements of this idea. The principal contributions of Taguchi include a reexamination of the role of specifications, an emphasis on using controlled experiments, a recognition that products are built in factories under environmentally "noisy" 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.

In particular, Taguchi 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 loss can be minimized if some characteristic of the product has an ideal target value and the loss increases as the square of the distance as the characteristic 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.

The benefits of robust design 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.

8. INTEGRATING TECHNOLOGIES

In order to facilitate concurrent engineering, team members from multiple disciplines must have access to each other and each other's work. This presents some technology problems. Concurrent engineering efforts have found the need for 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 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.

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.

9. ENVIRONMENT FRAMEWORKS

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 process. Thus an effort to manage complexity of designs increases complexity of the concurrent engineering process. Such an approach requires integrating and accessing automated tools easily, sharing design information in a controlled fashion, tracking design information, tracking design dependencies and changes, and monitoring the design process.

These are characteristics and requirements that 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, data exchange, engineering and manufacturing management and control, information management, and environment administration.

There are efforts to develop engineering environment frameworks in both commercial industry and the DoD (including efforts in the CALS program). The work is in its early development stages. When ready, the framework(s) will be a major support method for concurrent engineering.

10. PROCESS BENCHMARKING

Continuous improvement is the watchword in concurrent engineering. To make anything better, one must know how good it is. In the competitive world of commercial products this calls for benchmarking. If a company strives to make the best product, it develops a set of metrics and applies them to available information about products in the same market. A set of best values from the exercise is called a benchmark. The

company applies the same metrics to its own product and compares its results to the benchmark to see how good its product is compared with the best-in-the-world values for each measure.

Competitive benchmarking has been used for a long time to help companies reduce their costs and improve the value of their products by comparing to known standards. In the realm of concurrent engineering, another use of benchmarking has begun to be used. Progressive U.S. companies have begun to employ benchmarking to help improve processes.

Benchmarks do not have to be made from measurements of like products. One need only to develop metrics for similar precesses in order to develop benchmarks. The example of Xerox benchmarking its direct marketing and distribution against that of L.L. Bean demonstrates that measurements of the process can form benchmarks even though the products bear no resemblance.

Process benchmarking can be very difficult. First, one must determine metrics which will indicate merit. Then, using the metrics, a set of measurements is selected as the benchmark. As similar processes are developed the metrics are applied and their results applied to the benchmarks. The metrics must be continuously improved and new benchmarks established.

11. CUSTOMER INVOLVEMENT

Proponents of concurrent engineering emphasize the need to capture the "voice of the customer (VOC)." This simple sounding task has been poorly performed in project after project from time immemorial. Often the statement of requirements by the customer is poorly understood by the supplier from the beginning.

This is only part of the problem. The producer may have skill and knowledge which could lead to a better, more producible, more supportable product. To gain optimum use of all skills and knowledge in capturing the "correct" VOC, the customer and producer must work together. In other words, the customer needs to be part of the concurrent engineering process.

The VOC must be maintained throughout the engineering process. To optimize the entire project will require trade-offs at every level. When the customer becomes one of the participants in the overall project, his process, the VOC, becomes one of the

elements to be interactively considered. Major benefits offered by concurrent engineering can be lost because of barriers between producer and customer. Recognition and removal of any such barriers is an important activity by those organizations implementing concurrent engineering.

In the DoD arena, customer/supplier barriers have been legislated, regulated. or otherwise evolved around the mechanisms of arms-length contracted.

12. SUPPLIER INVOLVEMENT

In concurrent engineering implementations, anyone who can impact the product or its processes should interact and should be considered. Suppliers of either off-the-shelf components or subcontract product or process developments should be included in the development team.

Successful U.S. commercial industries are changing the role of the supplier from adversary to trusted partner. Suppliers should provide input to every phase of development they can impact. Companies benefiting from this change report the use of longer term contracts and fewer suppliers than traditionally used. The result has been higher quality and lower cost.

Bringing suppliers into the concurrent engineering process means interacting with them and making trade-offs to achieve the optimum, overall product and processes. In other words suppliers should be part of the effort the same way production engineering staff should. If the enterprise uses the integrated multi-disciplined team approach, suppliers should be represented on the team.

Leading U.S. and successful overseas companies report involving trusted suppliers in the early stages of their projects. Some projects have supplier representation on teams as early as the concept development phase. This prompts companies to decrease the numbers of suppliers and increase the length of contract periods.

APPENDIX G

CONCURRENT ENGINEERING

Don Clausing
MIT

Presented at the Winter Annual Meeting
American Society of Mechanical Engineers
San Francisco
December 13, 1989

Introduction

Concurrent Engineering is a seemingly simple idea that is based on a fundamentally different way of looking at how products are conceived, engineered, manufactured, and supported. The idea is that people can do a better job if they cooperate to achieve a common goal. To implement this concept successfully in a typical, functionally organized U.S. company, the members of management, labor, and technical staff must develop a profoundly different insight, namely the process insight, into the nature of industrial activity.

The "process" insight is the realization that all the activities which transform a collection of inputs into a product satisfying a need are a single "process". This process can be measured, managed, and continually improved. The improvements must include both the breakthroughs associated with new inventions and the small improvements that result from everyday suggestions.

For many products, even simple parts, the overall process will be broken down into more easily managed tasks, but the tasks are not viewed as ends in themselves. They are not optimized at the expense of the overall process.

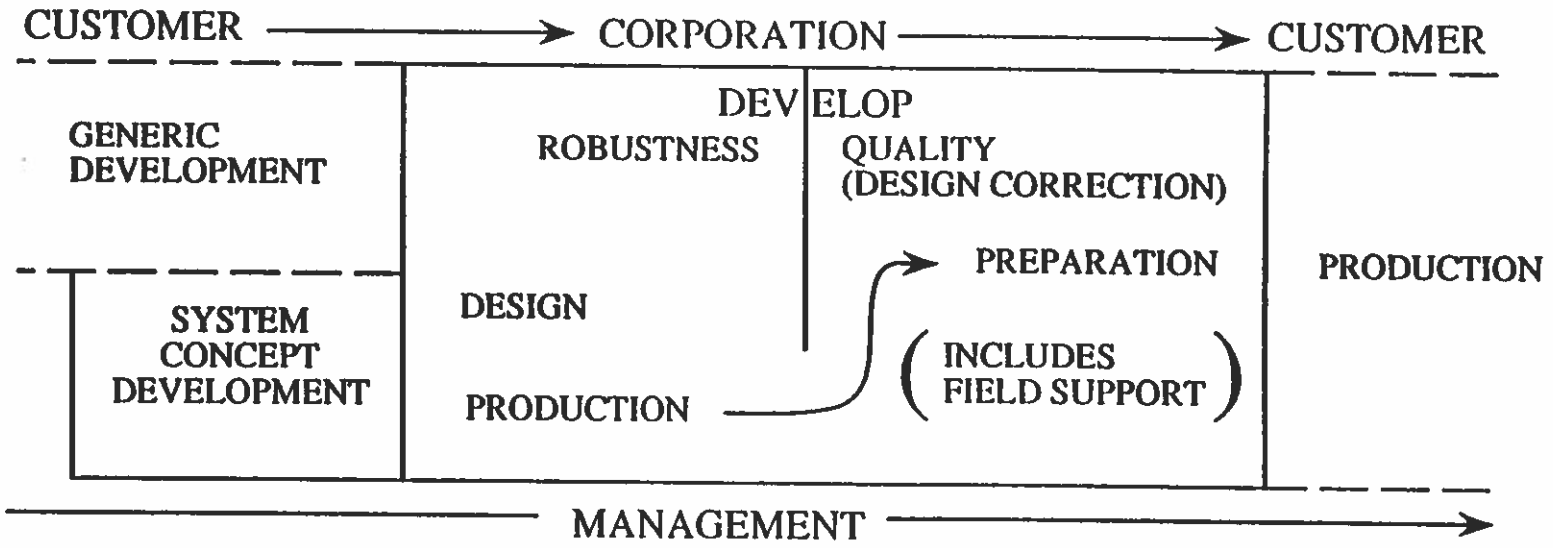
The Concurrent Engineering process is critical for successful product development. The basic concept is simple. In today's dynamic world the best form of Concurrent Engineering is rapidly evolving.

World-Class Concurrent Engineering

In the ideal form of Concurrent Engineering, the detailed design of the product is performed concurrently with the development of production capability, field-support capability, and quality. Quality is developed concurrently with the product design and the development of production and field-support capability, Figure 1. Although progress is being made in the evolution of quality development, and bringing it upstream to be concurrent with product design, more needs to be done before this is a demonstrated capability in American manufacturing companies. The activity that must be carried out concurrently with the product design is optimization of robustness. This is completed in time to include the optimized values for the critical design parameters in the design that is then used to make the first production-intent prototypes. The only further quality development that is then required

CONCURRENT ENGINEERING

(WORLD-CLASS)



CONCURRENT DEVELOPMENT
WITH MULTIFUNCTIONAL TEAM:

1. PRODUCT DESIGN
2. PRODUCTION CAPABILITY
3. FIELD-SUPPORT CAPABILITY
4. QUALITY

FIGURE 1

with the aid of the prototypes is the elimination of mistakes, which is usually quite simple to do, providing robustness was achieved during the earlier time period concurrently with the design. The system for robust design that has been gaining increasing application in the United States during the 1980s was developed by Dr. Taguchi.

In World-class Concurrent Engineering the development of the production capability and the field-support capability is started early, concurrently with the design of the product. This has four major benefits: (1) the development of the production and field-support capabilities has an earlier start; (2) tradeoffs are made among design, production and logistics, not simply within design; (3) good design for manufacturability and good design for maintainability are facilitated; and (4) the production and field-support people gain a clear understanding of the design.

In addition to the corporation bringing its own production-capability and field-support-capability people upstream to work concurrently with the product design engineers, it is also an essential element of Concurrent Engineering to bring in suppliers to play a major role in the design of the new product. In the old serial and sequential form of product development, the suppliers were usually brought in very late, at which time they could only respond to designs that were already completed, and compete with other potential suppliers primarily on the basis of lowest quoted cost. This led to a proliferation of suppliers, none of whom were contributing significantly to the design of the new product. As a result, the design was often ill-suited to the capabilities of the suppliers. In Concurrent Engineering, the supplier base is greatly reduced and the participating suppliers are treated in so far as possible as full members of the design team. In many cases the number of suppliers has been reduced substantially: at Xerox, for example, from more than 3000 suppliers in the past to fewer than 400 today.

One of the major objectives of Concurrent Engineering is to achieve low-cost production of the product in the factory. The design and development work to achieve low cost has two major elements. The first is the design, development, build, and debug of actual production hardware, such as holding fixtures and dies. The second major element is to design the product so that it lends itself to easy production with low cost. This is known as design for manufacturability (DFM). DFM, in turn, has two elements: design for assembly, and design for piece-part producibility. There are two styles of activities to achieve good DFM. One of the approaches to DFM occurs naturally as part of Concurrent Engineering. The design engineers and the process engineers work concurrently, exchanging information so that the product design continuously takes advantage of good production-process practice. This is usually very successful, but does require the presence of a significant number of skilled process engineers during the product design. It also creates a considerable transactional burden for the two types of engineers to exchange all of the relevant information. The second style for achieving DFM is to make the process information readily available to the design engineers in handbooks and computer formats. This reduces the need for skilled process engineers during the design process, and minimizes the interpersonal transactional burden. The approach of handbooks and computer software has been developed into an operational capability for design for assembly (DFA),

with the best known capability in the U.S. having been developed by Professors Boothroyd and Dewhurst, formerly at the University of Massachusetts, and now at the University of Rhode Island. Design for piece-part producibility is more difficult and much more diverse than design for assembly. There are many different types of production processes for making piece-parts, and information must be available for each of these many types of production processes. The extreme case of the pre-formulated design rules is achieved in "feature-based" computer systems in which the design is constructed from manufacturing features with known cost and yield, i.e., quality. Examples of this are to be seen in flexible mechanical manufacturing cells by John Deere which uses standard families of components as design building blocks.Although now considerable information in fairly standardized form exists to guide design for piece-part producibility, there is still a great need for more adequate handbooks and computer programs to assist the design engineers. Of course, the best handbooks and computer software will not eliminate the need for the direct participation of some process engineers during the design of the product.

An additional facet of Concurrent Engineering occurs even earlier in the product development cycle, during completion of the system concept. In the past it was common for market research to determine customer/user needs, throw them over the wall to planning who outlined the requirements for the product, and then threw them over the wall to product design engineering. This sequential development of the requirements and the system concept made it unlikely that the needs of the customer/user were adequately considered in choosing the system. These activities are now in best practice combined together and carried out by one multifunctional team. This is another application of the basic principles of Concurrent Engineering.

It is important to deploy systematically the voice of the customer throughout the development and production process. Since 1986 this has increasingly occurred in the United States with the assistance of quality function deployment (QFD)[1]. QFD also ties together the functions of the corporation: it helps in achieving a holistic response to the customer, and it utilizes the best experiential knowledge of the corporation. QFD can be well supplemented by the concept selection process of Professor Stuart Pugh. This process, which is useful for many important decisions, especially can help the multifunctional product development team (PDT) to select the best product concept. The combination of Robust Design (Taguchi), QFD, and Pugh is often referred to as Design for Quality, an important element of Total Quality Management (TQM). The considerable progress that has been made during the 1980s needs to be strongly enhanced so that Design for Quality in American manufacturing companies achieves the level of success that international competition requires.

Concurrent Engineering is being tried at the large system level; at the black box and subsystem level; and at the piece part or component level. While the basic principles remain the same, the methods and processes are quite different.

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[1]"The House of Quality," John R. Hauser and Don Clausing, *The Harvard Business Review*, May-June 1988.

The integration of large, complex systems emphasizes establishment of requirements; identification and management of critical subsystems; and distribution and exchange of subsystem and system design date so that the pieces will fit and work compatibly when brought together. Subsystem teams work concurrently on product design and critical process design for critical subassemblies. Perhaps the highest leverage is in constraining requirements and in solving early the product/process issues for long-lead subsystems.

At the other end of the scale, concurrent engineering of piece parts and components may be quite different, depending on whether the components represent new or difficult-to-manufacture materials and technologies. For new materials and processes, systematic application of performance and process simulations coupled with selected experiments may be the highest leverage approach to determine a feasible combination of product and process design to produce reliable components at reasonable cost and yield the first time out; whereas with existing and proven technologies, the objective may be to optimize (to produce high quality at low cost). In both cases, the objective would be a significant improvement over current experience.

Success requires that the many activities of product development be integrated into a closely coordinated, holistic operation. These are summarized on the following pages.

The development process is depicted as five major activities:

Generic Development (primarily precedes program)

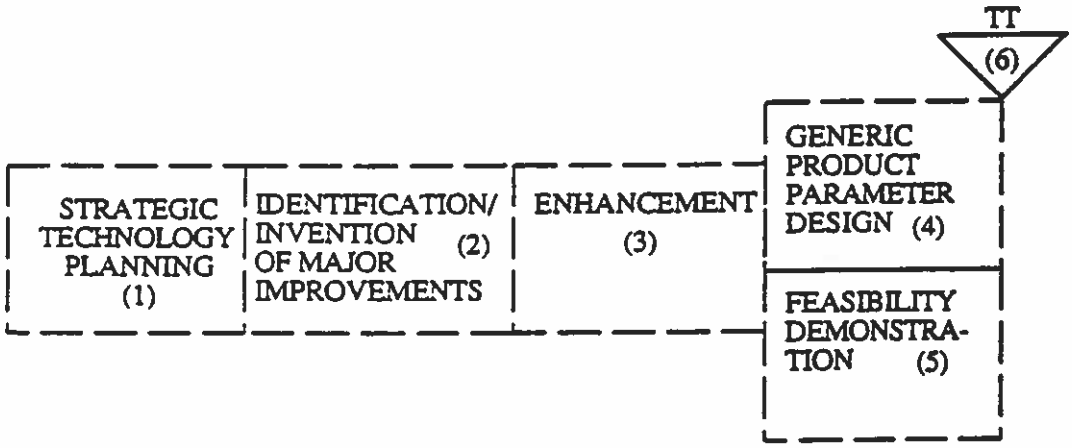
System Concept Development

Design

Product Parameter Design (optimization of robust quality)

Production Preparation

CONCURRENT ENGINEERING
(GENERIC DEVELOPMENT)



(1) Plan (5-10 years) for major cost/performance improvements; based on competitive benchmarking, cost/performance maturation curves, technology monitoring, and voice of customer. For complex systems this plan will be at subsystem level, and may include competing technologies (concurrent development of alternative concepts).

(2) Commonly this is invention in response to (1). However, this may include a wide range of activities, from integration and standardization of best practices to bringing in new technology from outside of company.

(3) For new inventions this is commonly refinement of the invention by experimentation and analysis; hypotheses are modified, and the invention is whole only after this activity is completed. For technology that is being transferred in, this activity is usually primarily tailoring to local needs. In general, the major improvement is enhanced to the point where feasibility demonstration is possible.

(4) Parameter design to optimize robustness of generic improvement. Most important requirement is to demonstrate that new concept is capable of robustness. Values of most-critical design parameters are optimized. Near completion this optimization often becomes focused on initial application.

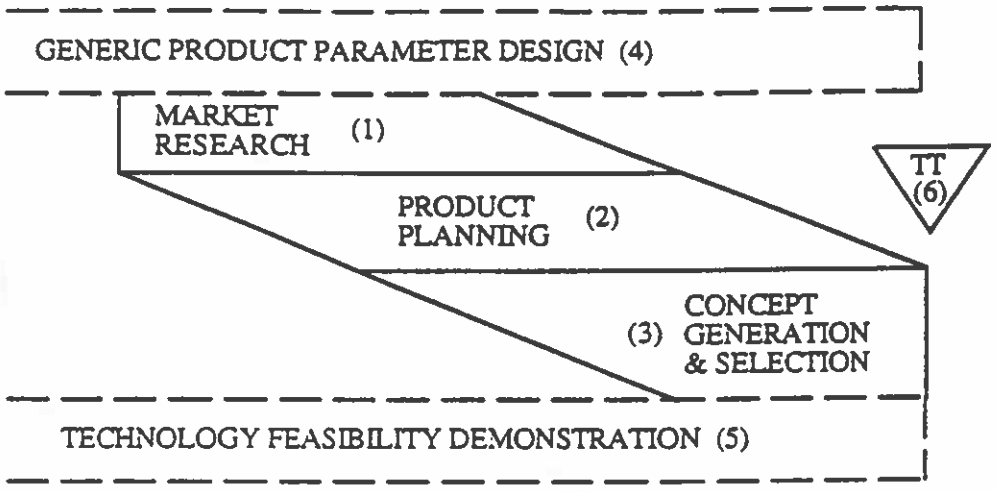
(5) Demonstration that concept can be implemented, and is appropriate to be selected. Includes demonstration of manufacturability (at a low cost), maintainability, and an ability to meet all standard specifications, such as mass and volume. Legality (patents, copyrights, uncontested right to use) is verified. Acceptance by other functions is developed. Commonly subsystem technologies are incorporated in an integrated feasibility test fixture, which can function as a complete product.

