**ENGINEERING RESEARCH TECHNOLOGY
FOR CONCURRENT ENGINEERING
FROM UNIFIED LIFE CYCLE ENGINEERING**

Captain Raymond R. Hill
Armstrong Laboratory
Logistics and Human Factors Division
Wright-Patterson Air Force Base
Dayton, Ohio 45433-6503

Abstract

In the summer of 1985, the Secretary and the Chief of Staff of the U.S. Air Force directed a study into new technologies demonstrating promise for improving the future war fighting capabilities of Air Force weapon systems. The results of this study formed the Project FORECAST II initiatives. There were a total of seventy initiatives identified. The Unified Life Cycle Engineering (ULCE) initiative (number PT-32) recommended changing the design environment to consider all design attributes during the design process and to do so by taking maximum advantage of computer techniques and technologies. The initial implementation plan for the ULCE initiative identified 18 ongoing research programs of interest to the ULCE effort. One such program was the Air Force Human Resources Laboratory research effort in Decision Support System (DSS) technology for ULCE.

The primary purpose of this paper is to summarize the research results of the AFHRL DSS research effort. Though the research produced essentially paper studies, these studies covered a broad spectrum of issues. Among the topics addressed were ULCE architectural issues, design measurement and methods research, ULCE-related design technique survey papers, and investigations into group support system technology. The resulting suite of technical papers produced have influenced recent concurrent engineering efforts such as the Army's Light Helicopter program (LHX).

The end result of this summary effort is to encapsulate the four-year research effort into a set of generalized findings and recommendations. Since the ULCE research program was a precursor to the current initiative in Concurrent Engineering (CE), or Integrated Product Development (IPD), this set of findings and recommendations is discussed in light of its impact on the current initiative. In particular, these findings and recommendations are discussed with respect to a more recent AFHRL effort called the Requirements Analysis Process In Design (RAPID) program. The purpose of the RAPID program is to make fundamental improvements in the weapon systems requirements process. This paper presents the RAPID concept and the influence previous ULCE research had in developing this concept.

Introduction

The purpose of this paper is to summarize research results from a series of Unified Life Cycle Engineering (ULCE) study efforts sponsored by the Air Force Human Resources Laboratory (AFHRL), Logistics and Human

Factors Division. Though primarily paper studies, the AFHRL-sponsored efforts addressed a wide range of issues pertinent to ULCE and still of concern to the ensuing initiative in Concurrent Engineering (CE). This paper familiarizes the reader with the ULCE initiative, what the more recent CE initiative is concerned with in the area of engineering design, and how CE is implemented in DoD under the label of Integrated Product Development (IPD). After this brief overview of ULCE and CE, ten ULCE studies are summarized with the purpose of the review being to briefly describe the paper and present the conclusions and recommendations from each. The objective of this summary effort is to derive a set of general findings to characterize the AFHRL ULCE efforts. One result of these ULCE efforts is a new project called the Requirements Analysis Process In Design (RAPID) project. The applicability of the ULCE findings to RAPID is discussed and the RAPID project described. This paper concludes with a summary of the benefits of the RAPID project.

Unified Life Cycle Engineering

In the summer of 1985, the Secretary and the Chief of Staff of the Air Force directed a study into new technologies demonstrating promise for improving the future war-fighting capabilities of Air Force weapon systems. The results of this study formed the Project Forecast II initiatives, of which a total of seventy initiatives were identified. The ULCE initiative recommended changing the design environment so that all design attributes could be considered during the design process. The ULCE objective was to improve Air Force weapon systems combat capability by integrating design for supportability and design for producibility with design for performance using emerging computer-aided engineering technology.

Rapid development of computer-aided techniques and increasingly available computers and design workstations brought increases in design productivity while decreasing design costs. However, the design environment changed as a result of this new technology with resulting uncoordinated design efforts, incompatible interfaces among design elements, and non-integrated design data structures. The ULCE vision was an advanced computing environment for design emphasizing integration across heterogeneous computer platforms, optimization among competing design goals, and an enhanced level of interaction and communication. This enhanced level of interaction was necessary both between software packages residing in the design environment and between the design engineers using the software and the design environment.

