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A PROCESS FOR THE AGILE PRODUCT REALIZATION OF ELECTRO MECHANICAL DEVICES (A-PRIMED)

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EXECUTIVE SUMMARY

This paper describes a product realization process developed at Sandia National Laboratories by the A-PRIMED project that integrates many of the key components of "agile manufacturing" (Nagel & Dove, 1992) into a complete, step-by-step, design-to-production process. For two separate product realization efforts, each geared to a different set of requirements, A-PRIMED demonstrated product realization of a custom device in less than a month. A-PRIMED used a discriminator (a precision electro mechanical device) as the demonstration device, but the process is readily adaptable to other electro mechanical products. The process begins with a qualified design parameter space (Diegert et al, 1995). From that point, the product realization process encompasses all facets of requirements development, analysis and testing, design, manufacturing, robot assembly and quality assurance, as well as product data management and concurrent engineering. In developing the product realization process, A-PRIMED employed an iterative approach whereby after each build, the process was reviewed and refinements were made on the basis of lessons learned. This paper describes the integration of project functions and product realization technologies to develop a product realization process that on repeated iterations, was proven successful.

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DISCLAIMER

In June 1993, Sandia National Laboratories (SNL) launched the Agile Product Realization for Innovative Electro MEchanical Devices (A-PRIMED) project. The stated goal of the project was to develop and demonstrate a much faster design to production cycle for high quality, electro mechanical devices. The quality goal was for custom electro mechanical devices to meet functional acceptance criteria first time, off-the-line, instead of requiring the fine tuning typically necessary with such custom mechanisms. An electro mechanical safety device, the pin-in-maze discriminator, was chosen as the example family of products. The pin-in-maze discriminator, hereinafter referred to as the discriminator, was an ideal subject for development and testing of agile product realization processes since a broad range of design variants could be envisioned. Also, the discriminator offered design complexity since depending on the requirements of the application, there are over 40 total parts, including 20 unique parts, as well as variations in materials and interface requirements.

The approach taken by A-PRIMED was to exploit the product realization paradigm, proposed by D.R. Strip, called Parent/Child™ design (Parratt et. al., in press). The fundamental idea underlying this paradigm is that a viable new product idea usually leads to a family of similar products. For example, a company that makes a new computer monitor will likely make a line of monitors with the following design variations: small, medium, and large screens; low, medium, and high resolution screens; electronic or manual screen adjustments; and different housing materials and colors. While pizza and auto makers have long provided some degree of product customization based on a small set of options, Parent/Child design broadens the boundaries of customization to the limits of imaginable applications for a given product family.

The intent of the A-PRIMED project was to integrate and demonstrate an extensible slice of an agile product realization enterprise. The project scope did not encompass all elements of an agile product realization enterprise (e.g., administrative functions received minimal attention), but focused on a complete design to production process emphasizing model-based design and production, computer simulation and automation: all vital components of agile manufacturing (Nagel & Dove, 1992) and "Information-Driven Manufacturing" (Brost et. al., 1992). In creating an agile enterprise, it was necessary that the project address organizational and technical aspects of agile manufacturing. Project team members were drawn from 20 different SNL organizations and grouped into seven (with some overlap) project teams: Management, Design, Manufacturing, Automated Assembly, Communications, Analysis and Quality Assurance. Concurrent engineering teaming techniques were implemented that encouraged team members to develop the familiarity with each other necessary for effective and efficient communication, and that assured involvement of all essential engineering functions in product decisions (Ashby et. al., 1995).

The A-PRIMED product realization process depends on each of the following agility-enabling capabilities:

(1.) Parent/Child Design utilizes the parametric programming capabilities now available in solid model CAD packages to design for a family of products, rather than a single point design. Economy is achieved through the reuse of product and process across a family of products defined by a design parameter space (Parratt et. al., in press).