(4)(5) Combination completes maturation of the new technology; ready for incorporation into specific product. Commonly the final phases of these activities are completed concurrently with the System Concept Development for the specific product, and provide needed information to that activity.

(6) Technology Transfer, into specific product program.

Note: With minor changes, the above applies to production processes and product improvements.

CONCURRENT ENGINEERING
(SYSTEM CONCEPT DEVELOPMENT)



(1) Voice of customer: needs for new product and evaluations of existing products; sometimes includes evaluations of proposed new product concepts.

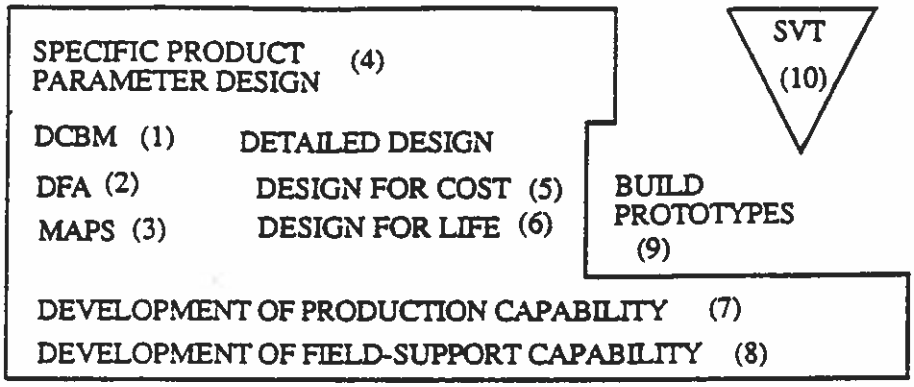
(2) Deployment of customer needs into corporate system specifications (expectations), technical evaluations of existing products, quantification of specifications, planning of expectations to be emphasized, and micro market segmentation; i.e., planning of customer-orderable options.

(3) Overall system layout, chosen subsystem (s/s) technologies, and s/s specifications; all responsive in detail to (2), utilizing the best technologies from (4)/(5), and systematically evaluated to be superior to alternatives.

(4)(5) Technology maturation: becoming eligible for selection in (3).

(6) Technology Transfer; formal completion of transfer after selection in (3). Actual transfer occurs by concurrent activities (3)(4)(5), and often is continued after (6) by a "product engineering"/"advanced development""team" (two or more people) within the Product Development Team until technology transfer is complete..

CONCURRENT ENGINEERING
(DESIGN)



(1) Design Competitive Benchmarking. The best products in the field are analyzed in detail by the Product Development Team. This helps to assure that the new design will be superior in all aspects.

(2) Design for Assembly (also Maintainability). Detailed analyses including function and assembly sequence, to determine which parts are required to be separate, and which features can be combined into one part. Provides guidance on shapes, and on fastening approach.

(3) Material and Process Selection. The material and part-formation process is selected; for example, aluminum die casting. This also includes the design of the part to enable low-cost formation.

(4) Optimization of nominal (target) values for the critical design parameters (to achieve robust performance).

(1)(2)(3)(4) Combination creates subsystem (s/s) design; provides specifications for detailed design.

(5)(6) Detailed Design is design of part features on major parts, and design of small (often standard) parts. Close communication with (4) to assure that the final design incorporates the optimized values. The features on major parts will be produced by material removal, and the design emphasizes Tolerance Design and Piece-Part Producibility to minimize Total Cost. Life is extended by getting the materials science right in keeping with the environment and the applied "loads" (forces, voltages, chemical potentials, etc.); sometimes includes the optimization of robustness against the noises of time and use. This is a complete production-intent design.

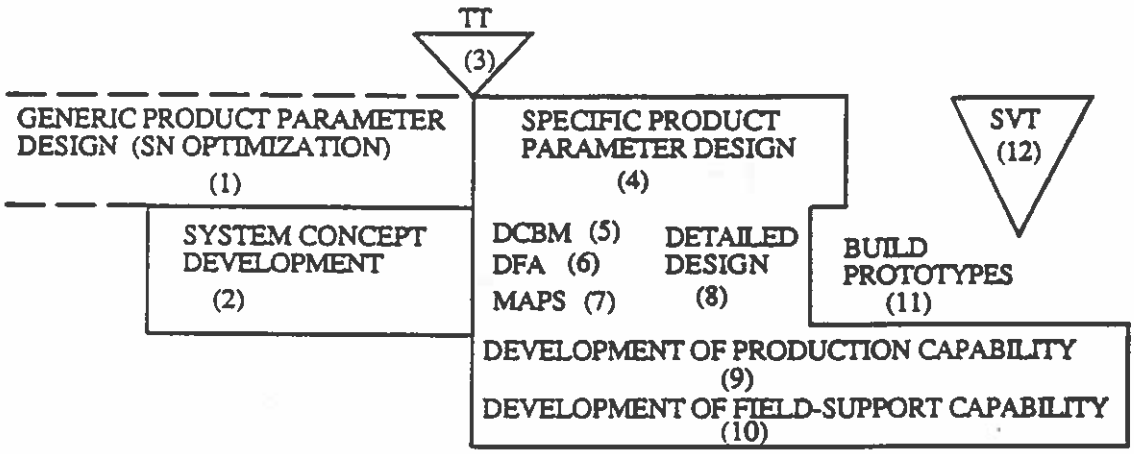
(7) Must be tightly integrated with the product design to assure the lowest possible cost, and to enable the production to start at the earliest possible date. Tooling design should be completed when prototypes are finished (9).

(8) Must be tightly integrated with the product design to assure excellent maintainability, and to enable the field-support operations to be ready when production starts. Includes distribution, service procedures and tools, service documentation and training, spares plan, and operator training.

(9) These are the first production-intent prototypes. As close to production conditions as possible, but production tooling will not be available. Geometry should be identical with production parts, including variations. Chemical composition should be the same as in production, but the microstructure will often be different because of the lack of production tooling. The prototypes have three objectives: (a) learn about production, (b) verify robustness, and (c) eliminate design mistakes. Also may be used for development of service and operator training procedures. The incorporation of the lessons learned while building these initial prototypes completes the design.

(10) System Verification Test

CONCURRENT ENGINEERING (ROLE OF PRODUCT PARAMETER DESIGN)



(1) Generic: i.e., maturation of the technology, not yet specific to any single product. Once the System Concept Development activity is started, the optimization activity usually starts concentrating on the specific product, often to answer specific questions from the system architects. Generic parameter design is often done by an upstream organization, with a name such as "advanced development".

(2) Voice of customer, system specifications, overall layout, selected subsystem (s/s) technologies, and s/s specifications.

(3) TT: Technology Transfer. Must have high confidence that s/s technology can be made robust in a manufacturable design on product schedule. TT is best achieved by the transfer of one or more "product engineering" people to work with one or more "advanced development" people. This team subsequently transfers into "product engineering", typically when (2) is completed. After the technology is transferred, the "advanced development" people usually cycle back.

(4) Completion of product* parameter design, with specific product constraints, which are increasing as the design proceeds. Starts with generic critical parameter drawing (output from (1)); ends with detailed critical parameter drawing.

(5) Design Competitive Benchmarking

(6) Design for Assembly; also must address Design for Maintainability.

(7) Material and Process Selection; for major parts.

(4)(5)(6)(7) Combination creates s/s design; provides specifications for detailed design.

(8) Design of part features on major parts, and design of small (often standard) parts. Close communication with (4) to assure that final design includes optimized values.

(9) Once MAPS is completed, tooling design can start. Tooling design should be completed when prototypes are finished (11); benefits from experience in building prototypes.

(10) Distribution, service procedures and tools, service documentation and training, spares plan, and operator training.

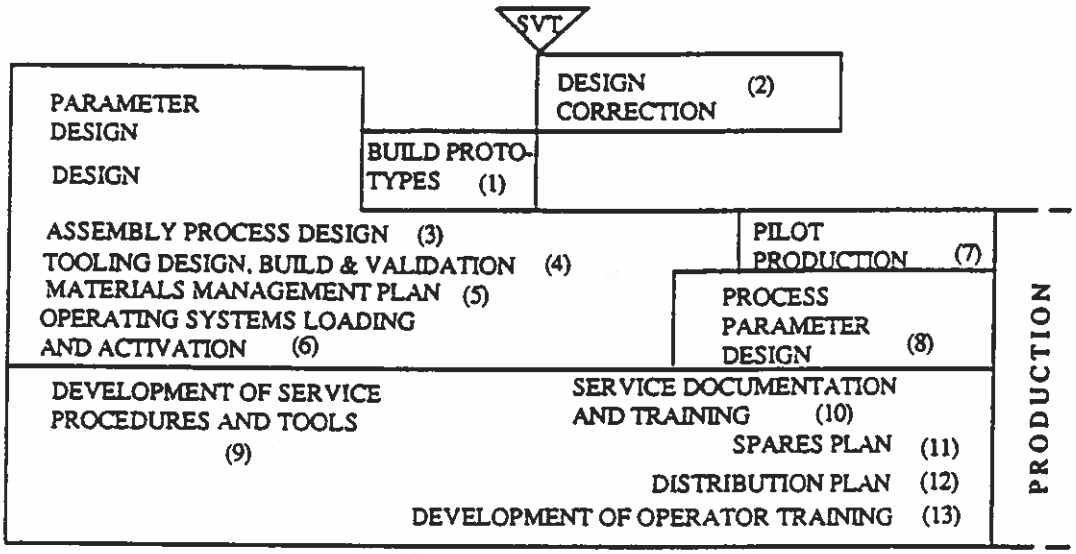
(11) Production-intent prototypes. As close to production conditions as possible; production tooling will not be available. Geometry should be identical with production parts, including variations.

(12) System Verification Test. After debugging and adjustment, some prototypes are tested for robustness; compared with competitive benchmark product. Verifies that superior robustness has been achieved.

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* Critical clean-sheet production processes are also optimized along with product. Other processes, whose feasibility is already certain, are optimized after production tooling is available.

CONCURRENT ENGINEERING
(PRODUCTION PREPARATION)



(1) These are the first production-intent prototypes. As close to production conditions as possible, but production tooling will not be available. Geometry should be identical with production parts, including variations. Chemical composition should be the same as in production, but the microstructure will often be different because of the lack of production tooling. The prototypes have three objectives: (a) learn about production, (b) verify robustness, and (c) eliminate design mistakes. Also may be used for development of service and operator training procedures. The incorporation of the lessons learned while building these initial prototypes completes the design.

(2) Elimination of design mistakes. Systematic cycle of Problem Identification Tests (PIT), Problem Solving Process (PSP), and corrections to the design. Much hardware will be changed in Fix Effectiveness Tests (part of PSP); often requires a second iteration of prototypes to avoid excessively reworked hardware. After robustness is verified in SVT, then design correction is relatively simple.

(3) Design of assembly steps and tools, layout of assembly area, and early tryout and debugging.

(4) Tooling design should be completed when the prototypes are finished (1). Tooling validation needs to be closely coordinated with Process Parameter Design (8). Ideally the critical parameters of the tool should be optimized along with the adjustable process parameters, such as speed. Validation may depend on the optimization of the process. The production tooling should be available for Pilot Production (7).

(5) Supplier selection, development, and contracting; ordering, including prototypes. Inventory and material flow plan.

(6) Loading with product data, and activation of all required operating systems for production and field operations.

(7) Initial production with production tooling and production assembly process. Used for verification of tooling and production processes, and for training of operating people.

(8) Optimization of robustness of important production processes, using production tools. (Clean-sheet processes, and any processes for which optimization may take longer or whose feasibility is suspect, should be optimized earlier.) Some optimization may be done as part of pilot production.

(9) Development of specific procedures for servicing product in field; also includes development of special service tools if required (should be avoided if possible).

(10) Development of documentation and training to enable required field maintenance.

(11) Quantity and storage sites for spare parts. Quantity is based on previous experience, modified somewhat by prototype results. System should be flexible; able to be quickly modified by field results with new product.

(12) Plan for distribution of new product; ordering process, storage sites, delivery and installation plans.

(13) Development of operator training; ideally self learning with aid of hard copy and/or display screen.

World-class Concurrent Engineering is typically practiced with some powerful tools. The appearance of these tools in the development process is shown in Figure 2.

OBSOLETE SERIAL DEVELOPMENT

Until recently, most product development in the United States was carried out as shown in Figure 3. The product was designed and then the activities to develop quality, production capability, and field-support capability occurred. The fundamental problems with this approach are now widely recognized, and it is often referred to in a derogatory manner as "throwing it over the wall". Each group of specialists does their work, and then throws it over the wall to the next group. There is much sub-optimization, loss of understanding, and late starts (waiting for the information to be thrown over the wall). The fundamental problems with this approach have been described by Mr. Lew Veraldi, Vice-President of the Ford Motor Company, who was the leader of the Team Taurus, that brought the Ford *Taurus* very successfully to market :

> Let me describe the traditional product development approach. You're familiar with the old organizational structure where design[2] engineers do their thing -- design then turn that over to the engineers. After the engineers do their job, Manufacturing is told to go mass produce the product and Marketing is then told to go sell it. That's an oversimplification, but it dramatically points out the flaws in the traditional system. What you have is each group of specialists operating in isolation of one another. Moreover, what someone designs and styles may be quite another matter to Engineering. And by the time it reaches Manufacturing, there may be some practical problems inherent in the design that make manufacturing a nightmare. The people who actually build the vehicle haven't been consulted at all. And, Marketing may well discover two or three reasons why the consumer doesn't like the product and it is too late to make any changes.

The sequential and segmented style arose in an environment in which product development was not considered as a process. Cloistered groups of specialists, looking inward within their own specialty, emphasized isolated tasks that were amenable to their specialized skills. Concurrent Engineering has evolved by thinking about the tasks as elements in an integrated process. The problems associated with the obsolete serial development programs have been summarized as the ten cash drains[3], Figure 4. The occurrence of the ten cash drains in the development process is shown in Figure 5. Concurrent Engineering must overcome the ten cash drains.

INTERMEDIATE CONCURRENT ENGINEERING

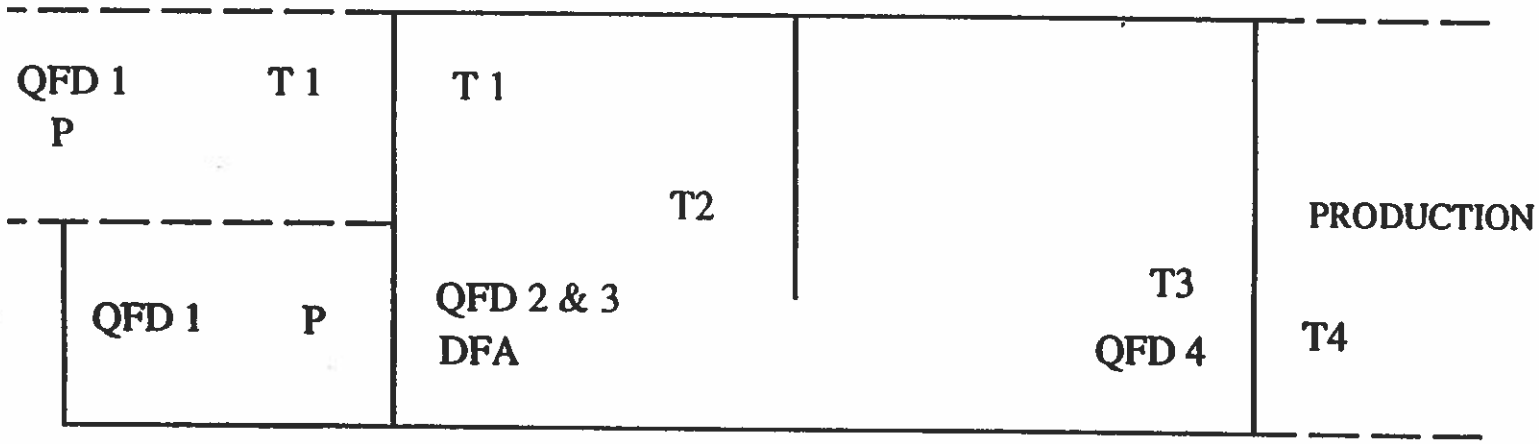
Ford and Xerox, leaders in the United States in Concurrent Engineering, are practicing an intermediate level of Concurrent Engineering, not quite World Class, but a vast improvement over the

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[2]"Design" in the automotive world means "styling".

[3]Don Clausing, "Improved Total Development Process, Overcoming the Ten Cash Drains", MIT Course Note, June 1986; also used in many industrial seminars.