A number of programs and initiatives were identified as ULCE-related, among them the Reliability & Maintainability (R&M) 2000 and Computer-Aided Acquisition and Logistics Support (CALS) initiatives. An ULCE implementation team was established to provide technical direction, guidance and advocacy for executing and directing the programs identified as central to ULCE success. Part of this coordination effort was to establish ULCE/CALS interfaces to allow ULCE efforts to contribute to CALS efforts in integrating automated R&M analyses into computer-aided design and design workstations. One such program was the Decision Support Systems (DSS) effort within the AFHRL. This program examined various research issues surrounding the development of an advanced, computer-based decision support environment for ULCE. It is the results from this program that this paper will summarize and build upon.

Concurrent Engineering

During 1988, the Institute for Defense Analyses (IDA) was tasked to investigate claims that CE could help achieve Total Quality Management (TQM) goals for engineering and acquisition of DoD weapon systems. IDA surveyed industry, produced thirteen case studies, and summarized their findings in the IDA report, "The Role of Concurrent Engineering in Weapon Systems Acquisition" [Winner, 1988]. The IDA team found evidence that implementing CE could in fact prove beneficial to the engineering design effort within weapon systems acquisition. These findings led in part to the DoD adoption of CE [Costello, 1989] as a critical technology for TQM. Another influential study, sponsored by DoD the same time as the IDA study is documented in the Pymatuning Group report, "Industrial Insights into the DoD Concurrent Engineering Program" [Pymatuning, 1988].

The IDA definition put forth in their report has become the de facto standard definition, and is surely the most cited definition in CE literature. The IDA [Winner, 1988] definition is:

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.

To some, CE is merely Systems Engineering (SE) revisited and re-emphasized. To others, CE is merely a TQM-based approach to engineering design. Among the more critical emphasis areas of CE are:

- use of multi-disciplined design teams,
- emphasis on customer satisfaction and requirements definition,
- integrated design environments not unlike those advocated in ULCE.

The most visible program in CE is the DARPA Initiative in CE (DICE) which has to a large extent focused on the integrated design environment and recently expanded their interests towards other, human-related components of design.

Integrated Product Development

DoD adopted CE as a critical technology for TQM and immediately began advocating its widespread use to industry. It is very important that in addition to advocating CE, DoD adopt internally the concepts, philosophy, and practice of CE. However, design within the government is quite different from design in industry. Government scopes the requirements for the systems while industry actually builds the systems. Thus, the practice of CE within DoD is different than in industry. To distinguish among the practices, Integrated Product Development (IPD) will be used to denote government CE practice. Though often synonymous with CE, IPD should really be used to distinguish implementations. Perhaps a better definition for CE more applicable to IPD is the following:

IPD is a philosophy of product design which emphasizes (1) coordination between interdependent design activities, (2) better support and tracking of product evolution, and (3) simultaneous consideration of all elements of the product life cycle.

This paper summarizes ULCE research which is more closely related to our definition of CE than our definition of IPD. However, the research project discussed later in this paper, RAPID, builds upon ULCE recommendations and findings, but is more closely related to IPD since RAPID targets the DoD sector.

ULCE-CE

Sometime in the 1988-1989 time-frame, ULCE became part of CE, though there doesn't seem to be any formal recognition of this event. The event was inevitable however. ULCE was an Air Force, largely Air Force Systems Command, initiative while CE is a DoD initiative. There some very clear similarities. ULCE envisioned the advanced computing environment for design which is what major projects (such as DICE) within the CE initiative are attempting to accomplish. But ULCE missed key components of engineering design emphasized by the underlying philosophy of CE. Design is still largely a human endeavor. Only during the later stages of ULCE did attention turn towards the crucial role of the human designer and the multi-disciplined design team. From the start, such emphasis was a part of the CE philosophy as evidenced in the numerous industry case studies such as those provided in the IDA study [Winner, 1988].