(2.) Qualification of Design Parameter Space involves the characterization of fabrication and assembly processes, and virtual prototype analysis and physical testing of variants within the parameter space (Diegert et. al., 1995). Emphasis is placed on qualification of processes and design attributes, over a design parameter space, rather than post-production qualification of single processes and product lines (Brost, et. al., 1992).

(3.) Virtual Prototype Testing provides an economical alternative to physical test for rapidly addressing questions that arise during design development.

(4.) Computer-Aided Manufacturing (CAM) streamlines the process of generating Numeric Control (NC) code for fabrication of component parts.

(5.) Automated Assembly Planning, driven directly from CAD models, generates robot code and workcell simulations enabling a flexible, predictable assembly process (Jones & Kaufman, 1993; Jones, et. al., 1995).

(6.) Electronic Communications to enable ready access to product information and to facilitate communication between team members.

The above agility-enabling capabilities introduced significant challenges in themselves and noteworthy progress was made in each area. However, for the A-PRIMED project to meet its objective of producing high quality, new products in substantially less time, it was necessary to integrate these agility-enabling capabilities into a beginning-to-end product realization process.

AGILE PRODUCT DEVELOPMENT PROCESS OVERVIEW

An overview of the product realization process is shown in Figure 1. It is presumed that a design parameter space has been developed and qualified (Diegert et. al., 1995). Likewise, the process presumes fabrication and robot assembly processes have been characterized. The process also presumes certain technical capabilities (e.g., design automation, product data management (PDM), automated assembly planning) that if not available, must be substituted with alternative approaches for accomplishing the same objectives.

The process begins with a customer who has an application for a discriminator, and a general understanding of the functional and environmental requirements of their application. Initially, customer requirements and design trade-offs are identified and requirements are matched to the parameter space. Early on, a decision is made regarding whether the customer's requirements fit within the qualified parameter space, meaning that design and production may proceed, or the customer's requirements fall outside the qualified parameter space. If the customer's requirements fall outside the qualified parameter space, a decision is required to either expand or not expand the qualified parameter space. If requirements fit within the parameter space, then Child Design Definition may proceed. Child Design Definition concludes when the child design passes a Child Design Review, at which time Child Design Build begins. Child Design Build concludes with Final Acceptance and Product Delivery.

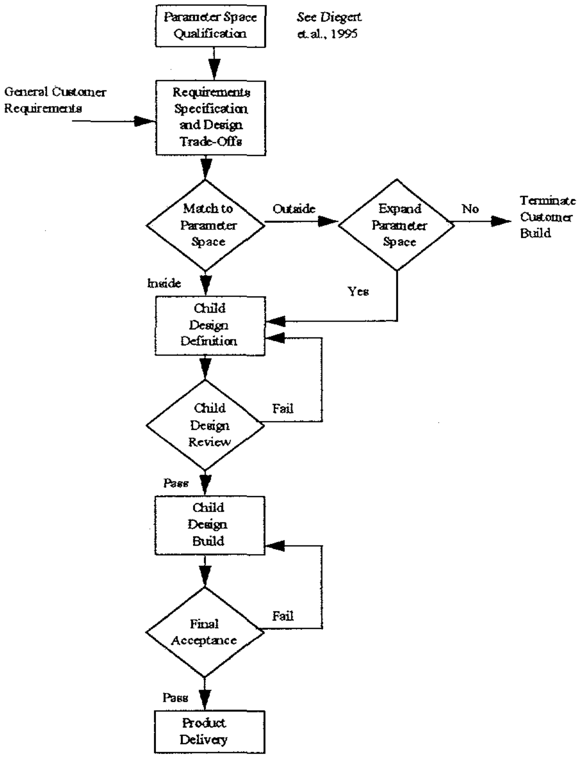
When the decision is made to Expand the Parameter Space, there is an initial feasibility assessment after which, at the direction of the customer, a decision is made to either proceed with Child Design Definition or terminate the custom build. When there is a decision to Expand the Parameter Space, Child Design Definition would include additional qualification activities not ordinarily undertaken for designs that fall within the qualified parameter space. The extensive product and process knowledge obtained during qualification of the parameter space allows confident assessments of the tasks, schedules and costs associated with expansion of the qualified parameter space. Consequently, the risk usually associated with new product development and qualification is greatly reduced, making expansion of the qualified parameter space a viable option for many customers. The following sections describe in greater detail the activities associated with steps shown in Figure 1.