CONCURRENT ENGINEERING TOOLS



DFA - Design for Assembly
QFD - Quality function deployment
T - Taguchi
P - Pugh (concept selection and static/dynamic status)

QFD 1	House of Quality
QFD 2	Parts deployment
QFD 3	Process deployment
QFD 4	Production planning
T1	Product parameter design
T2	Tolerance design
T3	Process parameter design (clean-sheet processes optimized at T1)
T4	On-line QC

FIGURE 2

PRODUCT DEVELOPMENT PROCESS

(SERIAL DEVELOPMENT)

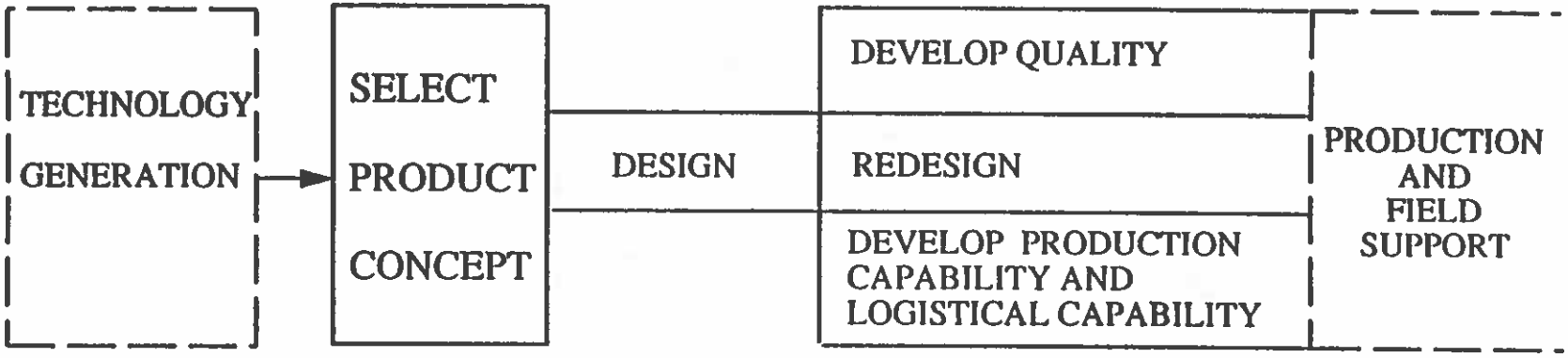


FIGURE 3

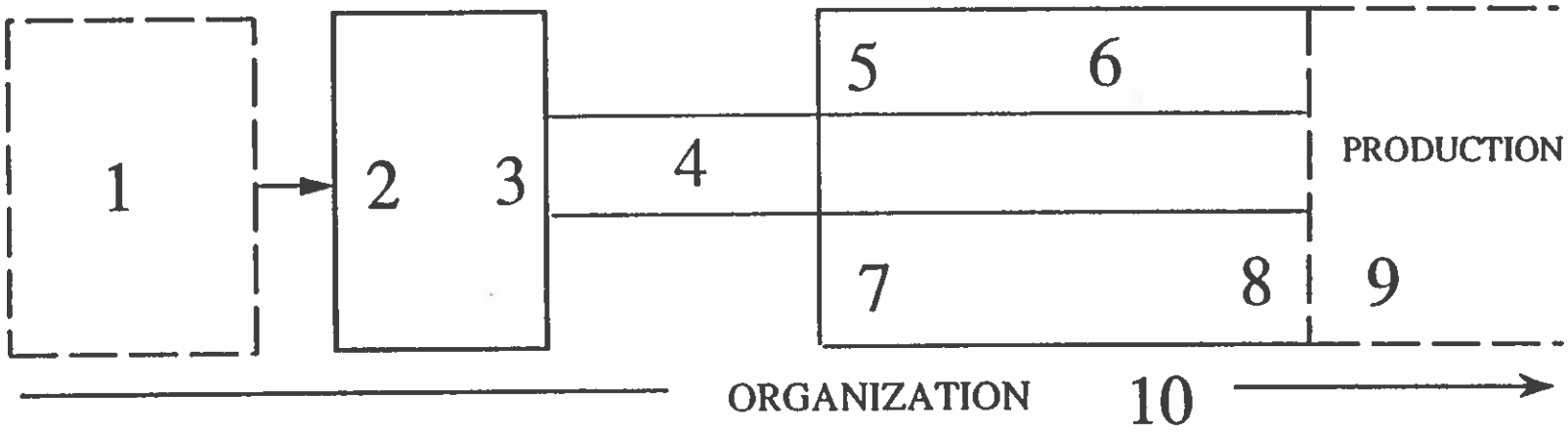
BENEFITS OF IMPROVED TOTAL DEVELOPMENT PROCESS

CASH DRAINS	OLD PROCESS	IMPROVED PROCESS
1. Technology Push, But Where's the Pull?	Concepts with No Needs, Needs With No Concept, Poor Technology Transfer	Technology Strategy and Technology Transfer Bring Right Technology to the Product
2. Disregard for Voice of the Customer	The Voice of the Engineer and Other Corporate Specialists Is Emphasized	House of Quality and All Steps of QFD Deploy the Voice of the Customer Throughout the Process
3. Eureka Concept	Mad Dash With Singular Concept, Usually Vulnerable	Pugh Process Converges on Consensus & Commitment to Invulnerable Concept
4. Pretend Designs	Initial Design Is Not Production Intent, and Emphasizes Newness Rather than Superior Design	Two-Step Design and Design Competitive Benchmarking Leads to Superior Design
5. Pampered Product	Make It Look Good for Demonstration	Taguchi Optimization Positions Product as Far as Possible Away From Potential Problems
6. Hardware Swamps	Large Number of Highly Overlapped Prototype Iterations Leaves Little Time for Improvement	Only Four Iterations (at most), Each Planned to Make Maximum Contribution to Optimization
7. Here's the Product; Where's the Factory?	Product is Developed, Then Factory Reacts to It	One Total Development Process, Product and Production Capability
8. We've Always Made It This Way	Old Process Parameters Used Repetitiously Without Improvement	Taguchi Process Parameter Design Improves Quality, Reduces Cycle Time
9. Inspection	Inspections Creates Scrap, Rework, Adjustment & Field Quality Loss	Taguchi's Optimal Checking & Adjusting Minimizes Costs of Inspection
10. Give Me My Targets; Let Me Do My Thing	Lack of Teamwork	Teamwork & Competitive Benchmarking Beat Contracts & Targets. Lead the Process, Don't Manage Problems

D.P. Clausing
86/07/08
89/09/11

FIGURE 4

TEN CASH DRAINS



1. Technology Push, But Where's the Pull?
2. Disregard for Voice of the Customer
3. Eureka Concept
4. Pretend Designs
5. Pampered Product
6. Hardware Swamps
7. Here's the Product; Where's the Factory?
8. We've Always Made It This Way
9. Inspection
10. Give Me My Targets; Let Me Do My Thing.

FIGURE 5

obsolete serial development. Ford and Xerox have concurrent development of product design, production capability, and field-support capability, all developed by a multifunctional team, Figure 6. This was a very strong factor enabling success in the development of the Ford *Taurus*. It has been the primary approach to the development of new copiers at Xerox since 1982. Again quoting from Lew Veraldi:

> So, in 1980, we had a recognized need and we had commitment. But something was lacking. When I headed up the Ford Fiesta Project in Europe in the early '70s, I found that getting the manufacturing and Engineering people together early in the program ultimately resulted in a better product. So, I expanded that concept in the Taurus project by bringing everyone in the program early under the Team Taurus banner.

The Team Taurus approach has been noted by Professor James Brian Quinn[4], of Dartmouth College:

> At the critical 1980 meeting senior management agreed to the creation of a management team, later known as Team Taurus, to implement the concept of concurrent rather that sequential car design and development. The program managment approach was to go even further than it had with the Fiesta project; representatives from all units -- planning, design, Engineering, manufacturing, marketing (etc.) -- would work together as a group and take final responsibility for the new vehicle. Veraldi even brought some team members over from Europe to help capture some of the luxury feel and nimble style of the European cars.

Xerox has also since 1982 used the multifunctional team under the direction of a Chief Engineer.

MANAGEMENT

Management must provide clarity and facilitate learning.

Clarity --Product Development Operations

- Reviews and Objectives
- Organization

Facilitate learning--Implementation and Promotion

- Implementation
- Promotion

Reviews and Objectives--A form of on-line quality control that uses checks (design reviews) to verify satisfactory performance is utilized to help the Product Development Team (PDT) to have clear objectives for the major phases of their developmental program. These occur in three major phases, each concluded by a major check (review):

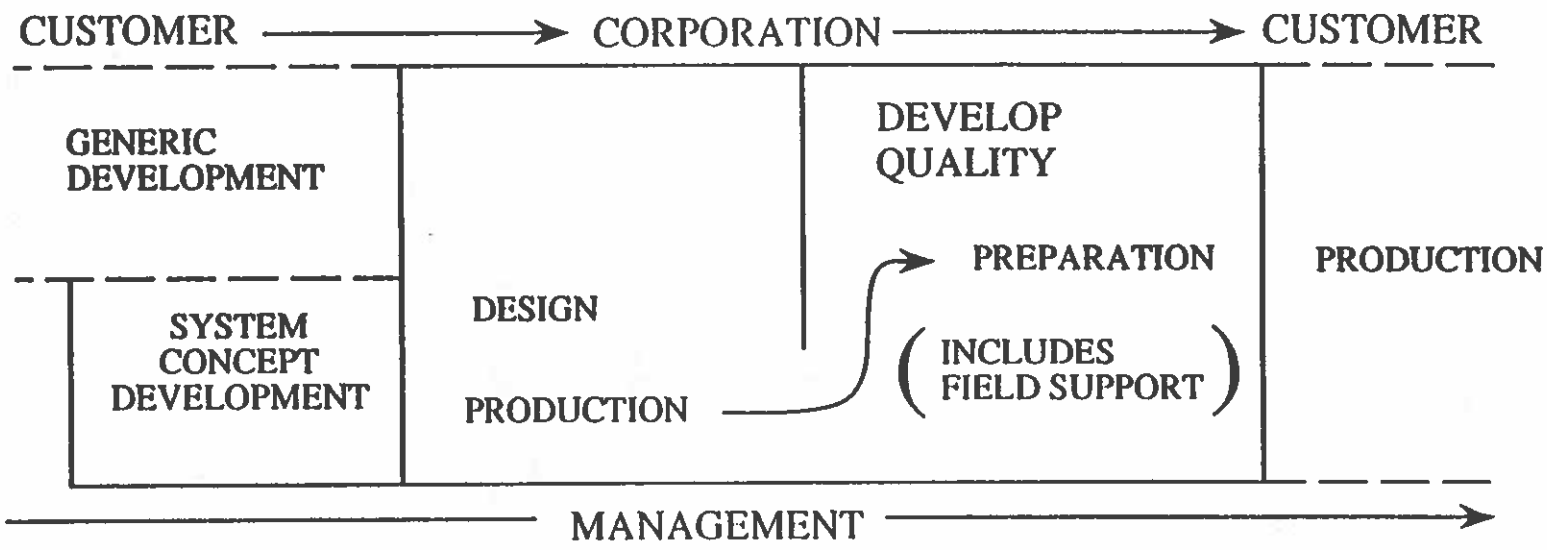
- Concept
- Design
- Production Preparation.

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[4]James Brian Quinn, "Ford: Team Taurus", Case Study, Dartmouth College.

CONCURRENT ENGINEERING

(INTERMEDIATE)



CONCURRENT DEVELOPMENT
WITH MULTIFUNCTIONAL TEAM:

1. PRODUCT DESIGN
2. PRODUCTION CAPABILITY
3. FIELD-SUPPORT CAPABILITY

FIGURE 6

The style of these reviews is critical for success. They should primarily be self-reviews by the PDT; an opportunity to take time out from the detailed daily pressures, raise up for a higher view so that they can see the forest, and assure that the desired progress has been achieved. All too often in the past these reviews have taken on the aura of an inquisition, with important "others" from outside the program coming to reviews with the attitude "I've got a secret that I'll bet you haven't thought of". The review should most emphatically not be an occasion for the revelation of previously closely-held information. Likewise, it is not an opportunity for executives to kick the tires and demand that the trim line be lowered 1/2 inch. Anyone who has information that might be helpful to the PDT should provide it at the beginning of the activity, or as soon as it becomes available, not saving it to spring on the PDT at a review. The review should largely be conducted by the PDT. It is often good to have an "outside" facilitator help organize and conduct the review. At least one executive should participate, with the authority to approve the funding for the next phase. Quality, cost, and product features should be emphasized, as well as the process that has been used. All functions of the corporation should participate, as an important objective is consensus throughout the corporation that the product will be a success.

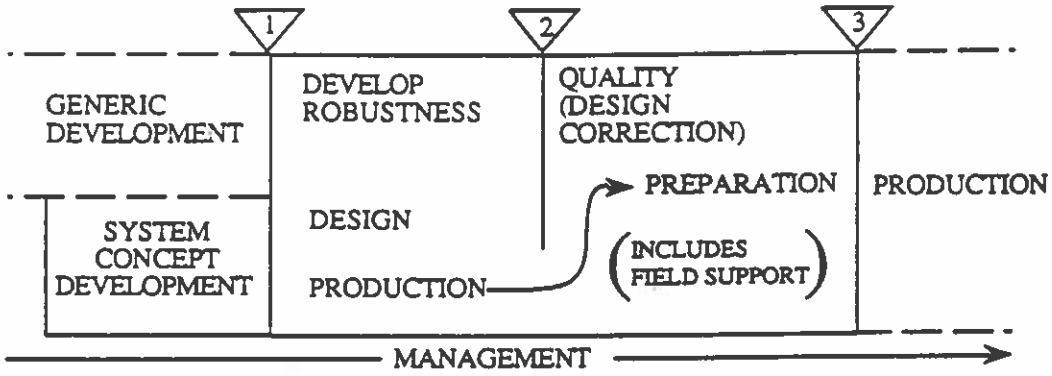
A very important effect of the reviews is to establish objectives for the work prior to the review. For example, the awareness that product robustness will be checked in the SVT, and the result will play a major role in the DESIGN REVIEW, strongly helps the PDT to understand that optimization of robustness is a high-priority activity.

The following page outlines the SUCCESS CRITERIA for the reviews. These must be developed in detail and thoroughly understood by the PDT to assure that the ten cash drains and other dysfunctions of obsolete serial development are avoided.

Organization--Concurrent Engineering is best carried out by a multifunctional product development team (PDT), led by a Chief Engineer. All functions of the corporation should participate. People who are doing significant work for the development program should be part of the PDT while they are doing this work. There is a vast psychological difference between doing a task within a support group and doing it as part of the PDT. As part of the PDT the contributor will (1) understand the specific requirements, (2) have the necessary close communications with other members of the PDT, and (3) be dedicated to the utilization of the task results to make design decisions. All three of these have a much lower probability of happening if the contributor remains within a support group.

It is important that the people from each function be able to (1) represent the knowledge of that function, and (2) gain the commitment of that function to the decisions that are made. Dysfunctions will occur if the information is not provided or is wrong, or if the function subsequently disowns the decisions and wants major changes. Some people will stay with the PDT throughout the development program, while others will only be on the team during the phase that requires their expertise. The important criterion is that there should not be any sudden changes in the composition or size of the PDT, as that would reduce teamwork and cause lack of continuity.

SUCCESS CRITERIA



1 CONCEPT REVIEW

1. Product concept is winner in systematic comparison over well-defined alternatives, is superior to competitive benchmarking (CBM) product(s) and is expected to meet specifications. Product has been located on static-dynamic scale, and the winning concept, the evaluation procedure, and the complete development plan are compatible with the product status. Product layout is complete, including macro styling. Technologies have been selected for all subsystems, compatible with corporate technology plan, and maturity has been demonstrated, including robustness. Technology Transfer (TT) is nominally complete, with remaining tasks clearly defined in a TT Plan.
2. Product expectation specifications are complete, and are the result of systematic, detailed deployment from the voice of the customer; includes micro market segmentation (customer orderable options), and enablement plan for product variants, compatible with corporate product strategy. Completed business plan, based on concept and specifications, satisfies corporate business strategy.
3. Plan for Product Parameter Design (optimization of critical design values) is complete, including identification of highly-critical design parameters.
4. Product Development Team (PDT) formed, with detailed plan for expansion. All functions of corporation have reached consensus on concept, specifications, and plans.

2 DESIGN REVIEW

5. Product has won System Verification Test (SVT), demonstrated superior robustness to CBM product(s).
6. Product design frozen, only subsequent changes will be to correct errors. Tool design complete. Production processes have been selected. Designs for dedicated machine tools are complete. Suppliers have contributed to designs, and have been selected. All problems that were encountered during prototype build have been identified, and corrective actions defined. Rigorous manufacturing cost estimate meets business plan requirement.
7. All corporate functions have reached consensus on probable success of product, and on plans for remainder of development. Final funding is approved.

3 PRODUCTION READINESS REVIEW

8. Pilot Production has been successfully completed. All problems have been identified, and corrective actions defined. Essentially all production tooling is available and verified. Critical process parameters have been optimized (Process Parameter Design). On-Line QC has been utilized during Pilot Production, and optimized values have been determined. Most processes have C_p greater than 1.0. Manufacturing costs satisfy business plan requirements.
9. Reliability growth curve has been achieved, and expected quality and reliability satisfy business plan. Launch Readiness Demonstration Test (LRDT) has been successful; data have been used to fine tune sales and service plans. Service documentation and spares are available in accordance with plan, and initial service and operator training have been successfully completed, with plans complete. Distribution plan is complete. All operating systems have been loaded and activated.
10. All corporate functions reach consensus that product will be successful, and that all plans are complete. Product launch is approved.

In World-class Concurrent Engineering the development is done by a multifunctional team. This leads to the consideration of an important organizational decision. There are three product activities within a manufacturing company, as displayed in Figure 7A. In the traditional organization, product development was an organization unto itself, and process development and production operations were organized together and usually called Manufacturing. This traditional organizational structure has two major problems. First, it tends to reinforce the serial approach to product development. Second, process development tends to become an orphan in the manufacturing organization, where nearly all of the emphasis is on production operations; shipping the product out the door. Often the product design engineers are not even aware that the process development Engineering organization exists somewhere deep within Manufacturing. An improvement is shown in Figure 7B; process development is integrated in the product development organization. The result is two organizations, development and production operations. This brings the process development people into a development organization where their developments of new processes are looked upon as a key element of developing new products, and the information is easily and directly integrated into the design activities. Xerox has gone a step further--apparently further that anyone else in the United States--and the pilot production for the new product is done as part of the product development process under the direction of the chief engineer who manages the multifunctional product development team. Of course, when pilot production is done, the appropriate production-operations people are temporarily assigned to the chief engineer's organization so that the required number of people and skills are available. This approach makes pilot production a key element of product development and centralizes responsibility with the chief engineer for managing the completion of product development, including the elimination of all problems before the product is turned over to production operations.
Implementation--Implementation of major improvements is a great challenge. The best scope to attempt is a critical decision. In any case, there will inevitable be resistance to change. Here we concentrate on two critcal questions about the style that should be used in implementing the major change.

Top down or bottom up?

Focus on content or organizational development?

The right answer, of course, is yes, we will utilize a little of each.

The questions can be diagrammed as a four quadrant plot, Figure 8. The four points can be further characterized:

Content focus--Favored by engineers

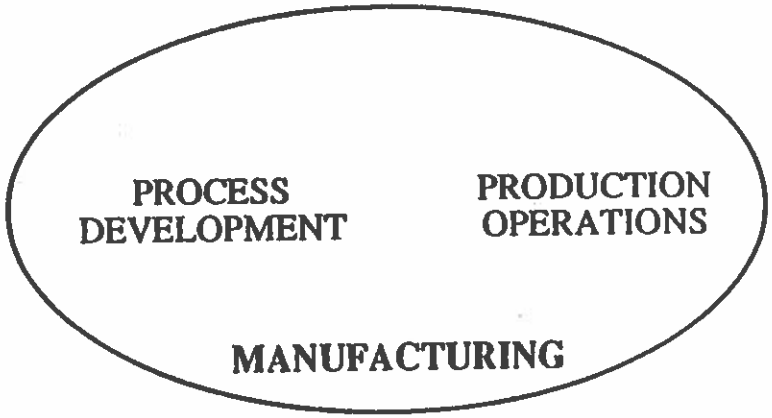
Top down--Dr. Deming's Lecture to executives

Organization focus--Rosabeth Kantor's writings

Bottom up--Quality circles.