One characterization of the ULCE-CE relationship is to define ULCE as an environment and CE as a process for design. The ULCE environment consists of integrated computer tools, databases, and improved optimization algorithms for design. The CE process consists of design teams, management commitment, improved quality, increased customer and supplier involvement, and other quality-based facets of a design organization. ULCE focuses on research and development, and automation improvements. CE focuses on changing the culture of the design organization. A better characterization is that CE is a necessary broadening of ULCE. Complex design requires a dynamic combination of the design process as well as the advanced computing tools and environments.

Thus, ULCE and CE are by no means independent efforts. The research results funded by ULCE are applicable to CE efforts. For instance, the McDonnell Douglas Light Helicopter (LHX) program makes strong reference to ULCE research [Meyer, 1990]. The next section of this paper summarizes ten AFHRL studies produced by its ULCE DSS project. These reports fall quite naturally into four groupings, and are presented in that fashion.

High-Level Architectural Reports

These first two summaries discuss reports that were ULCE architecturally oriented. The prime purpose of these studies was to identify research areas and ULCE implementation strategies.

Architecture and Integration Requirements for an ULCE Design Environment

This paper [Brei, 1988] documents a joint IDA/Lockheed Georgia study into the architectural issues to realize an ULCE environment. The study uses the C-130 landing gear as the design case with a focus on the specific design tasks involved. The goal of this study was to develop a top-level ULCE architecture and develop implementation requirements for the architecture.

The resulting architecture contains three high-level procedures. These are (1) Generate Design Alternatives, (2) Plan Design Decision Process, and (3) Make Design Decisions. The Generate Design Alternatives is an integrated process for creating and decomposing design alternatives based on customer needs. Plan Design Decision Process involves planning the time-ordered sequence of decisions within the design process. The Make Design Decisions involves the presentation and capture of quantitative and qualitative information for design decision making. A critical element of this architecture is a design-in-process element tasked as a repository for all design knowledge generated and containing the capability to present the stored information as required by the ULCE user.

Not surprisingly the envisioned architecture requires development of a large system of software and data management capabilities. Among the research findings reported are:

- The need for additional research on human interactions in design;
- Research supporting design process planning, execution, and control;
- Research in data base technology, data modeling, and object-oriented technology; and
- Additional research for automatic generation of design detail.

Decision Support Requirements in an ULCE Environment

This paper [Azam, 1988a; Azam, 1988b; ULCE, 1988] addresses the issue of how to optimize designs and perform tradeoffs addressing largely qualitative life cycle concerns in an integrated fashion with quantitative performance measures. This paper is the product of a working group of individuals from industry and is presented in three volumes.

Volume I examines research areas for decision support for ULCE. The key factor towards realizing an ULCE advanced design environment is the management of the design decision making process. In particular is the need to

guide engineers to produce designs optimized over a wide range of design goals, both quantitative and qualitative.

Volume II summarizes various numerical optimization techniques available to ULCE, focussing on how these optimization techniques should fit into the overall ULCE design process. The paper distinguishes among design models and analytical models while discussing multi-stage versus multi-level decomposition. Though primarily a review of existing techniques, the paper notes a gap in methods to optimize the design team negotiation process.

Volume III examines applications of design decision support to support an ULCE environment optimizing among five factors: cost, schedule, performance, producibility, and supportability. To accomplish this task a specific design example (a printed circuit board application) is examined with emphasis placed on reliability. Treating each design factor as a node in a hierarchical goal tree, this paper examines multi-criteria methods for optimizing among the competing factors. Realizing most optimization techniques are numerically-based, the study examines techniques supporting negotiation and tradeoff, such as game theory or decision analysis techniques, as ways to handle the qualitative aspects of design. Artificial intelligence (AI) is also examined as a decision support technology.

The findings from this paper recommend additional work in analytical techniques for design process synthesis, measurement of qualitative factors, and extended optimization techniques to accommodate the qualitative factors.

Measurement Issues and Design Techniques

This next group of reports examine a specific area of ULCE concern, that of design process measurement. They also examine and document new approaches to design for an ULCE design environment.