REQUIREMENTS SPECIFICATION AND DESIGN TRADE-OFFS

Experience from early A-PRIMED builds indicated that compared to traditional product realization, development of requirements and translation of requirements into design concepts could be greatly reduced in time and scope, as a result of the Parent/Child design approach. With Parent/Child design, a relatively exhaustive set of potential customer requirements covering a broad range of anticipated discriminator applications was created during development and qualification of the parameter space. Similarly, a set of design parameters was identified that could be varied to meet each potential customer requirement. New product development begins with a Requirements Specification Meeting attended by the customer and members of the product realization team. This meeting begins with a review of the customer's application and based on this review, requirements are specified for the new product. Using a Requirements to Design Specification Matrix (see Forsythe et. al., 1995), target values or design specifications are determined for each design parameter that reflects what the team believes is necessary to meet customer requirements. Combined, design specifications provide a conceptual (child) design.

Following completion of the Requirements to Design Specifications Matrix, the team constructs a Design Trade-Offs for Customer Requirements Matrix (see Forsythe et. al., 1995). For each design specification, the effects on performance are compared across requirements and any design trade-offs are noted. Having a well-defined parameter space allows customer requirements to be translated almost immediately into a conceptual (child) design. By accessing product data developed during parameter space qualification, the child design is made tangible through solid models, and illustrations of machine tool paths and robot assembly sequences. Likewise, parameter space qualification provides a thorough knowledge of design trade-offs enhancing the customer's understanding of the consequences of their decisions. When customers leave the Requirements Specification meeting, they have been presented with a conceptual (child) design and have either confirmed or disconfirmed that the proposed product meets their expectations. Thus, customers have an opportunity to provide highly constructive input to the early design process minimizing uncertainties the customer may have regarding the new product meeting their expectations. Furthermore, the Design Trade-Offs for Customer Requirements Matrix offers a succinct history of the relationship between design decisions and their impact on customer requirements, and guarantees traceability of design decisions.

Figure 1. Overview of Agile Product Realization Process



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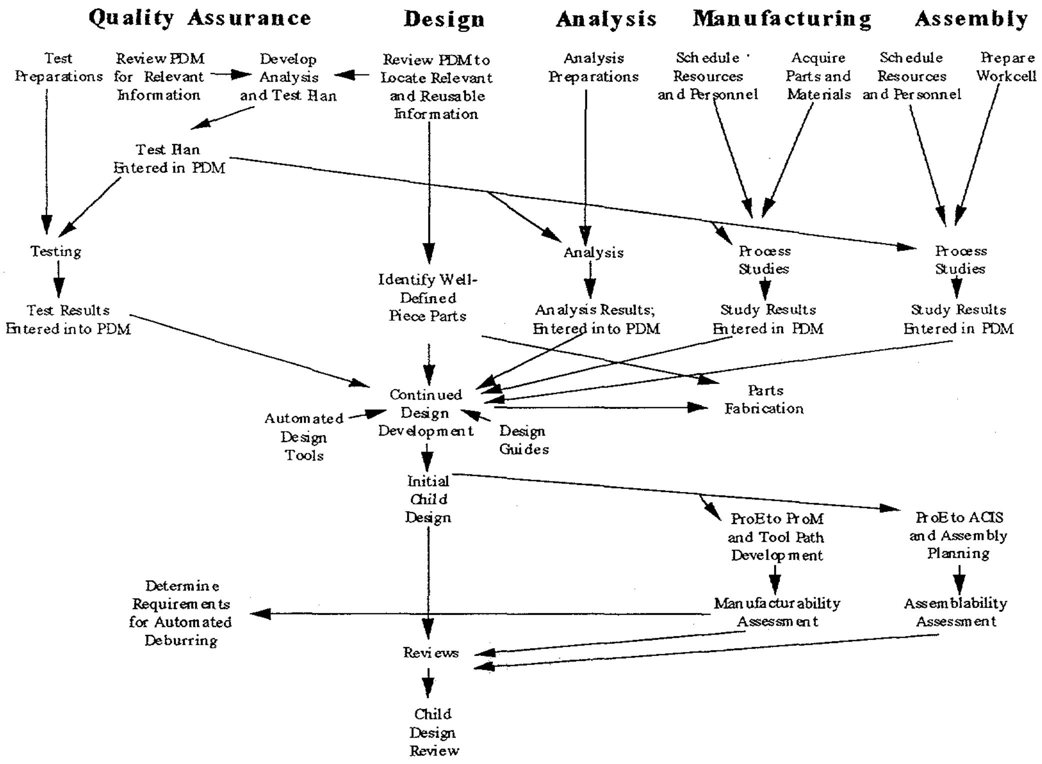
CHILD DESIGN DEFINITION