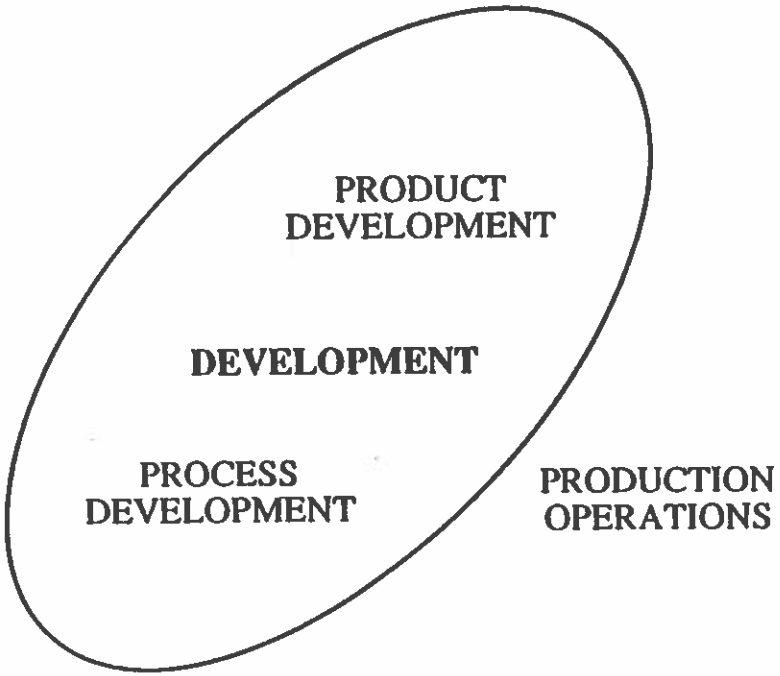
The characteristics of the four quadrants indicate that, if adhered to statically, none of them will bring success.

ORGANIZATION FOR PRODUCT WORK



SEGMENTAL DEVELOPMENT

FIGURE 7A

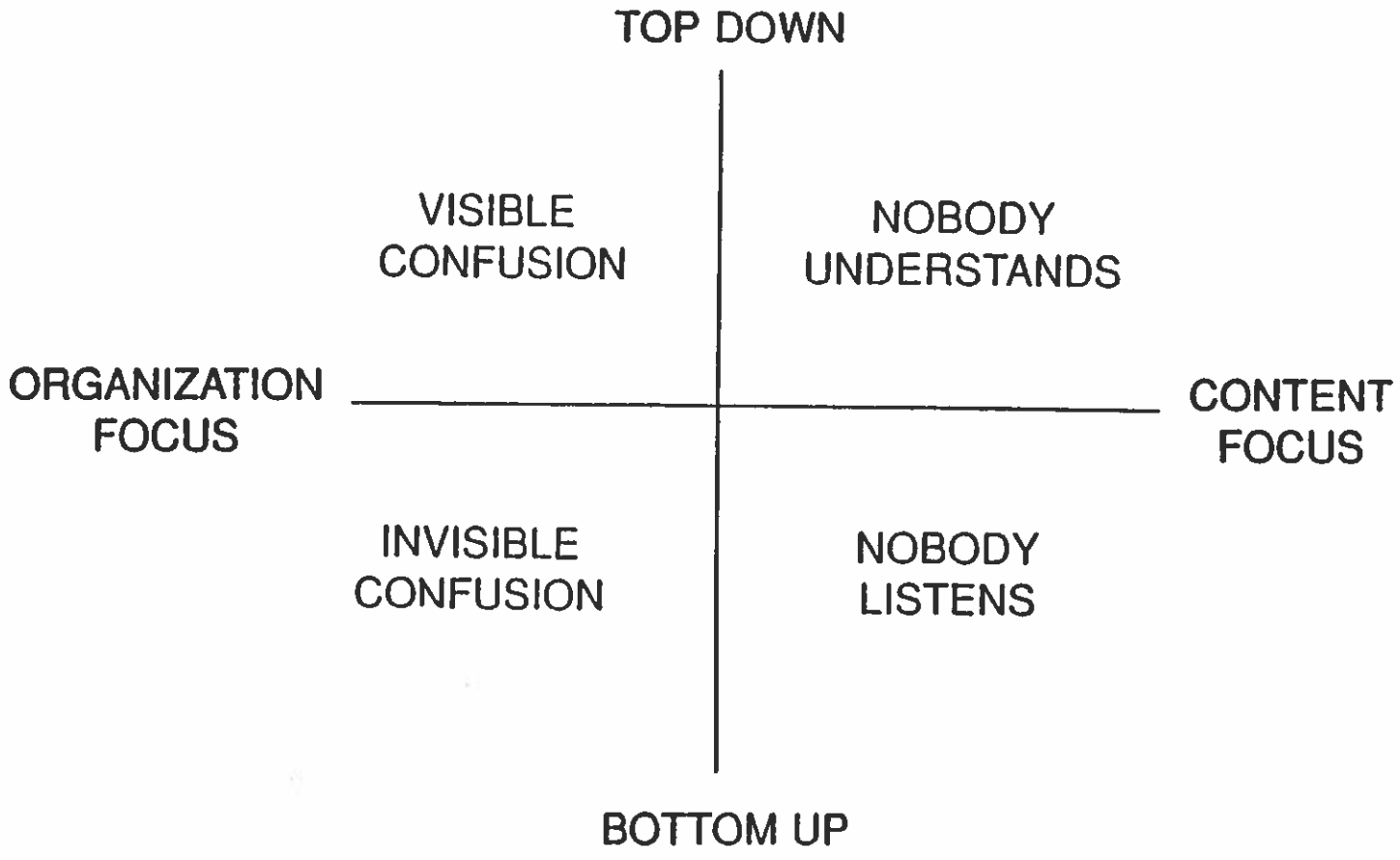


SIMULTANEOUS ENGINEERING

FIGURE 7B

IMPLEMENTATION STYLES

FOR MAJOR IMPROVEMENTS



CASTING WITH ONE ROD WILL FAIL

DPCLAUSING
88/10/11

FIGURE 8

1. Nobody understands: VP of design production issues a memo, "Reduce supplier base by 80%." Nothing is guaranteed to happen, because the initial, rational, and required processes are not understood.
2. Visible confusion: CEO says, "Let's all do Deming." Lower in the organization, no one knows how to translate Deming's philosophy into action, and confusion ensues, which is very visible because it was initiated by the CEO.
3. Invisible confusion: The people are energized by 29 interlocking committees and problem-solving activities, become very eager to do *it*, but have no idea what *it* is--no content focus. (This approach works on very local issues where the local group is the expert on the content.)
4. Nobody listens: A core group of gatekeepers learn *it*; the rest of the organization remains outside and suspicious, not very willing to listen.

It appears that the successful path is to start in the lower right quadrant with a core group. They will learn, bring in, and tailor the major improvement to the organization. Then move to the upper right quadrant, help upper management to learn and develop an implementation plan that addresses the organization. Next move to the upper left quadrant, organizational development, led by top management with clear understanding of the content. Next the implementation process moves to the lower left quadrant. Now implementation is deployed with the energizing benefits of organizational development and employee involvement, and the clear content further tailored to the context of the local work situation. Fine-tuning and enhancement may require another loop around the four quadrants. This process is arduous, but will bring success.

Promotion--Improved processes must be widely practiced and continuously improved to be effective. This requires explicit promotion, which is best done as Total Quality Management (TQM), also known as Total Quality Control (TQC) or Company Wide Quality Control (CWQC). Concurrent Engineering is best thought of as an important element of TQM, Figure 9. TQM will not be reviewed here. We note that a key element of TQM is Policy Deployment (policy management, *hoshin kanri*), which has the PDCA feedback control cycle as a key element. The three major reviews that have been described earlier can be thought of as important checks (C) for Concurrent Engineering.

To achieve a viably high rate of continuous improvement over the long term, it is probably necessary to have a central corporate (or major division) office that works full time to promote TQM, including Concurrent Engineering. Their prime task is to facilitate learning and maintain the corporate focus on continuous improvement.

TOTAL QUALITY MANAGEMENT (TQM)

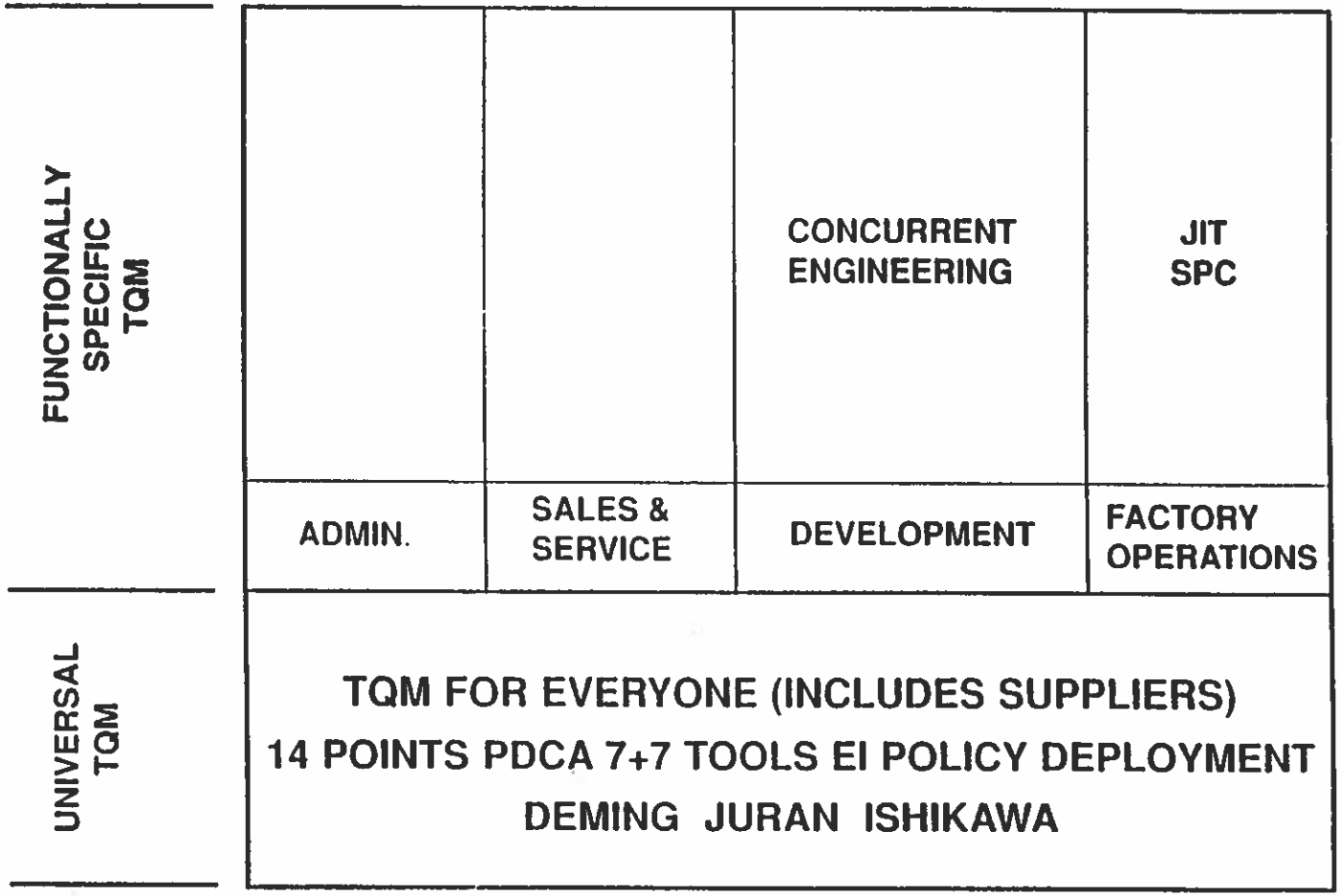


FIGURE 9

BENEFITS

The benefits of Concurrent Engineering are reduced costs, much better quality, and most importantly shorter time to market. Here we concentrate on development time.

The simple overlapping of activities, as displayed in Figure 1, will obviously help to reduce development time. When the selection of the system concept and the detailed design are carried out with best current practice, the time for completing these activities reasonably shortens. The time to get into production after the design is completed, as shown in Figure 1, is determined by the times required to develop quality and to develop the production capability. Further major reductions in development time require reducing the times required for both of these activities. The shortening of time for production-capability development is often referred to as the "time to obtain tooling". By tooling we mean holding fixtures that will hold parts on machine tools while they are being machined, dies, and other variable tooling that must be designed, built and debugged to enable the factory to make the new product. This tooling time has been rapidly reduced in Japan during the past two decades and must be even more rapidly reduced in the United States. This is largely a matter of Concurrent Engineering on a more microscopic scale, overlapping the different activities that are required to provide tooling, so as to shorten total schedule. This has been considered in some detail for dies that are used to stamp car panels in a working paper by Professor Clark and Mr. Fujimoto[5]. In the development of field-support capability, a similar Micro-Concurrent Engineering must be utilized for activities such as service documentation, service training, and spares management.

As the time for tooling and the development of other production capabilities yields to a relatively straightforward application of Micro-Concurrent Engineering, the remaining major requirement to shorten development times is a much more rapid development of quality. A fundamental problem occurs if robustness is not achieved concurrently with the design: the prototypes that are made from the design are not robust in their performance, and the temperamental performance causes chaos and confusion during the subsequent development of quality. In the best process, when robustness has been developed early concurrently with the design of the product, the only remaining activity after the design has been completed and robustness verified is to concentrate totally upon the elimination of mistakes from the design. There are literally millions of design decisions, and even those decisions where experience is sufficient will still have some mistakes, because even a very tiny error rate, applied to the huge number of decisions, will still result in hundreds of errors. These errors must then be rooted out systematically during the development of quality with the aid of the prototypes. This in itself is a relatively straightforward activity that does not take an excessive amount of time. However, when the product does not have robustness, its temperamental outbursts confuse development engineers by screening the mistakes, thus greatly extending the time that is required to

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5"Overlapping Problem-solving and Product Development", Kim B. Clark and Takahiro Fujimoto, Harvard Business School Working Paper 87-048, March 1987.

develop the quality to the point where the product can be put into production and then delivered to the marketplace. This is a very fundamental problem, especially because the approach for correcting mistakes differs greatly from the approach to achieve robustness. If robustness has not been achieved early, then the mistake correction process is fundamentally very weak in attempting to overcome the lack of robustness.

In summary, Concurrent Engineering is a key enabler for the reduction of development time. Current best U.S. practice must be rapidly enhanced by evolving better capabilities for tooling and for the development of quality.

CONCLUSION

Concurrent Engineering success stories have been found in companies whose product technologies range from mature to those recently emerged from the research laboratories. The products have included both simple piece-parts and highly complex, integrated systems.

The future is almost certain to bring rapid evolution in Concurrent Engineering, which will greatly reduce product development time, while improving quality and reducing costs. Developments that took five years before the decade of the 1980s may take one year by the year 2000. Concurrent Engineering and increased flexibility in the factory will enable a major increase in the variety of products that is available to consumers. Manufacturing companies must participate in the rapid evolution of Concurrent Engineering that will occur in the next decade if they wish to be internationally competitive. Consumer companies need to be at the forefront of Concurrent Engineering in order to compete successfully in the variety wars that will comprise the main competitive arena of the future. Defense contractors need Concurrent (Simultaneous) Engineering to provide quick response to the rapidly changing strategic and tactical situations, and to maintain secure defenses in a time of shrinking budgets.

ACKNOWLEDGEMENT

An earlier partial draft of this paper was contributed to by the members of the Concurrent Engineering Task Force of the Defense Manufacturing Board. However, they have not had an opportunity to review this paper, and any shortcomings are solely the responsibility of the author. The members of the the Concurrent Engineering Task Force areMr. William P. Brown, President, McDonnell Douglas Helicopter Co.; Dr. Charles Bernstein, Vice President for Analysis, Northrop Corporation; Mr. D. Travis Engen, President & CEO, ITT Defense Technology Corp.; Mr. Gordon England, Vice President for Engineering, General Dynamics Land Systems Division; Dr. Jacques Gansler, Senior Vice President and Director, The Analytic Sciences Corporation; Mr. Richard Godfrey, Vice President and General Manager, Avionics Manufacturing, TRW Electronics Systems Group; Dr. Robert E. Henderson, Director, South Carolina Research Authority; Dr. Norma Maine

Loeser, Professor of Business Administration, George Washington University; Mr. Frederick J. Michel, BDM International, Inc.; Dr. Robert Schell, COO, Hi-Shear Industries, Defense Systems Corporation; Mr. Russell Shorey, Consultant; Dr. Jerome A. Smith, Director of Research, Martin Marietta Corp.

APPENDIX H

Aeronautical Systems Division (USAF)
Integrated Product Development Process[1]

1. Introduction

By pursuing an approach to systems acquisition called "integrated product development", ASD seeks to increase the quality of our products and services, reduce costs, and decrease the time it takes to get new systems in the hands of Air Force operational users. The approach is based on a commitment to continuous improvement, the elimination of non-value-added work, and practical optimization of a system including its manufacturing and support processes. Such objectives are not new, but have too often been pursued in a piecemeal fashion by "stovepipe" organizations competing with one another for resources, top-management "emphasis" and recognition. This situation should be recognized as the traditional checks and balances approach. While sometimes achieving success in targeted areas, we have not fully realized the potential for improvement in performance, life and support characteristics, reduced life-cycle cost, and decreased development time. To achieve the efficient practical system optimization being sought, we must move beyond the constant inspection (checks and balances) process. We will now strive to achieve these objectives simultaneously by truly integrating the diverse specialty functions inherent in this complex business and the people associated with them into a unified development process. This approach reduces the emphasis on checks and balances while increasing emphasis on true teamwork.

Such an approach brings people representing different functions together at the beginning of development to work as equals in a climate of trust and ownership to incrementally refine the definition of the product and its manufacturing and support capabilities. Figure 1 depicts a functional architecture for this process. This process is to be governed by an enhanced product definition and control effort and an integrated product and process development effort. Each of these sub-processes are described in subsequent paragraphs. Their implementation will be enhanced in an integrated computer environment that permits the use of digital data, shared common data bases, 3D-solid

1. For further information, contact Aeronautical Systems Division/EN, ASD Integrated Product Development Critical Process Team, Attn: Mr. Vern Menker, Chair, Wright-Patterson AFB, OH 45433-6503.