Aerospace System ULCE: Producibility Measurement Issues

This paper [Calkins, 1989] addresses methods to incorporate producibility factors into the aircraft conceptual design process. All too often the total system is designed without regard to how to produce the system, causing problems later during production and manufacture. In keeping with the ULCE concept, the primary vehicle proposed for introducing producibility considerations into design is a software module within a computer-based model. The intent of such a module is to pull preliminary design detail necessary for producibility analyses back into the conceptual design stage. This allows continual producibility assessments to occur throughout the design process. The module itself contains both quantitative and qualitative data and uses life cycle cost as the primary driver in the design decision making process.

The study equates producibility design with good design practice. Among the producibility design benefits reported are:

- Simpler designs,
- Lower production costs,
- Improved engineering/manufacturing interface(s),
and
- Higher quality and improved reliability in the systems.

The study further recommends integrating producibility into early acquisition phases and calls this

integration effort Simultaneous Engineering or Concurrent Design, other terms considered synonymous with CE.

Product Supportability Issues in the Early Design Phase

This paper [Goldstein, 1989] considers the problem of evaluating designs for supportability issues (such as reliability, maintainability) and recommends improvements to the process. Avionics systems are used as the case study for the evaluation. For the selected hardware design, the report (1) documents the major performance design goals and requirements typically considered in the design process; (2) identifies and documents the supportability measures employed at each level of the equipment decomposition, and (3) identifies shortfalls in acquisition documentation preventing adequate supportability.

The paper presents three recommendations to improve the process to ensure adequate supportability. First, supportability requirements must translate into design features to integrate with performance requirements. Secondly, supportability requirements must be based on the need versus the solution to meet that need. And finally, supportability specifications must be properly written into contractual documentation.

Management of Risk and Uncertainty in Product Development Processes

This study [Tse, 1989] develops a conceptual framework for managing uncertainties (and risks) inherent in requirements and the downstream manufacturing and support processes. Uncertainties arise from many sources. Changing requirements, uncertainty in manufacturing process capabilities, part availabilities, and especially the introduction of new technologies increase the complexity and risk of the system design situation. The Taguchi loss function is introduced, modified and proposed as an approach for evaluating alternative designs from the standpoint of design robustness in the face of uncertainties.

Since the paper is conceptual in nature, the findings and recommendations favor additional research to prove out the concepts presented. For instance, the modified Taguchi function must be approximated, incorporate measures of uncertainty, and be applied to actual product development problems. Additional recommendations are to develop managerial practices to specifically deal with uncertainty in design and to develop an ULCE environment within which to conduct further research.

Meta-Design: An Approach to the Development of Design Methodologies

While the ULCE goal is advanced computing environments, such environments are not practical goals if the underlying design process is not supportive of ULCE objectives. This paper [Rogan, 1990] addresses a number of issues related to meta-design, which is defined as the "design of a design process" methodology. The product of a meta-design effort is a design process geared to producing designs optimized for performance, cost, schedule, producibility and supportability, integrated with CAD tools, analysis tools, and design databases. The proposed meta-design framework uses an analytical approach involving an optimization framework, and specific criteria useful as guidelines in synthesizing design methodologies.

The paper highlights the role of customer requirements in the design process and proposes a promising methodology for enhancing ULCE design. However, as an initial research concept, there is the lack of practical application of the technique. As such, further research into applying meta-design to actual design problems is suggested as well as efforts to link meta-design to existing techniques such as Taguchi design of experiments or Quality Function Deployment.

Survey Reports

The next two reports are primarily surveys of existing capabilities as they applied to ULCE efforts. The purpose of such reviews is to gain a better understanding of the design phenomena and design environment.

A Survey of Research Methods to Study Design

The purpose of this paper [Brei, 1989] is to gain a deeper understanding of engineering design by examining various research methodologies used to study the design process. These methods were grouped into six categories by the research team. More than 50 design research projects were reviewed, of which 18 were selected for additional review and appraisal. Design activity is classified at one of three levels. Level 1 represents the minute factors involved in individual designer decisions. Level 2, also based on the individual designer level of decision-making, examines the fundamental design process activity. Level 3 represents organizational design activities describing those activities at the design project level.

Among the common themes uncovered in the research projects examined are:

- Engineering design is ill-structured and difficult to solve using a single algorithm,
- Design requires an interdisciplinary approach,
- Design decisions are highly coupled decisions, and
- Designers satisfice versus optimize designs.