At the beginning of the Child Design Definition phase, the product realization team has customer requirements, a conceptual (child) design and an understanding of what efforts are required for design, production and acceptance of the child design. Figure 2 provides a chronological illustration of Child Design Definition activities.

- For the Design team, the PDM is referenced to locate existing assembly or part files that meet or approximate the new product's specifications. Due to the parametric design approach, relevant product data from previous design efforts may be readily identified and where unavailable, new product data may be quickly generated. For assembly or part files that approximate the new product's specifications, associated files (e.g., analysis, testing, manufacturing) may be reviewed and relevant knowledge applied to the new design. This information also serves as input to the Quality Assurance team in their development of the Analysis and Test Plan.
- While analysis and testing conducted during qualification of the parameter space eliminated most uncertainties, limited analyses and testing may be needed to resolve certain product-specific concerns. Thus, the Quality Assurance team must develop and initiate an Analysis and Test Plan. Tests may include shock, vibration, thermal, pyroshock and centrifuge, depending on the customer's environmental requirements. Test results are entered into the PDM with associative links to design files where appropriate and automatic notification of Quality Assurance team members.
- When analysis is necessary, the Analysis team begins by acquiring appropriate CAD data, translating CAD data into finite element models, conducting look-ups and modifying analysis codes. Analysis may consider: static and shock loading, vibration, operational environment and thermal environment. Virtual prototype analysis is essential for the A-PRIMED product realization process since it offers a much less expensive and time consuming approach to answer design questions than physically building and testing component parts. Reliance may be placed on the accuracy of virtual prototype analyses due to their faithful representation of physical processes and geometric features important in predicting performance of a design under a range of environmental conditions. Results from all analyses are entered into the PDM with associative links to design files where appropriate and automatic notification of Quality Assurance team members.
- Manufacturing begins by assuring availability of resources and personnel, acquiring stock and off-the-shelf parts and readying machines to be used for fabrication. The Manufacturing team also conducts any process studies that may be necessary and fabricates any parts that may be needed for test activities.
- Activities necessary for readying the robot workcell may commence. However, since the workcell was designed to assemble any design within the parameter space, only trivial workcell modifications are ever necessary. Also, necessary resources and personnel are scheduled and any process studies needed are conducted.

As described in the previous sections, most early Child Design Definition activities focus on answering outstanding design and manufacturing questions. At the discretion of the Quality Assurance team, and the Design team through their participation in the Quality Assurance team, fabrication may proceed for certain well defined piece parts. The Design team should have freedom to proceed on most, if not all, facets of the design since most design and process issues were addressed during qualification of the parameter space. As design and

Figure 2. Child Design Definition Process



manufacturing issues are resolved by other members of the Quality Assurance team, the design engineer is notified and may proceed with those facets of design development.