INTEGRATED PRODUCT DEVELOPMENT PROCESS

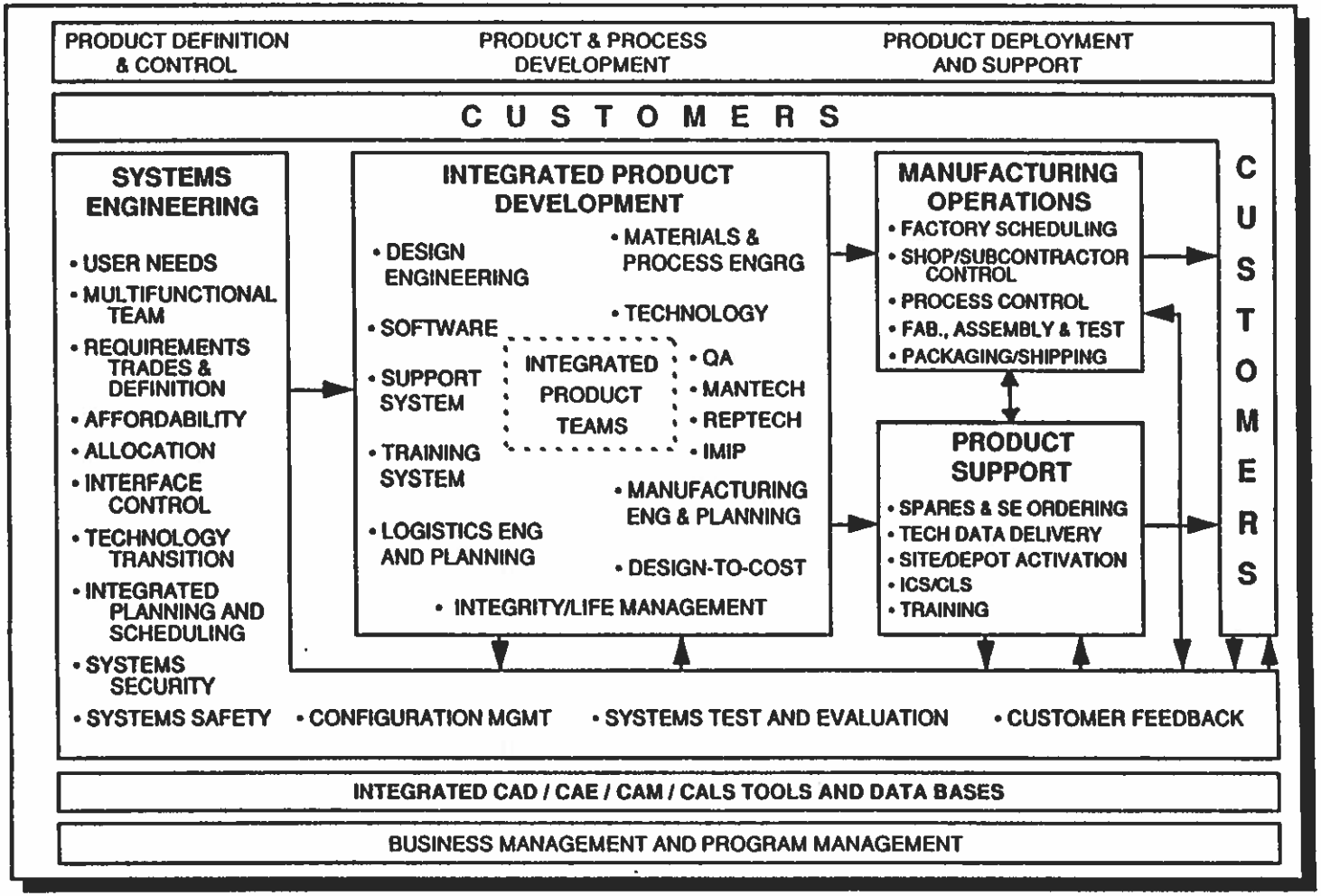


Figure 1

modeling, computerized mock-up equivalents, etc. to reduce design and fabrication times, promote product and process optimization, and improve the quality of product definition and support data which is inherently a more efficient and responsible process.

The integrated product development process is intended to facilitate the management of change and help the integrated product teams solve the customers' needs by recognizing that requirements, technologies and expertise co-evolve. Since customers often do not understand the subtleties of their needs and even more frequently the limits of technology, realistic product development becomes a problem-solving process among multiple customers and multiple functional experts working as a team.

In the past the developer viewed the customer as the primary supplier of the system needs and the systems engineering process provided the vehicle for translating these needs into a more formal set of requirements. Since end users frequently have only a vague idea of what they want at the beginning of the development process, end-user involvement throughout the process is crucial. Without their involvement, the delivered system may not be fully useful or the user may feel a lack of ownership. User needs analysis seems to be a conflict-based process in which significant negotiation takes place over the entire life cycle of a system. This occurs because there is usually not a single customer, but several classes of customers who may have conflicting needs (operator, maintainer, supporter, trainer) and the rate of relevant change in the customers' world clashed with the classical systems engineering paradigm. Keys to success for most development projects requires the recognition that requirements, technology and expertise co-evolve and the ability to balance and manage the issues in a changing contextual environment. The challenge is to meet the customers' needs for a wide range of customers with conflicting requirements, within budget and schedule constraints, and while planning for anticipated future growth through design flexibility.

2. Product Definition and Control

2.1 Systems Engineering in the Acquisition Process

The systems engineering process is used to analyze user mission and deployment needs and translate them into design requirements at successively lower levels. The need for mechanisms to control and manage the integration of the development of complex systems has long been recognized. The often elaborate system of contractually imposed checks and balances can even be viewed as a mechanism to manage development

integration. In the process shown in Figure 1, systems engineering encompasses a multitude of integrating mechanisms. Systems engineering in this case is not intended to be a "speciality" itself. Instead, it provides the framework to manage integration of the development of the product and its manufacturing and support processes. If increased product/process optimization is to be achieved, the integrating mechanisms included in the systems engineering framework must be carefully selected and they must form an integrated process that addresses all "critical" characteristics of the product and its associated manufacturing and support processes. This must be true from the beginning of a weapon system development, which implies a systems engineering process different than commonly observed in the past. It implies that even the very early systems engineering efforts must include all elements of the "team" e.g. cost, design, manufacturing, support, etc. It also implies that all members of the team must be working from a common baseline and that trade studies address all the critical product/process characteristics of the area being studied.

For these reasons, the systems engineering process will be accomplished by a multi-functional team during the early phases of the development cycle. The major product of this process are a set of integrated requirements, integrated specifications, interface control documents and integrated schedules and technical budgets. These products establish the "boundaries" for the efforts of "product" oriented integrated product teams. The systems engineering process will provide a set of integrating mechanisms for the entire acquisition process.

The industry's systems engineering activity during the concept exploration phase is translating system requirements into alternative design concepts, through functional analysis, synthesis, and trade-off analysis. This activity will be subject to careful up-front planning using the concept of the Systems Engineering Master Schedule (SEMS). For each segment of the design concept, allocated requirements, interface identifications, technology assessments, manufacturing feasibility and technical budgets are produced as systems engineering products. The industry output is reviewed by government program management for:

— Capability of the proposed system to meet the mission and deployment needs and program objectives, including resources required and risks associated with performance, technology, manufacturing and support.

— Benefits to be derived by trade-offs among technical performance, operational effectiveness and suitability (system effectiveness), deployability, manufacturability, supportability, life cycle cost (including support and operation), and

schedule (time to develop, manufacture, and field).

— Factory-wide manufacturing issues, such as overall tooling and facilities approach and new materials and material process requirements.

System descriptions and associated risk, cost, and development time estimates are used by the government to establish a systems requirements document. This document does not constitute selection of a specific design concept, but rather establishes system level operational performance requirements, employment and deployment environments and constraints and affordability constraints based on identification of feasible, affordable ranges of cost and system effectiveness. Proper identification is essential to an effective acquisition strategy since real competition requires a system requirements document which can be met by more than one design concept. The MIL-PRIME System specification is used by the government and contractor to mutually define, from a systems engineering perspective, the system level operational performance, capability, cost, functional and supportability requirements and the methods for their verification and validation. The results are documented in an offeror-unique system specification using the Air Force Guide Specification (AFGS-87253).

The objective in the Demonstration/Validation (D/V) phase is to identify and analyze major system alternatives, examine risky subsystems and manufacturing capabilities, and determine whether to proceed with Full Scale Development (FSD). D/V phase activities will be subject to careful up-front planning using the concept of the Systems Engineering Master Schedule (SEMS). The product of this phase is normally a set of firm and realistic subsystem/equipment development specifications that meets the operational, support, manufacturing capability, and cost requirements. These subsystem/equipment development specifications are developed using MIL-PRIME development specifications and the product integrity program guide specification (Aircraft Structural Integrity Program (ASIP), Engine Structural Integrity Program (ENSIP), Avionics/Electronics Integrity Program (AVIP), Mechanical Equipment and Subsystem Integrity Program (MECSIP) and Software Development Integrity Program (SDIP)). The MIL-PRIME development specifications contain a non-contractual handbook which provides rationale, guidance, lessons learned and instruments necessary to tailor the requirements and verification sections of the MIL-PRIME specification for a specific application.

As the systems engineering process progresses, required Configuration Items (CIs) are identified. The process includes trade-off analyses to ensure that the system will satisfy the development specification requirements with the best possible balance of

life-cycle cost (LCC), schedule, system effectiveness, manufacturability, and supportability.

Elements of the proposed system are continually assessed to identify areas of technical uncertainty that must be resolved in later program phases (risk assessment). Critical components, manufacturing processes, and support products will be rapidly prototyped to reduce risk. At the end of the D/V phase (or early on the FSD phase) the allocation of requirements to hardware CIs, data CIs, software CIs, personnel, training, support equipment, and facilities, are reviewed as an integral part of the specification approval. As such, the systems engineering process provides a technical management framework for the Integrated Product Teams.

The purpose of the Full Scale Development (FSD) phase is to provide the design documentation necessary to go to rate production and the Integrated Logistics Support (ILS) documentation necessary to field and fully support the system. This is done by completing detailed design, manufacturing and support process development, and demonstrating that all section three specification requirements have been met. The FSD design activity is based on development specifications and supporting in-process verifications using the Systems Engineering Master Schedule (SEMS). Risk is continually assessed using technical performance measurement process, SEMS success criteria, and cost schedule control system criteria. These activities are the primary responsibility of Integrated Product Teams.

After Integrated Product Teams are established, the systems engineering process focuses primarily on resolving interface compatibility problems and solving technical problems discovered during development testing, manufacturing process proofing and supportability verification that cut across team boundaries. Systems engineering ensures the auditing of Build-to-Package and Operation, Support and Maintenance Package documentation, auditing system test activities (test procedures, set-ups, and data), configuration control activities, ensures achievement of all systems level requirements including systems safety and systems security, and completion of the subsystem/system-level verification process.

The FSD phase provides verification of operational effectiveness and suitability before deployment by testing the system or equipment in its intended operational and support environment. The test results are evaluated in reviews and audits intended to confirm that the system design is sufficiently mature to proceed with production and support activities that initiate operational use. The output of FSD is a tested product and verified

manufacturing and support processes that meets contract requirements and the documentation necessary to enter the Production and the Operation and Support phases, including Build-to-Packages and Operation, Support and Maintenance Packages.

Integrated Product Development demands a team activity involving engineering, manufacturing, product support and customers (the user, the maintainer, the trainer and the program management offices). Achieving the required level of teamwork requires a structured process and competent people with specific expertise and understanding of the product line, users, technology base, materials, manufacturing capabilities, support capabilities and the acquisition process.

2.2 Translating User Needs and Establishing Integrated Requirements

To provide effective products to the users, the systems engineering process must first provide the framework for understanding the customer's real requirements and priorities. When resolving and placing priorities on requirements, the systems engineering process must also provide the framework for conducting and evaluating tradeoffs. There are an interminable number of questions that could be subject to tradeoffs. In the ideal environment, the needs of the customer are translated into increasingly more specific characteristics and features of the product. These, in turn, are related directly to the process operations and capabilities which affect those specific product features. In this way, the "voice of the customer" would remain consistent and be heard by all those defining the product and manufacturing and support processes, and at all stages of the design process.

Requirements must be translated concurrently and in an integrated fashion into optimal product definitions, manufacturing processes and support processes. The systems engineering process must encourage and, in fact, ensure that: (1) all requirements of the life cycle are considered and evaluated; (2) the cross-impact of various functional decisions are understood and evaluated with appropriate tradeoffs; (3) critical risks of various design options are identified and addressed early in the process; and (4) those responsible for the various functional areas participate with appropriate levels of responsibility and authority.

A major responsibility of systems engineering is to capture the "voice of the customer" in terms that an engineer and the integrated product team can understand. This is a necessary but difficult process. One formal technique for capturing the "voice of the customer" and mapping them into product and process parameters is called quality function

deployment (QFD). It consists of techniques for creating and completing a series of matrices showing the association between specific features of a product and needs representing the "voice of the customer." QFD uses teamwork, creative brainstorming and extensive customer dialogue to identify customer needs and design parameters. The correlation between the needs and the design parameters is ranked and normalized. Parameters of comparable systems/subsystems requirement are also identified and ranked. The top-down requirements definition process continues as functions, subassemblies, parts, failure modes, critical manufacturing steps, etc. are identified and traced to critical customer needs and comparable products (or predecessor systems). Matrices are a means of recording the information to show correlations. If the customers' needs are the rows of a matrix and product features are the columns, it is possible to show positive and negative correlations among the product features in a triangular table above the matrix. The triangular table above the matrix resembles a roof, hence the term "house of quality." This and similar techniques have been used with reported advantages of significantly reducing changes as a design enters production and decreasing the time needed to get a design into production.

2.3 Integrated Specifications

The "ilities" evolved in response to actual or perceived needs that once were not being addressed. As each "ility" matured, a separate terminology evolved and accepted analysis procedures became institutionalized. The need for proficiency in these procedures and terminology led to specialization. This, in turn, caused "stovepipe" functional activity by the contractors as well as the government.

Typically, an "ility" is institutionalized through a military standard and contractually implemented through assigned tasking in the statement of work (SOW) portion of the contract. It has an associated budget and requires delivery of a product, usually a report. The MIL-Standards on which the SOW tasking is based describe generalized procedures that are similar from "ility" to "ility" and often duplicative (e.g., four deliveries of Failure Modes, Effects and Criticality Analysis). The SOW tasking generates activity that is indirectly related to the derivation of essential product characteristics.

An alternative approach is to define the product characteristics that the "ility" seeks to influence and include them in the specification. The general rule should be that, if a characteristic is important, then it should be in the specification. To be in the specification, it must be quantifiable (stated in performance terms) and verifiable. This approach would ensure the appropriate top-down requirements process through the

specification tree.

The growing dependence on software in today's systems poses a unique challenge to the systems engineering process. One of the most significant problems in the software development process is the software requirements definition process and associated requirements change process. Development specifications should address the total system/equipment requirements including hardware and software and should be the responsibility on the integrated product team. Since software development has not been addressed from a total integrated product development perspective, software coding practices and standards have evolved by the various communities responsible for software development. For example, embedded software has been developed using higher order languages such as Ada; developmental test software has been developed using engineering language such as FORTRAN; factory test equipment has been developed using 10-12 different languages; support and test equipment has been developed using ATLAS; and training equipment has been developed independently often using a language that may or may not be the same as was used on the aircraft. This practice has hindered the reusability of software and has been a contributor to incompatibilities in testability and source of software error generation. The integrated product development process must also address these issues.

2.4 Performance Based Progress Criteria

The Systems Engineering Master Schedule (SEMS) approach provides a tailored work package of tasks, schedules, and success criteria for all of the essential product characteristics in each of the specifications that were negotiated between the program management office and the contractor. These packages provide the basis for developing program cost and schedules as well as performance-based progress criteria. The agendas of all technical reviews and contract progress payments should be based on performance-based progress criteria identified in the SEMS.

The mutually-defined, time-phased in-process verification actions contained in the Systems Engineering Master Schedule and the technical performance measurement process provide the means for risk management of contractor progress. Technical performance measurement assesses product design by estimating through engineering analysis and tests the values of essential specification parameters of the current design. It forecasts the values to be achieved through the planned technical program effort, measures differences between the achieved values and those allocated to the product element by the systems engineering process, and determines the impact of these differences on

system effectiveness, manufacturability and operational suitability. This process provides the necessary management tools to put discipline in the integrated product development process by establishing accountability and ensuring management involvement.

Key measures of success in implementing the integrated product development process that industry has found helpful are:

— Product Cost - Target cost versus current estimate

— Product Quality - Process performance index or first pass test yields (targets versus actual using a learning curve)

— Product Schedule - Total time versus planned time and schedule performance of successful completion of key tasks by major event milestones

— Implementation Costs

- Development hours (targets versus actuals or current estimates)
- Tooling costs (targets versus actuals or current estimates)

2.5 Integrated Planning and Scheduling

A fundamental change to the planning and scheduling process is an essential part of the integrated product development process. The current practice of maintaining separate plans and schedules for each discipline must be replaced by a single integrated schedule. This requires more than combining all existing functional schedules into a single document and cannot be achieved by an automated system. It requires a change to the scheduling process. Within an overall schedule tied to a capability need date or similar milestone, schedules should be event oriented using successful completion of development tasks and incremental release products. The System Engineering Master Schedules contained in the annex to the development specifications are key building blocks of the Integrated Master Schedule.

Integrated product development teams given responsibility for Development Specifications, Build-To-Packages, and Operation, Support and Maintenance Packages should be given responsibility for developing and maintaining an integrated schedule which is "owned" by all members of the team. Schedule milestones should be negotiated within the team and should be the basis for performance-based progress criteria and risk management. If milestones are missed, all disciplines should assume responsibility for determining work around plans and, if necessary, rescheduling of event milestones. The

focus of all members of the team must be on the timely completion of the specification verification tasks and the timely release of a quality Build-To-Package and Operation, Support and Maintenance Package. Historical engineering development times, manufacturing span times, and support development times should not be the driving consideration since they only serve to perpetuate the inefficiencies of the past. Instead, schedules should be created from a detailed understanding of the specification verification tasks, Build-To-Package content, and Operation, Support and Maintenance Package content together with the capability and capacity of the resources required.

2.6 Funding Profile Impacts on the Integrated Product Development Process

Money phasing is a critical element of integrated product development. Improperly phased money introduces major risks because it impacts the ability to keep the program in technical balance. Past experience has shown that scheduling of technical tasks and commitments to their accomplishment by key technical milestones has not been the basis for determining the funding profile as it needs to be. Significant program dollars could potentially be saved if the proper funding profile exists to execute a sound technical strategy that supports the objective of integrated product development. Funding must be made available for inclusion of all necessary disciplines early in the design process. This will change the traditional funding profile by greater up-front loading of costs. At the same time, experience shows that potential saving in development and life cycle costs more than offset the higher initial costs. The use of integrated specifications and the Systems Engineering Master Schedule is intended to provide a sound basis for developing technical budgets.

3. Integrated Product and Process Development

3.1 Integrated Product Development

Integrated product development shall be accomplished by integrated product teams responsible for accomplishing all activities necessary to develop and qualify a complete Build-To-Package and a complete Operation Support and Maintenance Package. This activity shall address as a minimum all the classical development activities such as those reflected in Figure 1.

Each integrated product team will function within the boundaries established by the systems engineering process.

Integrated product development requires that the engineering description of a part, assembly, etc., and the processes to build and support the product are defined simultaneously. This integrated product development process is based on an incremental product release process which ensures that all requirements are compatible by ensuring horizontal integration of all elements. Figure 2 shows an integrated product development process flow with incremental release products.

The development of layouts defining the product and the processes to produce and support it are fundamental to the integrated product development process. Attempts in the past to bypass or shortcut the layout development process have resulted in non-value added activity including redesign, poor quality, difficult to manufacture and support designs, and rework. The layout development process has two phases.

The first phase of the layout development process is the conceptual layout defining the design, manufacturing, tooling, and support concepts. Completion and release of conceptual layouts provide the basis for make/buy decisions, generating interface control documents, and achieving a multi-disciplinary consensus on the system configuration and operating and support concepts. In the traditional process, conceptual layouts may be created, but are not formally released.