Managing Engineering Design Information

The objective of this paper [Fulton, 1989] is to evaluate currently available data/process modeling methodologies, in particular how the coupling of these methodologies with database management systems (DBMSs) apply to aerospace vehicle systems design. Using an aircraft wing composite panel design as a test case, the study examines seven data/process modeling methods. Not surprisingly none of the methods adequately support the overall aerospace vehicle design process. This supports other views regarding the necessity of Information Resource Management (IRM) as a critical component to managing the suite of methods and models, depicting the processes and information of the organization [Cullinane, 1990].

Group Support Technology Reports

As previously mentioned, CE incorporated ULCE and with that brought increased emphasis to the important role of the engineering design team. Later ULCE research in fact highlighted this trend, suggesting ULCE consider the issue, and a series of three reports specifically target aspects of group decision making within design.

Computer-Aided Group Problem Solving for ULCE

This initial paper [Dierolf, 1989] in ULCE group support research addresses the application of computer support to facilitate the multi-functional team approach to

design. The primary goal of group computer support is to improve design solution quality and reduce meeting time while not decreasing group satisfaction with the final solution. This paper reviews ongoing research projects in computer-aided group problem solving and raises the following research questions:

- What methods are needed to combine judgments among design team members?
- How should decision audit trails be retained and then exploited?
- What is the best group structure for design?

The paper concludes by presenting computer-aided group problem solving as an unexploited opportunity for enhancing the efforts of the design team. The initial ULCE focus of single-user design workstations is cited as too narrow a focus. Proper incorporation of producibility and supportability, as well as other "ilities" requires a multi-disciplined team process, a process which ULCE should support. Thus, the overall recommendation is that ULCE direct efforts into this research area.

Computer Support for Conducting Supportability Tradeoffs in a Team Setting

One group problem solving technique investigated in the Computer-Aided Group Problem Solving paper was the Boothroyd-Dewhurst Design for Assembly (DFA) methodology. The original premise for the study presented in this particular paper [Cralley, 1990] was that the DFA concept and problem solving process can be applied to maintainability. Although the DFA premise for maintainability was not attained as originally envisioned, a methodology was developed and documented with which a design team can conduct supportability tradeoffs using single-user computer support. Using a ground-based radar unit as the design case, the methodology allows tradeoffs among component redundancy and maintenance site visits to achieve a required level of system reliability while trying to achieve the lowest life cycle cost. The resulting methodology and demonstration were successful particularly in highlighting the significance of relatively simple approaches to computer support to aid the design team negotiation process. The study opened up avenues of research into further developing maintainability assessment methods and tools, the proper role of team computer support and just how to go about organizing and managing engineering design teams for CE.

Concurrent Engineering Teams

The evolution of ULCE into CE, and recommendations from previous group support technology studies, set the stage for the last of the studies under review. In this study [Dierolf, 1990] the primary research questions are how CE design teams are organized and managed and what kind of computer support will enhance their efforts. The study team reviewed literature on teams and group dynamics, visited defense contractors to obtain their views and experiences with CE teams, and built upon previous research experiences related to the study.

The paper presents three findings pertinent to CE teams. The study found, and discusses, a strong relationship between TQM and CE. Though not a new insight into this relationship, the industry site visits found that too often TQM and CE efforts are independent. The more practical and consistent approach is to combine the efforts, thus

promoting the concept of CE as TQM applied to the design process. Another finding is the crucial role of open communication within the team facilitated in most cases by collocation of the team members. A final finding is a reaffirmation of earlier conclusions that computer support for groups and group decision making represents a key opportunity to enhance engineering design efforts.

General Findings

The ULCE papers reviewed represent a wide range of topics addressed by a diverse group of researchers. The central theme of each report is ULCE and the envisioned ULCE environment of advanced computing workstations. Through the course of each research effort, issues were raised and recommendations made, some of which are provided as part of the individual summaries. Some general issues and findings from the ULCE research are:

- The need for better definition of requirements for systems;
- Increased use of multi-disciplined design teams;
- Early consideration of product supportability and producibility, if possible as early as the conceptual design phase;
- The consideration of design as a decision making process;
- The capture and exploitation of design decision audit trails;
- The need for qualitative and quantitative analysis methods; and
- An environment of integrated design tools and databases.