From the earliest opportunity in Child Design Definition and throughout Child Design Definition, the design is reviewed to determine which if any well defined piece parts may be identified for formal release. The intent is to apply the engineering judgment of the Design team to identify well-defined parts, and release those parts so that fabrication may begin at the earliest practical point in the process. Ordinarily, releasing parts for fabrication prior to formal review and acceptance of the final design would be quite risky. However, this risk is largely mitigated due to the knowledge gained in qualifying the parameter space and the ready accessibility of product data from earlier efforts, through the PDM.

For certain parts, parametric design automation is employed. For example, if a new maze wheel design is required, the automated maze generator would be used for development of a CAD model of a new maze wheel with the appropriate sequence of left and right turns. The maze design produced with the maze generator would then be subjected to automated mass reduction and automated mass balancing.

As results from the Analysis and Test Plan become available to the Design team, these results are incorporated into the design. The translation of these results into design decisions occurs collaboratively. Two forums exist for making collaborative design decisions. First, meetings of the Quality Assurance team provide a forum where design decisions may be discussed among representatives of Design, Analysis, Testing, Manufacturing, and Automated Assembly. However, scheduling and time constraints limit the frequency with which the Quality Assurance team may be brought together. Consequently, Interactive Collaborative

Environments (ICE) is used as a second forum for making collaborative design decisions (Ashby & Lin, 1994). With ICE, the Pro/Engineer application (and other X-windows based applications, as well) may be shared between the workstations of members of the Design and other teams allowing graphical representations of designs to be viewed and manipulated by each participant in the ICE session. Through these collaborative design approaches, only the most routine design decisions are made in isolation and input/feedback to design decisions is obtained early in the decision making process when minimal time and resource commitments have been made to any particular design direction.

Upon receiving automatic notification of the availability of the Pro/Engineer model of the assembly design, the Manufacturing team may transfer that model into Pro/Manufacture® for development of tool paths for fabrication of constituent parts of the assembly. Combining Pro/Manufacture models of stock, parts, tooling and tool paths, Pro/Manufacture enables development of graphical illustrations of the fabrication process for each part. Through illustrations based on Pro/Manufacture solid models, the Manufacturing team may detect potential problems in manufacturability such as points in the design where extensive deburring would be required because tooling is incapable of removing all the material called out in the CAD model. Pro/Manufacture illustrations provides a final check, prior to finalization of the child design, to assure the quality of manufactured parts and the efficiency of the manufacturing process.

Assemblability of a child design is assessed using the Archimedes automated assembly planning system (Jones & Kaufman, 1993). Archimedes takes a Pro/Engineer assembly model and converts it to an ACIS® solid model. The Archimedes planners then analyze geometric characteristics and augment this data with heuristics such as the need for vertical assembly actions, minimization of the number of fixtures, assurance of tool accessibility, etc. These analyses produce an optimized assembly sequence and an animated graphical illustration demonstrates the assembly sequence.

Robot assembly can be tested using the Archimedes Illustrator, which automatically interprets assembly plan scripts to graphically display a robot assembling the device in a simulated workcell. Where the assembly requirements of a design exceed the capabilities of the workcell, either design modifications or workcell modifications are identified and implemented before finalization of the child design.