The second phase of the layout development process is the creation of assembly layouts. These layouts define structural joints, manufacturing splices, tooling requirements and interfaces, and have structural sizing sufficient to proceed with detailed design. The structural and systems interfaces and manufacturability, assembly and supportability elements of the design will be validated using computer graphics. Assembly layouts are also formally released and subject to configuration control. The creation and release of assembly layouts is one of the major differences between the integrated product development process and traditional design practices.

In the next phase of the integrated product development process, detailed part and assembly Build-To-Packages are then released. These Build-To-Packages will contain all the information necessary for a manufacturer to build the required product. This will require improved communications between the developer of the product and its manufacturer. Verification, whether it be performance, fit, function, tool proofing, numerical control definition, etc., is an important ingredient of the package and will be subject to configuration control.

- The 3D/2D as designed/as planned data contains a complete geometric and potentially feature description of the product. The exact form of the 3D/2D

INTEGRATED PRODUCT DEVELOPMENT PROCESS FLOW

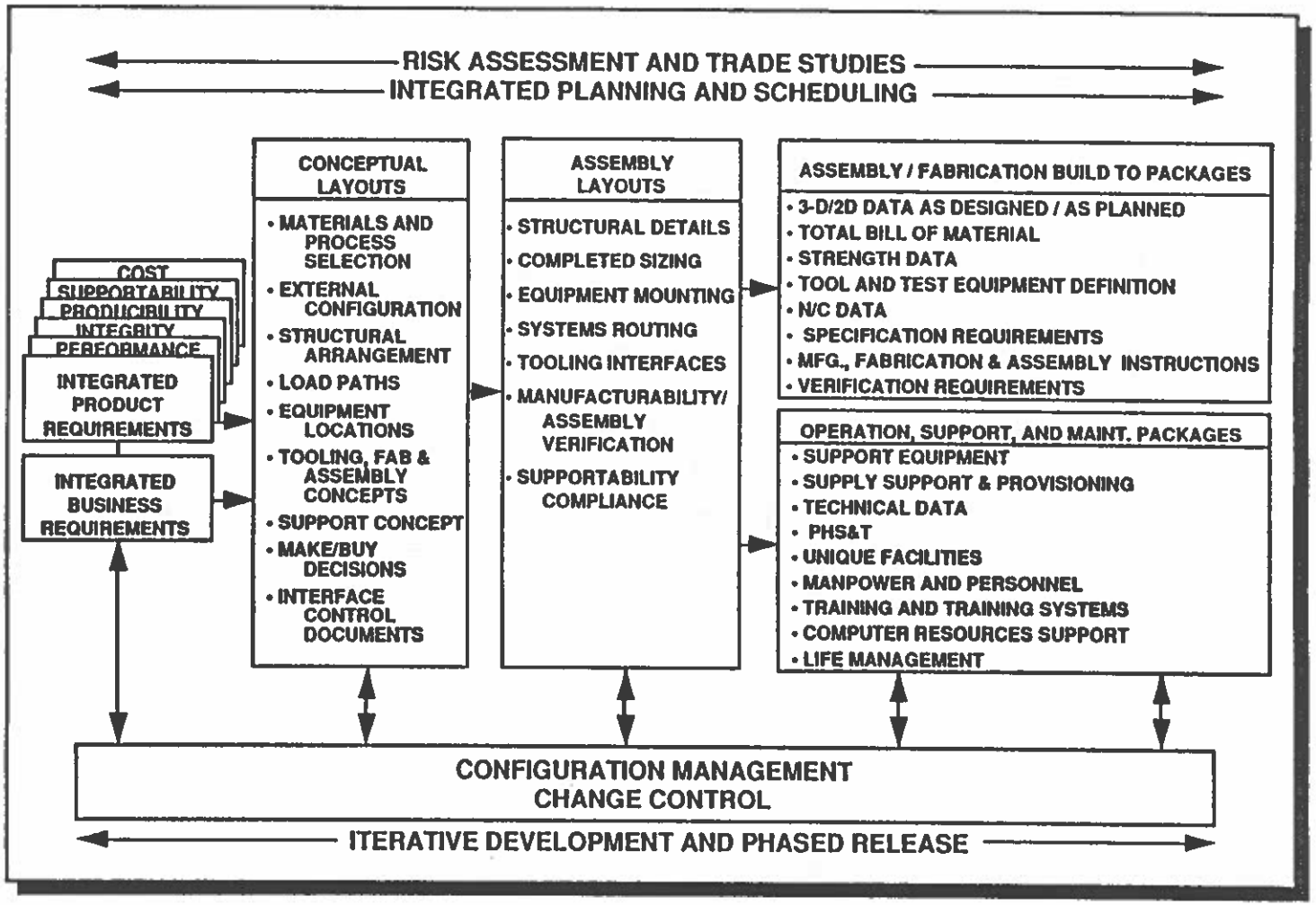


Figure 2

description is flexible and can over time adapt to anticipated changes in computer graphics technology including solids and feature based modeling. Traditionally as-designed data was created by engineers and as-planned data was created by production planners. Under the integrated product development process, both must work together to create the complete product description.

- The Total Bill of Material will provide the manufacturer with a single internally consistent source of needed data. It combines the engineering bill of material and the manufacturing bill of material thus eliminating the lack of integration between these bill of materials which often resulted in inconsistencies and inaccuracies especially when changes occur. As-built and as-supported information can be combined with the as-designed and as-planned data into a total bill-of-material for each part/assembly.

- Strength data captures the design loads information and documents the critical features of the product from a strength point of view and captures all the design margins. Weight data is included for tracking actual weight performance by the manufacturing shop. The exact form of the data should be flexible and determined to a large extent by the program. The key is to achieve greater discipline in the process by bringing the loads and strength data under configuration management rules and creating a common data base for product developers and follow-on repair and engineering change activities.

- Tool and test equipment definition data is essentially a Build-To-Package for the tools and test equipment required to build the detailed part or assembly covered by the overall Build-To-Package. It includes 3D/2D data, tool order, and tool and test equipment usage information. Information required to initiate long lead tool design, fabrication, and procurement efforts (e.g., loft surfaces, tool datum planes, forging specifications) will be incrementally released. Scheduling of these incremental releases will be contained in the integrated planning and scheduling process.

- Numerical Control Data provides a good description of a product from a manufacturers point of view. This data is provided for machining parts, routing sheet metal parts, cutting composite plies and for tooling. Traditionally, numerical control programming has been done by the manufacturing organization based on data provided by Design and Planning. Under the integrated product development process, this activity will be accomplished as an integral part of the Build-To-Package and tailored to the needs of the manufacturer whether it be in-house or subcontracted.

- Specification requirements contain the product specifications, (hardware and software) the verification/test procedures and verification results. For example, it will contain specifications and test instructions to validate proper operation of hydraulics, fuel, and electrical subsystems as assembled in a major component. For individual pieces of equipment, the specification requirements would typically include the procurement specification and all qualification test results.

- Manufacturing, fabrication and assembly instructions will contain all the information required to build the part or assembly. It will contain any necessary visual aids, a complete work order and non-conformance disposition rules and data. Process instructions will contain all the information contained in process specification such as finish requirements, marking, labeling, packaging, handling, storage, and shipping requirements, Non-Destructive Inspection requirements, heat treatment, etc., which apply to the part or assembly. This should be a stand-alone document for the manufacturer and should not refer to any information beyond the Build-To-Package. The packaging, handling, storage, and shipping requirements shall be developed concurrently with PHS&T requirements for follow-on support to insure compatibility. The work order will contain the stock requirements, operations sequence planning, tool requirements, industrial engineering targets, etc. Manufacturing, fabrication and assembly instructions have traditionally been generated after the product definition was released. Under the integrated product development process they are integrated into the Build-To-Package and early estimates of this information is used to generate the Build-To-Package release schedule.

- Verification Requirements provide the means for clearly communicating the important factors for fabrication of the part/assembly from the integrated product team to the manufacturer. Any special fit, form, function, and verification requirements identified by the verification compliance planning information developed by the integrated design activity will be included.

The last phase of the integrated product development process is the creation of the operations, support, and maintenance package. To the extent practical the support data will utilize the data from the integrated development process and the Build-To-Packages to develop the Logistics Support Analysis Record and the provisions for life management developed by the integrated design activity. The Operations, Support and Maintenance Package should be developed in parallel with the Build-To-Package to capitalize on the synergistic effects. Substantial benefits should be achieved in the areas of spares definition, diagnostics, support and test equipment, technical data, training, software

support, etc. The integrated product development shall accomplish all the planning processes necessary for Manufacturing Operations and Product Support to accomplish the Product Deployment and Support functions as shown in Figure 1.

3.2 Integrated Design

Mutual agreement must be reached on the general nature of development processes if some of the guidance and constraints within the traditional military standards are to be subject to tailoring and streamlining. This agreement should focus on an integrated design process emphasizing time-phased sequence of tasks, mutual understanding and discipline. Guidance for implementing this process is as follows:

- Service life in years; design usage in terms of aircraft/platforms, mission profiles, mission mix; total operating hours in the air/on the ground; and the number/type of operating cycles for in-flight operations, ground operations, off vehicle (intermediate and depot shops) will be specified. This information will be established through close coordination between the program offices, the user(s), and the contractor. It will then be used by the contractor to establish the design criteria to be documented in the integrity program documentation that will be used to verify compliance with requirements.

- Required environments will be established and used to verify functional performance throughout the environmental range.

- Characteristics of material to be used in the design will be defined and worst case material characteristics that will be allowed to pass through the manufacturing and/or maintenance processes and/or process control/inspection process. Process capabilities and process control requirements will be established using process capability studies, process modeling/analysis, parameter design and tolerance design techniques, as appropriate.

- Design criteria and design margins will be established that provide sufficient design margins to achieve an acceptable design service life and stable manufacturing processes, compatible with the design requirements and margins to control scrap and rework. Design criteria will also be established for assembly, testability and for maintainability to include manpower, skill levels, repair times and repair tools/equipment.

- Manufacturing feasibility, producibility analyses, and repairability analyses will identify the most economical means of production through individual or collective consideration of design criteria, materials selection, manufacturing techniques or

processes, and repair techniques or processes. Manufacturing and repair technology requirements will be identified.

- Components that meet the required service life and life limited items/components will be identified.
- Preliminary analysis of the design will be complete prior to Conceptual Layout Release and formal analyses will be performed prior to Assembly Layout Release on components of the system to evaluate their initial and residual strength, life requirements, and maintainability requirements.
- Testing of materials, parts, and components will be performed to the design usage spectrum to simulate usage environment, to verify life analysis procedures, to verify allowable stress and strain levels, materials selection, etc., and to develop guidance for truncating durability testing.
- Damage tolerance and durability control planning will identify and define all of the tasks necessary to ensure compliance with damage tolerance and durability requirements. This will include corrosion prevention and control, environmental protection, materials selection and materials procurement specification requirements, manufacturing process specification requirements, critical design drawing information, and incremental verification of subsystem and equipment maintainability requirements.
- One lifetime of durability testing will be completed prior to the Build-To-Package Release. This will be supported by ground test and flight survey data, as appropriate. Two lifetimes of durability testing plus a close visual inspection will be completed prior to the full rate production decision. If the economic life is reached prior to two lifetimes, testing will end and an analysis will be required to determine if production changes are required. Durability testing including development testing and qualification testing will be performed on development units that are representative of the production configuration. It will be performed on the full subsystem or on major assemblies as approved by the program office. All inspection/diagnostic procedures and intervals used on the durability test article(s) will be the same as those scheduled for operational use.
- Damage tolerance testing will demonstrate compliance with the damage tolerance design requirements for one design service life or the maintenance/failure-free operating period prior to the Build-To-Package Release. Damage tolerance testing will be flexible and tailored to specific systems. The size of the test program will depend on the number of assemblies in the test, extent of verification

obtained during durability testing, and the extent of previous component tests. Detailed test requirements (type of tests, quantity, choice of specimens, damage/fault locations, etc.) will be established by the contractor and approved by the program office. Corrective actions (e.g., design changes, special inspections or process changes) will be required for deficiencies disclosed during these tests.

- Durability/damage tolerance test results along with a hardware quality audit and failure analyses/fracto-graphic examinations will be used to demonstrate that requirements are met or the impacts resulting from deficiencies are quantified to support program decisions. A hardware quality audit and failure analyses/fractographic examination will be performed upon completion of the durability/damage tolerance testing for the purpose of locating critical areas not previously identified; verifying life (age) limits; assessing the adequacy of inspection/diagnostic procedures and intervals; and assessing the initial quality of the equipment. The scope of the inspection, the specific inspection procedures used, and the extent of the detailed examinations will be tailored for each program.

- Manufacturing processes will be verified before the Build-to-Package Release and validated no later than low rate initial production to confirm the adequacy of the production planning, tool design, assembly procedures, work motivations, training procedures, etc. Manufacturing process verification and validation will be done at the prime contractors, subcontractors, and key suppliers. Rapid prototyping and computer-aided visualization techniques such as animation, simulation, and rendering systems may be used to support the verification process.

- Failure investigations/analyses will be performed during design, development, qualification, and production to ensure timely identification of root causes and corrective actions, and an assessment of the effectiveness of the implemented corrective actions.

- Verification compliance planning will be completed and verified prior to Build-To-Package Release, validated during Low Rate Initial Production (LRIP), and fully implemented during full rate production. This planning will include manufacturing process controls and/or inspection requirements derived from the design criteria. Process control requirements will be established for each level of assembly (statistical process controls, adaptive machine controls, environmental stress screening, non-destructive procedures, automated inspections, etc.) based on material characterization, manufacturing processes and strength/durability requirements. The planning information will also cover the failure

reporting/feedback process including physics of failure analysis and disposition criteria for non-conforming material based on their effect on functional performance and life. Material management of critical, controlled or strategic material will be included.

- Subsystem and equipment level maintainability analyses will be completed prior to Build-To-Package Release. Incremental maintainability verifications will be completed on developmental items from components to configuration items and formal maintainability demonstrations will be completed prior to the LRIP go-ahead decision. Maintainability demonstrations will be conducted in an environment which simulates, as closely as practicable, the operational and maintenance environment planned for the item. This environment will be representative of the installation conditions, working conditions, tools, support equipment, spares, facilities, and technical publications that would be required during operational service at the defined maintenance level and will be accomplished by personnel of the equivalent skill level having received the specified training.

- Provisions for life management will be completed prior to the LRIP go-ahead decision, verified prior to completion of Initial Operational Test and Evaluation (IOT&E), and implemented on all fielded equipment. Life management provisions will include the expected break rates for the equipment, the time phased maintenance tasks for preventive/schedule maintenance, maintenance process controls/inspection requirements, the expected fix rates for the equipment, the process and monitoring devices for monitoring field usage and installed environments, a methodology for modifying break rate prediction, maintenance tasks based on changes in operational usage and installed environments, and provisions for updating the Logistics Support Analysis Record. Life management data will provide a continual assessment of the in-service integrity of the equipment; provide a basis for determining logistics and force planning requirements; and provide a basis to improve design criteria and methods of design, evaluation, and substantiation for future systems/equipments.

The above process constitutes a generic description of an integrated design process that is responsive to the objectives of integrated product and process development. Many of the elements of this process are already addressed in the product integrity programs.

3.3 Integrated Technical Reviews

Technical reviews are an integral and essential part of the integrated product development process. Technical reviews can range from very formal reviews to very informal technical reviews concerned with product and/or verification elements of the development specification that involve only a few government and contractor personnel. All reviews share the common objective of determining the technical adequacy of the existing product and process design to meet requirements.

As the acquisition program moves through the life cycle, the reviews become more detailed and definitive. Technical reviews consider all aspects of the product and process design that are relevant to the progress of a particular design phase. While contracts usually require formal technical reviews, they have in the past often lacked specific direction and discipline, resulting in an unstructured review process that fails to fulfill either of the two main purposes of the technical review, which are: (1) to bring to bear additional knowledge to the integrated product and process development process to augment the basic program design and analytical activity; and (2) to challenge the satisfactory accomplishment of specified design and verification tasks needed for approval to proceed with the next step in the acquisition process.

The SEMS and Technical Performance Measurement process are key to a structured review process. Formal reviews should be part of the process for approval of key technical data created in the integrated product development process. This key technical data is the system specification, development specifications, interface control documents, conceptual layouts, assembly layouts, build-to-packages and operation, support and maintenance packages. Approval of this incrementally developed technical data establishes the baseline for configuration management. The technical review and audit process culminates with the validation of the Build-To-Packages and the Operation, Support and Maintenance Package with the as-built/produced products and DT&E/IOTIE & Factory Tests. (See Figure 3.)

The integrated product development process requires control of product and process configuration at all levels, not just for drawings as it is done today. Increased interactions of many disciplines with the product definition and product and process development activities contributes to this need. Product data must be managed to ensure all personnel are working with the latest data.

INTEGRATED TECHNICAL REVIEWS & AUDITS

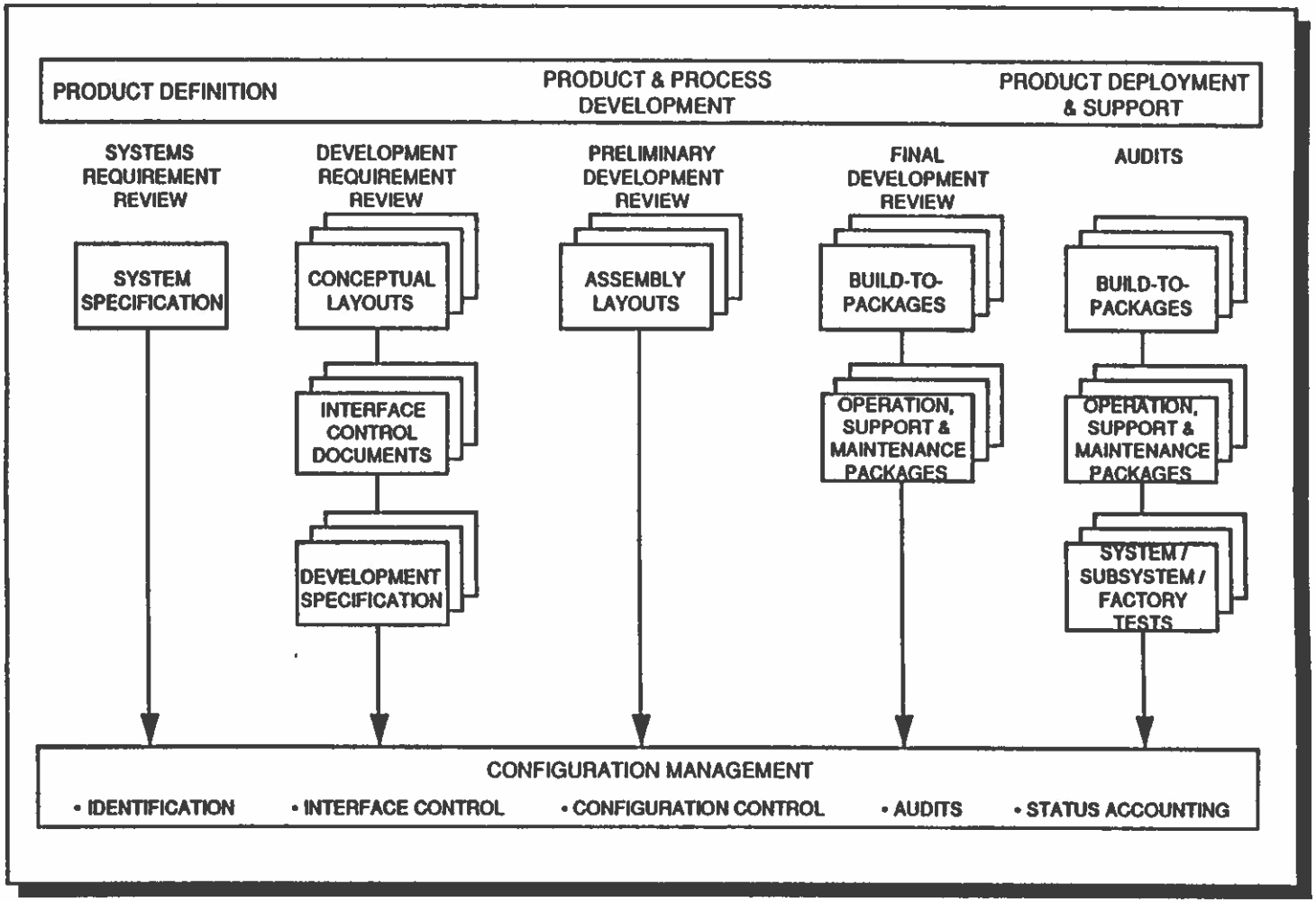


Figure 3

Current configuration management systems use cumbersome procedural methods. Providing enhanced access to product definition data brings the responsibility to be able to find data and manage that data. The system must provide the capability for versioning data at the part level as well as capture specific part or subcomponent attributes. Support for data sharing, which includes the means for change notification to inform users of data when revisions are made is also required. The system must provide the capability to use digital data. It must also support the review and revision process.