To some extent, each of the above is now part of the CE initiative. ULCE and CE are also similar in that their primary focus, their customer, is on the industrial design community. Since it is industry, not the government, that actually builds the physical systems and equipment, it is natural for the industrial design community to be the prime users of advanced design environments.

However, to realize CE goals of (1) improved quality, (2) reduced cost, and (3) shorter developmental time horizons, CE must also find a place in the government design and acquisition efforts. As previously discussed, this version of CE is what we have called Integrated Product Development (IPD). The products produced by an IPD team are contractual documents such as specifications or statements of work. The IPD team defines what functions are required in the end product weapon system. To extend the IPD team role further, we can say the IPD team consists of those involved in defining needs for new capabilities as well as those tasked with defining those requirements in contractual documents. To a large extent, the IPD team consists of those government personnel involved in a particular design and acquisition effort.

RAPID

The AFHRL Requirements Analysis Process In Design (RAPID) research and development project targets the IPD team as its prime user. RAPID builds upon the ULCE recommendations for better requirements definition, early consideration of product "ilities" in an integrated fashion, capture and exploitation of decision rationale, and enhanced design tradeoff processes. The objective of RAPID is to define, develop and demonstrate a decision support

environment to enhance weapon system acquisition. In particular, RAPID seeks to enhance the determination, analysis, and management functions of weapon systems requirements. These efforts commence when a need is first realized, continue through the evolution of that need into increasingly detailed requirements, and continue through weapon system operations and support.

The rationale for a RAPID capability is to save acquisition costs by simply not incurring the avoidable costs. Properly defining requirements early alleviates the need to change the requirement later, thus the system is built right the first time. Various studies and papers quote rules-of-thumb that 70% of life cycle cost is committed after just 5% of actual cost is expended. Actual figures vary, though the importance of this 70/5 relationship is that very early design decisions often have significant effects on the total system cost. Early design decisions by the IPD team involve system needs and build-to requirements. Methods and tools covering performance, manufacturing, and support requirements consideration can improve the quality and appropriateness of these early, influential design decisions. This helps avoid some of the production start up problems and high system support costs.

RAPID seeks to accomplish its objective through a combination of computer tools (such as traceability tools, rationale capture tools) coupled with expert systems, knowledge-based systems, and other productivity and efficiency enhancing technologies. By capturing expert knowledge and pooling currently available general knowledge into a knowledge base, RAPID can bring more accurate and system-pertinent information to bear on the design situation than is currently available. This information, so captured and made available, can further be brought to bear earlier in the design process as recommended in the ULCE studies. Better, more pertinent information should lead to better design decisions by the IPD team. These IPD decisions translate into less design problems encountered by the CE team tasked with building the system or equipment.

Since RAPID targets the IPD team, RAPID will provide particular capabilities for supporting the functions within the requirements process. Such capabilities include:

- Weapon system need conceptualization tools,
- Tradeoff analyses tools,
- Traceability tools,
- Documentation correlation and consistency tools,
- Tools to include/tailor standards and guidelines,
- Risk management tools and methods,
- Tools to support the conduct of design audits,
- Tools to enhance test planning and management.

There are numerous efforts concerned with improving the weapon systems requirements and weapon systems acquisition process. These efforts address cultural and procedural issues involving personnel at all levels of the DoD hierarchy. The RAPID concept is to work on improving tools and techniques at the acquisition worker level while high-level initiatives address the tougher, longer-range cultural and legal issues. By introducing improvements into the existing requirements process, RAPID can produce savings and efficiencies from within the overall process. Some of the potential benefits include:

- More robust alternatives to accommodate rapidly changing threat scenarios;
- Early consideration of "ilities" in conjunction with system performance characteristics;
- Consistency in the definition and evolution of system requirements as embedded in program documentation; and
- Lower developmental and life cycle cost through better understanding and parameterization of the weapon system requirements.