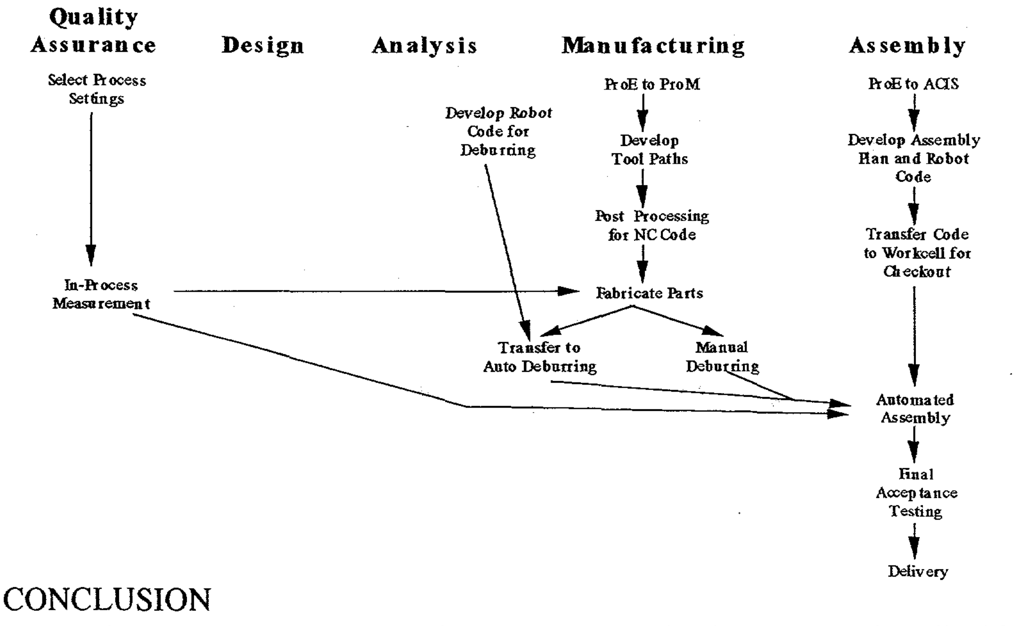
Throughout Child Design Definition, the objective is to assure every foreseeable problem in functionality, manufacturing and assembly is identified and addressed prior to beginning Child Design Build. While this may extend Child Design Definition, this is acceptable given the potential delays and costs that could be incurred if a redesign was necessary due to either fabrication problems or deficiencies in product performance. However, qualification of the design parameter space eliminated most problems that could have arisen during traditional design efforts. Consequently, the greatest likelihood is that any problems uncovered will be highly product specific. With most generic problems resolved in qualifying the design parameter space, there exists a greater opportunity for attention to potential design specific problems and Child Design Definition has incorporated numerous opportunities for identification and resolution of such problems. Child Design Definition also recognizes that each new product development effort begins with tremendous knowledge of the range of possible design variations and where uncertainties do and do not exist. Where there is great certainty regarding specific design features, every effort is made to allow parts fabrication to begin at the earliest point possible. Where uncertainty exists, fabrication is delayed until there has been opportunity for thorough analysis and testing, and extensive review so that every effort has been made to resolve the uncertainty prior to fabrication.

CHILD DESIGN BUILD

Besides receiving formal release to begin production of certain well-understood piece parts during Child Design Definition, Manufacturing gets an additional head start through activities associated with proving out the manufacturability of piece parts. In translating Pro/Engineer CAD models into Pro/Manufacture, and developing tool paths for the fabrication of parts, much of the pre-fabrication work of the NC programmer is accomplished. Likewise, the Automated Assembly team should have completed preparations of the robot workcell.

Figure 3 provides a graphical depiction of the Child Design Build process. For a given part, fabrication and assembly may proceed once electronic notification is received that the part has been formally released. If the NC programmer has not already done so, Pro/Engineer design files are downloaded from the PDM and transferred into Pro/Manufacture. Pro/Manufacture is then used to generate tool paths for cutting each part within the assembly. After post-processing of tool paths, NC codes are transferred to the machinist along with documentation specifying the tooling, machine set-up, stock and any special instructions. Automated Assembly downloads the assembly model from the PDM and uses the Archimedes assembly planner to generate first, an assembly plan, and second, robot code to drive the assembly process.