APPENDIX I

Acquisition Process Expectations

This appendix describes what should be seen — expected as products — at various phases of acquisition programs that implement simultaneous, integrated product/process engineering. The phases of programs in today's DoD acquisition process are: concept definition; concept demonstration/validation; full scale development; and production (generally in two steps, low rate and full rate). The expectations resulting from activities in these phases will vary substantially when simultaneous product/process engineering is employed in contrast to the sequential engineering approach now in use. Overall, the system to be produced will be defined sooner, the manufacturing costs will be lower and the system will enter production quicker and with less problems. The remainder of this appendix will address expectations by program phase. It should be noted that the program phases are not rigid and there is substantial room to restructure as discussed in the Recommended DoD Actions section of this report.

Concept Definition In the concept definition phase, the system approach and associated cost and performance goals are selected. Competitive benchmarking of comparable Defense and commercial processes should be used to help in deciding on the goals and identifying feasibility issues. *Manufacturing and logistics process requirements should become an important consideration during the concept definition phase.* Under the existing sequential process, the principal activities focus on identification of product performance requirements, and validation of these requirements through a Cost and Operational Effectiveness Analysis (COEA).

Concept Demonstration/Validation *During the concept demonstration/validation phase, the manufacturing, operation, and logistics processes should be defined and feasibility issues should be resolved at the same time the product is defined.* New technologies and process capability indexes should be identified and robust product quality will be taken into account as product design decisions are made. If unusual manufacturing, logistics or training technologies are to be used, they should also be evaluated for both feasibility and cost consequences as final product and process design decisions are made. In today's sequential process, the feasibility of achieving performance objectives is demonstrated using brassboard models built without adequate regard to manufacturability and support feasibility.

Implementing simultaneous product/process engineering in this phase implies a level of activity and expenditure greater than in the comparable phase under the sequential process. The payoff for the increased activity is that remaining phases leading to production will be substantially shorter, the production risks lower, and the production costs better defined.

Full Scale Development During the full scale development phase, a "production-intent" system should be delivered. It should be built in as close to production conditions as possible. Equipment field repair procedures and tools should be developed. *The "production-intent" system is tested to begin validating that the planned production processes, even with whatever uncontrollable variations might exist taken into account, will produce systems with the desired characteristics.* All feasibility issues associated with manufacturing and logistics to achieve performance and cost goals have been resolved. In contrast, in the sequential process, the emphasis is on verifying performance using a full scale development model.

Low Rate Initial Production In the low rate production phase, the initial production activities should confirm that manufacturing processes can achieve full rate *with expected quality*. The robustness of the design and manufacturing process is demonstrated. Design maturity should have been achieved, *driving the need for engineering changes down* (ideally to zero). Planned reliability targets should have been achieved, production tooling should be in place, field equipment repair documentation and tools should be available, and operators should have been trained. The sequential process usually involves performance testing with design changes for producibility and reliability testing that will not be completed until well into full rate production.[1]

Full Rate Production During the full rate production phase, the production activities transition to a mode of continuous improvement. Statistical feedback on manufacturing processes are gathered and organized for use by designers and by production operations. In contrast, the sequential process is only now achieving reliability goals, the field repair capability is verified, and the manufacturing process is finally verified. These sequential process events occur when it is very expensive to correct problems that surface.

In summary, the application of concurrent engineering to the acquisition process

1. This statement of ideals does not imply that sound engineering judgement can be systematically eliminated. For example, there are times when initial production should be entered when subsystems that are not critical to the essential function of the system are not yet ready (perhaps, because of a change in threat). In that case, there is a *planned* necessity for non-critical engineering change.

results in lower engineering change activity and a much more stable design during the production phase. Table 1 lists key expectations by program phase resulting from the application of concurrent engineering.

Table 1

NOTIONAL EXPECTATIONS
SEQUENTIAL ENGINEERING (TODAY'S) VS.
CONCURRENT ENGINEERING (PROPOSED)

	SEQUENTIAL ENGINEERING	CONCURRENT ENGINEERING
CONCEPT DEFINITION	- "Initial" system performance objectives established - Cost objective established	- Initial performance objectives established - Cost objective established - Manufacturing/logistics competitive benchmarking
DEMONSTRATION/ VALIDATION	- Performance specification finalized	- Performance objectives validated - Manufacturing feasibility issues resolved -"Build to" packages initiated
FULL SCALE DEVELOPMENT	- Design specifications finalized - Engineering prototype built - Initial performance testing	- Production intent prototype built - Performance tested/verified - "Build to" packages delivered - Manufacturing process in place
LOW RATE INITIAL PROD	- Performance tested/verified -"Build to" package delivered	- Manufacturing process and tech data verified - Reliability growth curve achieved - Field repair capability verified
FULL RATE PRODUCTION	- Final production configuration delivered - Reliability growth curve achieved - Field repair capability verified - Manufacturing process verified	TRANSITION TO "CONTINUOUS PROCESS IMPROVEMENTS"

APPENDIX J

Creating Incentives for Concurrent Engineering Implementation in the DoD

In order for the Department of Defense to create the needed incentives for effective implementation of concurrent engineering in the development of its future weapon systems, three broad changes are required - all geared toward increasing the emphasis on schedule, cost, and quality in the defense acquisition process. Specifically, these three changes are: (1) A redistribution of resources, so that process technology can receive a far higher level of emphasis (compared to the current DoD focus almost exclusively on product technology); (2) a restructuring of the acquisition process, so as to allow the needed "up front" emphasis on subsequent production and support costs; and (3) changes in program requirements and concept formulation activities, in order to place far greater emphasis on "affordability" and its impact on the trade-offs associated with performance vs. quantity and schedule. These three sets of changes would be implemented in the following fashion:

- Resource Reallocation - A Directive should be put out from the Office of the Secretary of Defense (and then its implementation carefully monitored) that would do the following:

  a. Require the use of program R&D funds - during the "concept definition" and "feasibility demonstration" phases - on manufacturing process design, manufacturing process feasibility demonstration, and product vs. process improvement tradeoffs. The objective here is to encourage the use of R&D funds in the early phases of a program to assure that the initial concept focuses on a lower cost approach (from the viewpoint of manufacturing and support).

  b. Require that detailed manufacturing and support process designs be completed and proven out during the "development phase" of a program, and that this be done using R&D money. The critical point here is that this process design is a critical part of the development activity and that adequate funds must be provided for it.

  c. Require a significant share of defense "applied research (6.2)" and "advanced development (6.3)" be devoted to process technology, and that this process technology be specifically focused on future DoD products.

The idea here is that, as with commercial products, the advanced development and applied research efforts should be "market relevant" and thus not only should there be significant process technology efforts but that these should be related to specific future weapon activities. Obviously, the principal focus of this initiative is, again, to assure that a larger share of the resources be shifted towards the process arena (than is currently the case).

d. Emphasize that a significant share of corporate IR&D funds be devoted to process innovation. There is currently considerable ambiguity as to either the desirability or even the appropriateness of such investments, and this ambiguity must be eliminated so that industry clearly understands that it is the DoD objective to achieve higher quality and lower costs through greater process investments.

- Acquisition Process Restructuring - It is important that the acquisition process be made flexible so that if early concurrent engineering efforts are successful, a new weapon system can rapidly evolve through the acquisition process to earlier field deployment. For this to be achieved, the Department of Defense must shift its emphasis (in the acquisition process) towards stipulating the explicit "expectations" resulting from each phase of the process (rather than focusing on the "activities" that would take place during each phase). Thus, if a product satisfies the requirements for transition to the next phase, it can be moved ahead. For example, if process feasibility has been fully defined and resolved by the completion of advanced development (which would be a necessary requirement for concurrent engineering, but not a requirement in the present acquisition process), then the product would be ready to move into the next phase. By rigidly insisting that a product meet the expectation of each phase, but by allowing it to rapidly evolve through the process, it will then be possible to achieve a much more rapid acquisition schedule; yet with far lower risk than the current process (and, in fact, this lower risk might even be achieved with a development time that is cut in half).

- Early Introduction of Affordability as a Requirement - The "requirements" and "concept definition" processes must explicitly require the introduction of "estimated total program dollars available" and "needed development time" as critical, early system requirements. Only in this way can the necessary tradeoffs between required weapon's performance and required quantities and development schedules be made. As part of this process, unit production costs will have to be determined - based upon process designs (rather than the more traditional parametric estimates) - and these unit production costs, together with the

determined weapon's performance and schedule, will then be the outputs of the concept definition process and the "firm requirements" for the weapon's development process. Additionally, similar steps are required regarding support cost determination during this early concept definition phase.

While the concurrent engineering task force strongly believes that changes in the above three areas are critical to the full and successful implementation of concurrent engineering in the Department of Defense's future weapon system developments, they did not explore in sufficient detail the actual implementation of these three changes in the time that was available. Thus, they recommend that subsequent efforts — either as a follow-on to this task force or as a part of some other activities (perhaps, for example, within the Defense Science Board's "Streamlining" Task Force) — must explore these three areas in far greater detail and come up with specific implementation plans. The Concurrent Engineering Task Force strongly urges the development of detailed analyses in these three areas and the enumeration of specific changes for their achievement.

APPENDIX K

Professionalizing the Procurement Work Force

1. OBJECTIVES

The program described in this appendix is part of the initiative on the Transition from Development to Production. The program is designed to enhance the professionalism and effectiveness of the Government/industry acquisition work force, by educating personnel in the technical processes involved in design, test and production, through a network of public education institutions throughout the country. In addition, on-site instruction will be provided at selected industry sites.

2. BACKGROUND

The current Government acquisition system, in particular the DoD 5000 Series, does not mesh with the industrial processes of design, test and production. As a result, Government program managers use a system which is incompatible with the way industry does business, and which does not provide the means to control technical processes effectively, in that it fails to stress prevention/risk reduction of potential problem areas. Present results are dependent on individual knowledge, which has not been institutionalized throughout DoD. To make matters worse, experience levels in Government are declining. Few Government personnel have sufficient industry technical experience to effectively manage programs. The necessary practical technical knowledge is not taught in university engineering curricula.

Practical university-level instruction is required, but not now available. In 1985, the President's "blue ribbon" commission on Defense Management – the Packard Commission – made a number of significant recommendations concerning defense acquisition. Generally, the commission suggested that we should model defense acquisition after the practices of the best industrial companies. One specific area addressed the need of enhancing the quality of acquisition personnel or "professionalizing" the force. The need for college level education and specialized education in the acquisition field were specifically addressed. Subsequently, a document providing Templates for reducing risk in critical areas of the acquisition process was developed. It is based on extensive data

developed by a Defense Science Board (DSB) Task Force formed to study the difficulties encountered in the transition of Government programs from development to production. The document is DoD Manual 4245.7-M, "Transition from Development to Production." A companion document, "Best Practices," was published by a DSB ad hoc group to expand on the Template manual. Both documents were created using the best technical practices and experience of leading industrial organizations. To insure the effective use of the risk reduction/identification Templates and to enhance the professionalism of the acquisition work force, the Navy is instituting a unique approach for developing and deploying a technical education program.

3. APPROACH

The Navy has under contract a company (AT&T/Bell Laboratories) with recognized expertise in how to design and build long life equipment, who played a major role in the highly successful APOLLO Lunar Landing Program. An extensive library search by Bell Laboratories revealed a lack of stand-alone material covering the design and manufacturing Templates, and without suitable text material in these important areas, there cannot be a continuously effective industrial process. Consequently, AT&T has as its prime responsibility the task of generating this all-important text material for each risk area identified as a Template, in addition to providing classroom material. Also under contract is a small non-profit company called Technology Exchange Center who will be responsible for conducting the actual courses, based on their previous successful experience distributing technical concepts through an industrial/community college network. This program offers:

- DoD controlled curricula
- Defense contractor participation
- College credit for work force
- Experienced industry instructors
- Localized course offerings
- Reduced TDY costs
- Degree programs
- Technical assistance and guidance

4. AUDIENCE

Courses are designed for Government and industry program management, technical, budget, and contracts personnel. There is a potential for 50,000+ Navy engineers alone. Seats will be allocated to provide a mix of Government and industry personnel in each class to allow cross-cultural exchange of experience.

5. LOCATIONS

Community colleges in localities where acquisition personnel are concentrated will be used to reach the greatest numbers of personnel with the least impact on TDY funds and time away from the job, while providing excellent facilities. See Table 1 for planned locations.

Courses will also be delivered on-site at companies who have expressed interest in the program. Expected industry participants identified as of the time of this report are shown in Table 2.

6. SCHEDULE

Table 3 shows the relationship between the 48 Templates and the six course modules. The expected start date for each of the six modules is shown along with the templates covered in each course.

State	Location
CA	China Lake
CA	Los Angeles
CA	Oxnard
CA	San Diego
CA	San Fransisco
DC	Washington
FL	Panama City
FL	Pensacola
IN	Crane
IN	Indianapolis
MA	Boston
MD	Patuxent River
OH	Dayton
PA	Philadelphia
PA	Warminster
RI	Newport
TX	Dallas
VA	Mechanicsburg
VA	Norfolk
WA	Keypost

Table 1: Community College Network.

State	Company
AR	Garrett
AR	Hughes
AR	Loral
CA	General Dynamics
CA	Hughes
CA	Litton
CA	Lockheed
CO	Martin Marietta
FL	Martin Marietta
FL	Harris
IA	Collins
MN	Control Data
MN	Honeywell
MN	Unisys
MO	McDonnell Douglas
NC	AT&T
NH	Sanders
NJ	RCA
NJ	ITT
NY	General Electric
NY	Grumman
NY	Raytheon
NY	Sikorsky
NY	Sylvania
PA	Westinghouse
TX	General Dynamics
TX	Texas Instruments
VA	IBM
WA	Boeing

Table 2: Potential Industry Sites.

Overview Sept 1989	Logistics Oct 1989	Design 1 Dec 1989	Design 2 Apr 1990	Production Oct 1990	Management Mar 1991
• Introduction • Transition Plan • Money Phasing	• Logistics Support Analysis • Manpower & Personnel • Support & Test Eqpt • Training Mtl & Eqpt • Spares • Technical Manuals	• Mission Profile • Design Rqts • Design Policy • Design Reviews • Design Analysis • Design Process • Design Limits • Trade Studies • *(CAD)* • *(Transition Plan)*	• Software Design • Software Test • Design for Test • Integrated Test • Failure Reporting System • Built-In Test • Computer-Aided Design • Parts & Materials Selection • Design Release • Configuration Ctrl • Test, Analyze & Fix • *(Hardware Design)*	• Manufacturing Plan • Quality Mfg Process • Tool Planning • Computer-Aided Mfg • Defect Control • Piece Part Control • Mfg Screening • Life • Uniform Test Rpt • Field Feedback • Special Test Eqpt • *(Transition Plan)*	• Total Quality Mgt • Technical Risk Assessment • Production Breaks • Mfg Strategy • Personnel Rqts • Transition Plan • Subcontractor Ctrl • Data Rqts • Modernization • Factory • Improvements • Productivity Center

Table 3: Course Organization and Schedule.

APPENDIX L

Robust Product Design

1. INTRODUCTION

Robust design, one of the engineering innovations connected with concurrent engineering, is often associated with the work of a Japanese engineer, Genichi Taguchi. Phadke calls it "an engineering methodology for improving productivity during research and development so that high-quality products can be produced quickly and at low cost"[1] and credits[2] Taguchi with introducing the concept. Other authors [Box88, Tag86, NIST89] use terms such as *quality engineering* or *quality technologies* and, although they are not in total agreement on ways to implement the concept, they generally agree that it holds the potential for achieving the goals described by Phadke.

2. BACKGROUND

Since the introduction of mass production techniques with interchangeable parts, engineers have been dealing with the concept of tolerance specifications. Such specifications were needed to insure that parts would fit during assembly. Inspection using gauging was used to ensure quality. Shewhart recognized the role of variability in the manufacturing process and developed statistical tools for managers and engineers. The goal was to achieve processes that would produce a predictable level of quality. Taguchi emphasized the importance of applying the quality effort upstream in the design process. He stressed that improved quality is associated with reducing the variability of products and the reduction did not have to increase costs. He also stressed that products and processes should be robust and that this characteristic was a result of decisions made during design.

3. DISCUSSION

The term *robust* when applied to a design implies that the object designed remains firm in purpose in the presence of variability resulting from use, age, or manufacturing conditions. Robust design, as the concept was described to members of the task force, seeks to achieve this firmness in purpose while using the widest allowable tolerances and the cheapest available materials. In terms of a mathematical expression, if the

1. Madhav S. Phadke, *Quality Engineering Using Robust Design,* Prentice Hall, Englewood Cliffs, NJ 1989. p. 1.
2. ibid p. xvii.

symbol Y represents some characteristic of a product, and if the value of Y is determined by some combination of factors $\{x_1, x_2, \ldots, x_n\}$ such that one could write

$$Y = f(x_1, x_2, \ldots, x_n),$$

then robust design seeks to find the vector of $\mathbf{x}_0 = (x_{1_0}, x_{2_0}, \ldots, x_{n_0})$ so that $Y =$ *target value* and $|\nabla f(\mathbf{x}_0)|$ is minimal. In other words, find the settings for the different design and process parameters that ensure the product will function as intended even when the supplies are not perfect, the factory machinery is somewhat worn, and the customer uses it in a variety of environments. If the behavior of the product at the target value $Y_0 = f(\mathbf{x}_0)$ is considered to be the signal and the errors in the x_i are viewed as noise, then robustness can be considered as maintaining a desired signal in the presence of noise. The design problem is analagous to finding the vectors, $\mathbf{x}_0$ and δ and the largest neighborhood $N_\delta(\mathbf{x}_0)$ so that for all x contained in $N_\delta(\mathbf{x}_0)$, the quality characteristic will be *close* to the target.