Conclusion

The ULCE initiative provides some very good research products and particularly pertinent recommendations to improve weapon systems design and acquisition. CE is the newest initiative, broadening the scope of the predecessor ULCE initiative so as to address such issues as human design teams and design cultural issues. Real improvements in weapon system acquisition requires a team approach with government and industry working together to define, develop, and field high quality, highly functional, and robust weapon systems and equipment. The government's role in the acquisition process is to define and scope the requirements for the weapon system, and then oversee (manage) industry efforts to satisfy that set of weapon system requirements by producing and fielding the end-use system. RAPID is an environment to enhance the definition, analysis, and management of those requirements. The RAPID vision is to create a computer tool system, employing advanced computing techniques, combine that system with improved methodologies to realize TQM and CE goals of increased quality at decreased cost available to the system end-user in a shorter length of time.

References

- Azam, Shapour, et al. (May 1988). Decision Support Requirements in a ULCE Environment. Vol. II. Institute for Defense Analyses, IDA P-2064.
- Azam, Shapour, et al. (May 1988). Decision Support Requirements in a ULCE Environment. Vol. III. , Institute for Defense Analyses, IDA P-2064.
- Brei, ML, et al. (April 1988). Architecture and Integration Requirements for an ULCE Design Environment. Institute for Defense Analyses, IDA P-2063.
- Brei, ML; David A. Dierolf; Karen J. Richter. (June 1989). A Survey of Research Methods to Study Design. Institute for Defense Analyses, IDA P-2155.
- Calkins, Dale E., et al. (May 1989). Aerospace System Unified Life Cycle Engineering (ULCE) Producibility Measurement Issues. Institute for Defense Analyses, IDA P-2151.
- Costello, Robert B., The Under Secretary of Defense for Acquisition. 9 March 1989. Concurrent Engineering - A Total Quality Management Process. Memorandum for

Secretaries of the Military Departments, Attention: Service Acquisition Executives, with attachments.

Cralley, William E.; David A. Dierolf; Karen J. Richter. (January 1990). Computer Support for Conducting Supportability Trade-offs in a Team Setting. Institute for Defense Analyses, IDA P-2313.

Cullinane, Thomas P. and Richard J. Meyer. Information Resource Management in a Concurrent Engineering Environment. AUTOFACT '90 Proceedings. Society of Manufacturing Engineers. Dearborn, MI. 12-15 November 1990.

Dierolf, David A. and Karen J. Richter. (February 1989). Computer-Aided Group Problem Solving for ULCE. Institute for Defense Analyses, IDA P-2149.

Dierolf, David A. and Karen J. Richter. (September 1990). Concurrent Engineering Teams. Institute for Defense Analyses, IDA P-2516.

Fulton, R. E.; Chou Pin-Yeh; Karen J. Richter. (October 1989). Managing Engineering Design Information. Institute for Defense Analyses, IDA P-2154.

Goldstein, Siegfried; David Owen; Karen J. Richter. (October 1989). Product Supportability Issues in the Early Design Phases. Institute for Defense Analyses, IDA P-2150.

Meyer, Stephen A. Integrated Design Environment-Aircraft (IDEA): An Approach to Concurrent Engineering. Paper presented at the American Helicopter Society Forum, Washington D.C., 21-23 May 1990.

Pymatuning Group. (October 1988). Industrial Insights on the DoD Concurrent Engineering Program. Arlington, VA: The Pymatuning Group Inc. DTIC #AD A204715

Rogan, J. E. and William E. Cralley. (January 1990). Meta-Design -- An Approach to the Development of Design Methodologies. Institute for Defense Analyses, IDA P-2152.

Tse, Edison and William E. Cralley. (June 1989). Management of Risk and Uncertainty in Product Development Processes. Institute for Defense Analyses, IDA P-2153.

ULCE DSS Working Group. (May 1988). Decision Support Requirements in a ULCE Environment, Vol. I. Institute for Defense Analyses, IDA P-2064.

Unified Life Cycle Engineering (ULCE) Implementation Plan. February 1987.

Winner, Robert L.; James P. Pennell; Harold E. Bertrand; Marko M. G. Slusarczyk. (October 1988). The Role of Concurrent Engineering in Weapon System Acquisition. Institute for Defense Analyses, IDA R-338.