Figure 3. Child Design Build Process



CONCLUSION

As A-PRIMED developed the product realization process described in the preceding sections, the goal was to develop and demonstrate a process for much faster product realization of quality electro mechanical devices. All evidence indicates that the A-PRIMED product realization process has been successful in reducing the product realization cycle and in assuring product quality.

For the first A-PRIMED build, a discriminator for a robot quick change adapter was designed and produced in 24 days. The second build focused on developing a discriminator that met the requirements of an electronic defense system, with the specific application being a armored combat vehicle. Not considering customer-imposed delays, the second build required 30 days and delivered a discriminator that met the stiffest requirement, fast operation time. Also, significant changes to tolerances were made to improve manufacturability and assemblability with testing to assure product performance was not degraded by these changes.

Tests have indicated that the A-PRIMED product realization process was also successful in assuring product quality. Whereas previous discriminators have been built to meet specific random vibration requirements and tested to those requirements under non-operational conditions, discriminators built using the A-PRIMED product realization process have been shown to meet random vibration requirements within both non-operational and operational modes. Similarly, life cycle testing has shown discriminators built using the A-PRIMED product realization process exhibited life cycles of 4,000 cycles and greater. These results far surpass the performance obtained from earlier product realization efforts.

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REFERENCES

Ashby, M.R., Forsythe C., Benavides, G., Diegert, K., Jones, R., Longcope, D. and Parratt, S. (1995). A' *(A-PRIMED): A Case Study in Team work.*

Ashby, M.R. & Lin, H.W. (1994). *Interactive Collaborative Environments (ICE): Platform Independent X Application Sharing and Multi-Media over Wide Area Networks at Sandia National Laboratories.* Proceedings of the Fifth International Symposium on Robotics and Manufacturing. Maui.

Brost, R.C., Strip, D.R. & Eicker, P.J. (1992). *The Technology Base for Agile Manufacturing.* Presented at the 1992 NASA Workshop on Space Operations, Applications and Research, Houston.

Diegert, K.V., Easterling, R.G., Ashby, M.R., Benavides, G.L., Forsythe, C., Jones, R.E., Longcope, D.B., & Parratt, S.W. (submitted). *Achieving Agility Through Parameter Space Qualification.* Agility Forum, Atlanta.

Forsythe, C. & Ashby, M.R. (1994). *Developing Communications Requirements for Agile Product Realization.* SAND Report No. 94-0481C, Sandia National Laboratories, Albuquerque.

Forsythe, C. & Ashby, M.R. (1995). *User-Driven Product Data Manager System Design..* Proceedings of the Human Factors and Ergonomics Society, 1170-1174, San Diego.

Forsythe, C., Ashby, M.R., Benavides, G.L., Diegert, K.V., Jones, R.E., Longcope, D.L. & Parratt, S.W. (1995). *A Process for the Agile Product Realization of Electro Mechanical Devices.* SAND Report No. 95-0536, Sandia National Laboratories, Albuquerque NM.

Jones, R.E., and Kaufman, S.G. (1993). *Automatic Assembly Planning and its Role in Agile Manufacturing: A Sandia Perspective.* In W. E. Alzheimer, M. Shainpoor and A. Bagchi (eds.) Rapid Prototyping: A Paradigm to Agile Manufacturing, ERI Press, Albuquerque NM.

Jones, R.E., Ames, A.L., Calton, T.L., Kaufman, S.G., Laguna, C.A., Saavedra, M., Wilson, R.H. & Woods, R.O. (1995). *The Automated Assembly Team Contributions to the A-PRIMED Agile Manufacturing Project. SAND Report No. 95-1340, Sandia national Laboratories, Albuquerque.*

Nagel, R.N. & Dove, R. (1992). *21st Century Manufacturing Enterprise Strategy.* Iacocca Institute, Lehigh University, Bethlehem, PA.

Parratt, S.W., Diegert, K.V. & Ashby, M.R.. (in press). *A Parent/Child Design Paradigm..* Agility Forum, Boston MA.