Phadke[3] describes three phases of design—concept, parameter, and tolerance—during which robust design concepts may be applied. During concept design, the designer (design team) creates different concepts that might satisfy the required functions. The different concepts are compared for ease of use, cost of production, reliability of operation, etc. The concept that is judged to provide the greatest benefit for the developer's business goals is selected. If robust design concepts are used during concept design then the evaluation also considers how alternatives demonstrate sensitivity to noise (variation) in manufacturing and use.

Parameter design is concerned with selecting the best values for each design parameter. It follows concept design, and represents the most active area for the application of robust design. Assuming "wide tolerances on the noise factors [uncontrolled or uncontrollable parameters] and assume[ing] ... low grade components and materials ... [are] used... minimize the sensitivity to noise...".[4] Among the tools found useful during parameter design, the statistical design of experiment is often cited as being most effective. Although some disagreement can be found regarding the exact approach to using this tool, there is general agreement that it is a powerful technique for selecting values for design parameters so that the resultant product is robust.

The third step, tolerance design is a recognition that products built with the cheapest materials and widest tolerances may not achieve the quality levels intended for the product. Tolerance design[5] consists of selectively reducing tolerances and selecting higher grade materials in order of their cost/benefit until the desired level of quality is

3. Phadke, op. cit. p. 33.
4. ibid. p. 33.
5. ibid p. 34.

achieved in the sense of minimizing life-cycle cost.

Since 1981, the concept of robust design has been gaining wider acceptance within U.S. industry. The use of robust design has been credited with some of the most spectacular cost savings, including up to 80 percent, and cases[6] with preventing the early termination of entire product lines.

The benefits of robust design 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.

4. TAGUCHI'S CONTRIBUTION

The principal contribution of Taguchi was to systemetize an approach to engineering for robustness, including reexamination of the role of specifications, emphasis on using controlled experiments, recognition that products are built in factories under environmentally "noisy"[7] 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"[8] has sparked renewed interest in ways of reducing variability.

Taguchi views quality as a loss to society associated with a product. He assumes that for some class of products, the average loss to society can be approximated by a quadratic function. (He proposes other continuous functions for other classes, depending on whether important characteristics are intended to be close to some target value, as large, or as small as possible.) The loss is assumed to be a 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 characterists and to select the lowest cost concept, parameter, and tolerance design that will result in the minimum mean square error between the actual values and ideal target for the quality characteristic. The result is a product with minimum loss function.

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6. 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. p. 59.

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

8. Although the *loss function* $L = K(Y_i - Y_0)^2$ has been shown to be equivalent to the mean square error about the target value, it has helped engineers to recognize the importance of minimizing this value. It is a change from the view that any value within specification is equally acceptable.

The robust design concept differs from a belief that once tolerances are established all products satisfying the tolerance limits are equally good. Robust design does not eliminate the need for tolerances, but it also seeks to define a target value and to minimize the variation of the product around that target by finding design concepts and parameters for both products and processes that are robust to the effects of noise. If such a target value can be found, then not only will the loss be minimized when that target is achieved, but also the expected loss can be calculated when the target is not achieved. 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 expensive materials and close tolerances be used only as a last resort when other methods fail to achieve the desired robust behavior.

5. OTHER ROBUST CONCEPTS

The concept of robust product performance was not unknown before Taguchi. Many products have been designed to operate in a range of severe environmental conditions. In some cases, military specifications require vendors to demonstrate such performance. Backup systems, redundancy, fail-safe designs, and high-reliability components are common in many industries, particularly those where safety is critical. The change associated with the current focus on robust concepts is the involvement of people across functional boundaries (as in other aspects of concurrent engineering) and the importance of reducing variation in all quality characteristics (as with Total Quality Management).

6. DESIGN OF EXPERIMENT

Although design of experiment did not originate with Taguchi, he has 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. 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 Tippett 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.[9]

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 some technical debate over the connection between these techniques and those of Taguchi. Evaluation of the benefits and limitations of various approaches to robustness is a subject of continuing research [NIST89].

7. ROBUST DESIGN AND CONCURRENT ENGINEERING

Just as the ideas of Total Quality Management and the simultaneous development of products and processes (concurrent engineering) are often found together in practice, so too are robust design and concurrent engineering. Removing the causes of variability during concept design and parameter design have the effect of producing designs that are

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

easier to manufacture. Involving manufacturing engineers with the product development team so that they can begin to engineer the manufacturing processes during early phases of development can result in manufacturing engineers identifying product features that are sensitive to "noise" on the manufacturing floor. The same can be said for product support, reliability, and other functional specialists.

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APPENDIX M

Related Studies Summary

There have been many studies of the defense industrial base and of the effects of the acquisition process on the schedule and cost of DoD systems. The industrial base studies focus on the ability of industry to support the defense effort in time of war, the economics of the industrial base, and the effects of various government policies on industry and, hence, on the defense posture of the nation. The acquisition process studies concentrate on ways of establishing competition in defense acquisitions, on ways of ensuring that progress is being made in programs, on budgeting issues, on the utility of actual or proposed regulations, and on the general business structure of the DoD. Five of these past studies contain particularly relevant points.

In a 1977 Defense Science Board Summer Study, the notion of "concurrency" appears in a form different from what is intended in the phrase "concurrent engineering".[1] In that study, "concurrency" is defined as "the conduct of the steps leading to production for inventory before the end of the full-scale development time span." Even though the report states that this could include "low-cost" actions like manufacturing planning, this form of concurrency ultimately was interpreted as the overlap of design and production. This overlap is emphatically *not* what is being proposed in the present report. In fact, integration of product and process realization implies that all designs should be mature prior to beginning production.

A 1985 Defense Science Board Summer Study recommended ways to improve the acquisition process by "changing the way requirements are generated, documented, and implemented."[2] These recommendations are directly relevant to the present report because of a shared view that an iterative requirements analysis process is needed during system development. This process should permit continuous trade-offs between performance, cost, and user utility. The report calls for "technical risk reduction and cost/capability trade off efforts, with industry participation..." and consequent revision of DoD Directive 5000.1. The recommendations address the maintenance of cost/performance trade-off flexibility via giving chief executive officer authority to program

1. Defense Science Board, *1977 Summer Study on the Acquisition Cycle*, March 1978, p. 47. Recall that "concurrent engineering" is often used to describe the sort of product/process integration proposed in this report.
2. Defense Science Board, *1985 Summer Study on Practical Functional Performance Requirements*, March 1986, p. 1.

management and continuous involvement of the CINCs in requirements iterations.[3] The report makes the case that prudent flexibility in requirements trade-offs is important to successful delivery of products with substantially increased capabilities.

A major point made in the report is that adherence to schedule ought to have highest priority during full scale development. The intent is to inhibit requirements change and to force capability-improvement changes to be deferred to block upgrades. The present report differs on this point. If coherence is a goal, then an overall integration approach denies the preeminence of any one objective. Only through an integrated approach can cost, quality, and schedule objectives be met. Another point of difference is that the 1985 study appears not to differentiate between non-recurring system development cost, recurring production and acquisition cost, and recurring cost of ownership. Since cost trade-offs tend to be related to development schedule in the developments studied, the report implies that development cost, not product cost, was a major driver in the studied trade-off analyses. The present report does differentiate these costs and claims that both unit production costs and life-cycle costs can be contained by integrating product design with production and support process designs respectively.

Another focused approach related to the current study is *design-to-cost*. A recent Institute for Defense Analyses study on acquisition initiative effectiveness analyzes many acquisition initiatives over the past two decades.[4] One of these initiatives is design-to-cost, with a history sketched back to 1971 when it became official policy in DoD Directive 5000.1. Of the 89 programs studied, 32 had design-to-cost application. The conclusion was that design-to-cost had little effect, *particularly when applied late in the program* or when there was an "absence of continued technical evaluation of design/effectiveness/cost tradeoffs."[5] In cases where design-to-cost was applied early and consistently, cost growth was lower than the average. *The Task Force position is that design-to-cost can be an effective integrating factor when applied early and consistently within a program managed under an overarching principle of product and process integration.* When applied in a typical, sequential program, other factors tend to override the effect of design-to-cost.

A 1989 Defense Science Board Report reinforces several concepts relevant to product/process integration.[6] One general theme of the report and its predecessor from

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3. There is some difference of opinion as to the effectiveness of this CINC connection in the various Services.
4. Tyson, Karen, *et al.*, *Acquiring Major Systems: Cost and Schedule Trends and Acquisition Initiative Effectiveness*, Institute for Defense Analyses Paper P-2201, March 1989.
5. *Ibid*, p. IX-13.
6. Defense Science Board, *1989 Summer Study on the Use of Commercial Components in Military Equipment*, June 1989.

1986 was that DoD would be better off by focusing on needs, not on design details. This focus is consistent with recommendations in the present report that contracting mechanisms be used which tend to capture the total high-level requirement rather than approaches which tend to fragment the effort through attention to minutiae. Also, the 1989 report suggests increased use of streamlining, an acquisition approach supported by the recommendations in the present report as well.

On a more general level, a 1988 Defense Science Board Report paints a rather bleak picture of the state of the defense industrial base.[7] The study recognizes the increased level of mistrust in DoD/industry relations and the consequent inefficiency of the product realization process. The report calls for a more "goal-oriented businesslike arrangement" and decries the tendency of U.S. industry and government "to ignore the effects of their management philosophies." These findings are all consistent with the present report. The recommendations in Section 3 of the present report address the relationship between the DoD and the contractor as represented in a more integrated, less directive contracting approach and in terms of teamwork during requirements generation and during the execution of the contract. Also, a change in management philosophy is implied by product/process integration. A longer term view by both industry and government is called for in order to deal with downstream process issues early in the product realization process.

7. Defense Science Board, *1988 Summer Study on the Defense Industrial and Technology Base*, Volume I, October 1988.

APPENDIX N

Implementation: Quick-Start and World-Class

It is often stated that the implementation of concurrent engineering is a very major change, and therefore must require a long time. This is too pessimistic. While it is true that it can easily take five years to *complete* the transition to world-class concurrent engineering, major partial benefits can be achieved in one year. The implementation can be conveniently thought of as having two tracks: quick-start actions and world-class actions. The quick-start actions are primarily changes in management practices and process, and can be completed in one year. The actions to reach world-class status are the implementation of powerful development tools (operational practices), which take roughly five years to implement. These two elements can best be implemented when integrated together.

1. Quick-Start Actions

The quick start actions are summarized in Figure 1. These correspond to Industry Implementation Suggestions 1, 2, and 3 in the main body of this report. In Figure 1, the first two points emphasize the shift from localized, suboptimized goals to a focus on the ultimate objectives of the development project. Points 3 and 4 shift from stovepiping to a team. We have a choice; be all-stars or be on winning teams. Point 5 emphasizes knowing the best in order to be the best. Point 6 empowers people to initiate improvements. Point 7 emphasizes that suppliers have much to contribute. Viewed more globally, there are two major thrusts: (1) objectives to be the best in meeting customer needs (Points, 1, 2, and 5), and (2) working together to achieve the objectives (Points 3, 4, 6, and 7).

These quick-start actions can be implemented in less than one year with strong leadership from the top of the development/production division. Management can directly reorganize to integrate the organization (Point 3). Benchmarking teams can be organized (Point 5), which will help the organization to focus on quality, cost, and delivery (Point 1). This focus can be enhanced by constant top-management emphasis on QCD and the division's competitive QCD status. Customer satisfaction can be emphasized (Point 2) by switching from internal metrics to external metrics. This can utilize direct feedback from customers. Over-wall transactions can be eliminated (Point 4) by continuous top-management emphasis on the unity of all activities and goals. People who have traditionally thought of themselves as "product design engineers" can be helped to understand that their performance is satisfactory only when they fully take into

QUICK-START ACTIONS
MODEL IMPLEMENTATION
CONCURRENT ENGINEERING

MANAGEMENT AND PROCESS
(TIME CONSTANT = 1 YEAR)

1. Focus all activities on quality, cost, and delivery (QCD).
2. Emphasize satisfaction, perceived by customer
3. Integrate the organization
   A. Product planning, development, production
   B. Multifunctional team (PDT); colocated
4. No over-wall transactions
   A. Specifications (multifunctional team)
   B. Concept (multifunctional team)
   C. One system (multifunctional PDT): design, production capability, field-support capability, quality
   D. Disciplined design reviews and criteria
5. Emphasize competitive benchmarking (CBM)
6. Utilize employee involvement (EI) and participative management
7. Strategic relationships with suppliers.

FIGURE 1

account production capability, field-support capability, and robust quality. Employee-involvement teams can be started (Point 6), and the importance emphasized by having one or two EI councils that meet monthly with the general manager of the division. Divisional team contests (better yet corporate) with major rewards also help greatly. The materials management activity can be refocused to achieve strategic relationships with suppliers (Point 7). To assist this, materials management should be appropriately integrated with the product development teams.

All of the above can be done within one year by determined leadership. Constancy of purpose is required.

2. World-Class Actions

The world-class actions are the implementation of world-class operational practices, Industry Implementation Suggestion 4 of the main body of this report. These are primarily Quality Function Deployment (QFD)[1], Robust Quality[2], and the concept selection process of Stuart Pugh[3], in conjunction with his evaluation process of product status: static/dynamic[4]. The objectives of these tools are to focus on the customer, choose the best concepts, optimize robust quality, and integrate the corporate activities, such as design and production. Major shortfalls will continue, particularly in development time, until these improved practices are implemented.

These world class improvements take longer to implement than the quick-start actions, in part because considerable education is required. Also, the improved practices are not so intuitively obvious, which tends to diffuse top management leadership. The best implementation approach has not been fully verified. Everyone agrees that some initial applications (case studies) are essential.

The problems with implementing the world-class practices are summarized in Figure 2. Should the focus be top down or bottom up, on the content of the change or on energizing people? Figure 2 suggests that any single-minded approach will encounter major problems.

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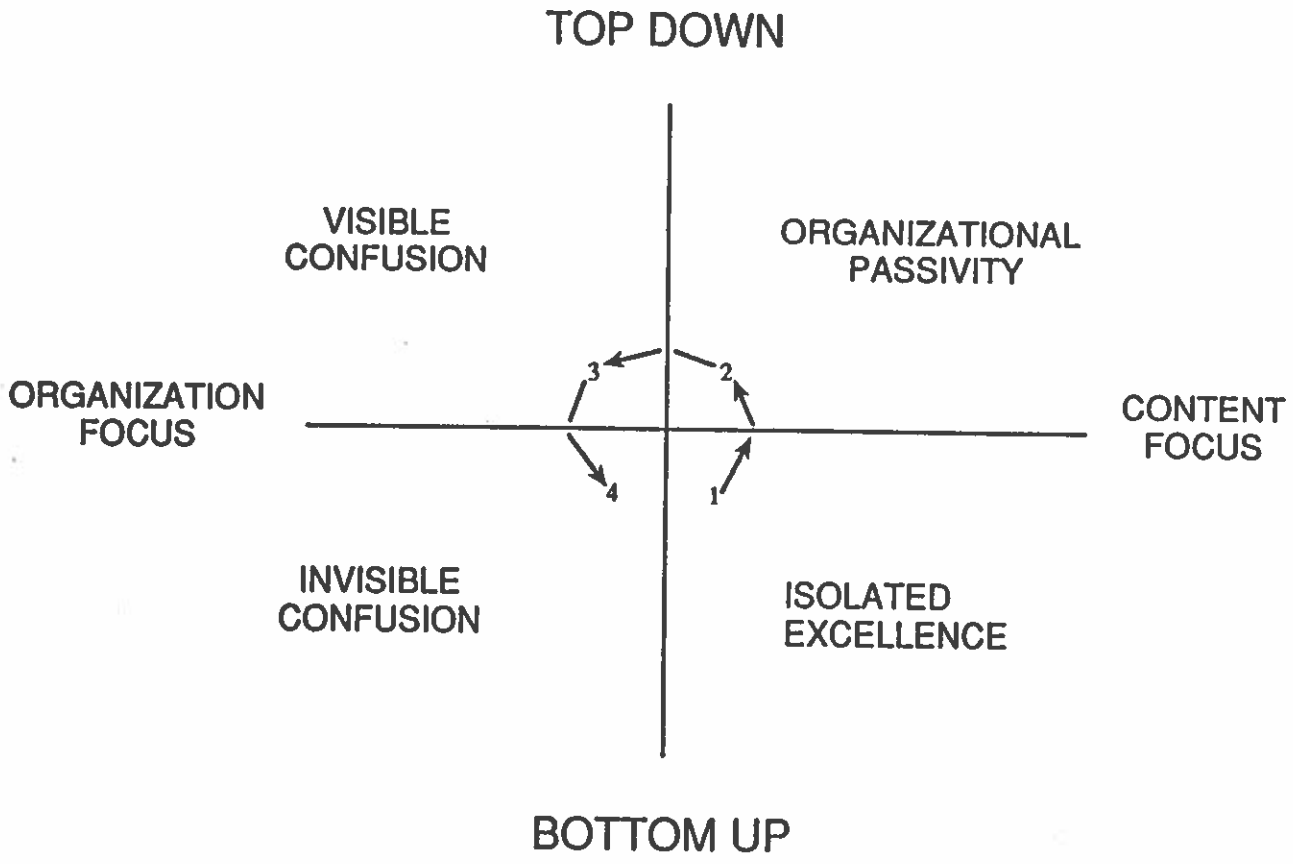
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The best approach starts in the lower right quadrant, with a core team of enthusiastic gatekeepers who bring in the improved practice, lead initial applications, and tailor the practice to the divisional needs and language. Then this team trains the top management of the development/production division (upper right quadrant). Top management then leads the institutionalization of the improvement (top left quadrant), much in the same style that they lead the quick-start actions. Work groups can then enhance the practice to fit local conditions (lower left quadrant).

3. Summary

Quick-start actions will start producing major benefits in one year, so long delays will not be necessary. The full benefits will be achieved with the institutionalization of world-class operational practices. Enlightened leadership and constancy of purpose are required. After the major implementations are complete, continuous improvement will provide continuous competitiveness.

IMPLEMENTATION STYLES
FOR MAJOR IMPROVEMENTS



S-N

CASTING WITH ONE ROD WILL FAIL

DPCLAUSING
88/10/11
90/03/19 (REVISION)

FIGURE 2