Complex Product Realization 2020: Key Issue Areas

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Preface

In July 1999, DARPA tasked the Institute for Defense Analyses to identify long-term issues associated with the development of complex systems. A study team was assembled to articulate these issues. The team reviewed current literature, interviewed design system customers, vendors and researchers, and organized a workshop. The workshop was held at the Institute for Defense Analyses in Alexandria, Virginia, on September 9, 1999. A listing of the participants and agenda appears at the end of this paper.

The ideas and opinions expressed herein are interpretations by the study team. They do not necessarily reflect the point of view of any individual participant in the interviews or workshop, and this paper does not report all inputs received. Errors and omissions are solely the responsibility of the authors.

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Executive Summary

“Complex Product Realization” refers to the technologies and processes associated with conceiving, designing, and manufacturing highly integrated, multi-component systems. This project focused on the intricacies associated with the overall design of such systems. The primary research goal was to begin to identify challenges beyond those being addressed by existing, near-term research efforts. This paper reports the preliminary findings of literature reviews, interviews, and a workshop conducted between July and September 1999.

The ultimate vision for complex product realization is a new paradigm born out of the confluence of radical advances in information technologies, analytical tools using this information, and the changes in organizations these advances will enable. In this new world, sophisticated simulations are seamlessly integrated with conceptual and detailed design tools. These tools allow customers, designers and managers to learn and adapt together as they experiment in real time with a multitude of product concepts. Intelligent agents monitor the process and provide guidance on overall design strategy, technical risks and opportunities, manufacturing issues, reliability and life cycle cost.

As product realization progresses, the learning and adaptation process expands to encompass all participants in all product life cycle areas. Large, international teams of designers, developers, manufacturers, marketing personnel, and managers—all trained in working effectively across organizational—are facilitated in their product tradeoff negotiations by multi-attribute, cross-disciplinary optimization tools. High-level managers and senior product architects take advantage of their wide and detailed view into the evolving web of business relationships to facilitate the absorption of new technologies, provide guidance on changing customer needs, and formulate a product portfolio strategy.

The foundation of this future product realization environment is based on advancing information technologies — i.e., the convergence of digital technologies for voice, data and images, combined with increasing processing power, network capacity and software efficiency. Much of current research aims to leverage emerging information technologies to coordinate the activities of design teams, managers, and supply chain players so as to reduce product cycle time and life cycle cost while increasing user satisfaction with the resulting products. Sophisticated, network-based design tools that facilitate concurrent optimization of component and subsystem designs are already being used in certain product areas and are expected to diffuse widely over the next decade.

But even if current research and design tool applications come to complete fruition, capabilities in complex product realization will likely fall short of the vision. Researchers and industry are far from achieving a science of complex, integrated systems. New mathematical and analytical capabilities will be needed to underpin complex product realization tools in 2020. These tools will also need to incorporate scientific understanding and characterization of new types of production processes for emerging technologies; e.g., MEMS, bio-mechatronics, and nano-structures.

Researchers and industry are far from achieving a science of complex, integrated systems.

Four general issue areas that will require substantial progress *beyond current trends* are listed below:

❒ **Knowledge Management/Decision Support**
“Information is not the same as knowledge”

❒ **Business Process Re-Engineering**
“Knowledge is not the same as capability”

❒ **Characterization and Communication of User Needs**
“Capability is not the same as doing the right thing.”

❒ **New Frontiers**
“New capabilities needed to build ‘systems of systems’ from incongruent emerging technologies.”

Within these general issue areas, this study has identified a set of overlapping research challenges that will need to be addressed if progress toward this vision is to be assured:

❒ **Logic of knowledge abstraction**

There is a need for product definition capabilities that can represent the product in fine detail for parts designers, less detail for systems engineers, and even less detail for the chief engineer’s perspective. Research areas include data structures and intelligent agents.

❒ **Distributed, Adaptive Algorithms for Optimization of Multi-Dimensional Designs**

The different levels of the design space mean that tradeoff problems tend to be discontinuous and ill conditioned. This suggests that there may be mathematical properties that are characteristic of these spaces, and that search algorithms might be created which could exploit these characteristics to yield more optimal and more robust solutions. Research areas include visualization technology and, again, intelligent agents.

❒ **Mathematics and Science of Product Architecture and Modularity**

The interconnection of design challenges means that complex product realization will increasingly involve integrating “system of systems.” To do so, it will be important to identify interdependent risk drivers and manage total risk posture across entire platforms and across time. Key areas include representing and valuing flexibility, structuring supply chains, and cost modeling.

❒ **Virtual Characterization and Qualification of “System of Systems” Products and Processes**

The physical models that underlie current product realization systems will need to keep up with new technologies, which frequently exceed customary operating regimes. Emerging technologies such as MEMS, bio-mechatronics, and nano- technology will require entirely new manufacturing processes and process characterizations.

Future work in projecting trends in complex product realization will need to identify these research areas more specifically and delve into how particular aspects of the ultimate vision might happen. Key questions to be addressed would include the following:

- **How and where are advances in complex product realization happening now?**
- **What are expected improvements along the commercial evolutionary path?**
- **What assumptions are embedded within the current research paradigm?**
- **In what ways might government funds facilitate leapfrog improvements, infrastructure development, and advances, especially those that lead to US defense advantage?**

1 Knowledge-Based Complex Product Realization

The ultimate vision for complex product realization is a new paradigm born out of the confluence of radical advances in information technologies, analytical tools using this information, and the changes in organizations these advances will enable. In this new world, sophisticated simulations are seamlessly integrated with conceptual and detailed design tools. These tools allow customers, designers and managers to learn and adapt together as they experiment in real time with a multitude of product concepts. Intelligent agents monitor the process and provide guidance on overall design strategy, technical risks and opportunities, manufacturing issues, reliability and life cycle cost.

As product realization progresses, the learning and adaptation process expands to encompass all participants in all product life cycle areas. Large, international teams of designers, developers, manufacturers, marketing personnel, and managers—all trained in working effectively across organizational cultures—are facilitated in their product tradeoff negotiations about by multi-attribute, cross-disciplinary optimization tools. High-level managers and senior product architects take advantage of their wide and detailed view into the evolving web of business relationships to facilitate the absorption of new technologies, provide guidance on changing customer needs, and formulate product portfolio strategy.

This product realization environment is based partly on extrapolation of current trends in information technologies—i.e., the convergence of digital technologies for voice, data and images, combined with increasing processing power, network capacity and software efficiency. Certain elements of it are based on known demands for new capabilities, contemporary management challenges, and current points of departure for technology development. These trends and technologies will be discussed in Section 2.

But many aspects of this vision represent profound changes in design strategy and organizational behavior. The daunting question arises: Are we now failing to recognize the emergence of new methods of production, those that will qualitatively change the ways we do product development? Will the nature of competition and opportunity change in such a way that current producers will undergo radical organizational change, or be wiped out by a new and fundamentally different kind of firm? Is the concept of a stable “firm” itself a concept appropriate for the year 2020, when adaptable enterprises may be the norm?

In order to try to transcend the traps posed by extrapolation, this project proceeded by assuming that the technologies and approaches presently being pursued have matured within the next 5-10 years. Furthermore, it is assumed that tools and organizational structures have effectively integrated the results of current mainstream research. At this point, the questions become “what next?” “What is missing?” “What is it that we still can’t do?” “What will become the pressing problems—the next generation of unforeseen obstacles hidden within the shadows of these advancements?”

Consider, for instance, the type of advances in understanding, infrastructure, and tools that would be required to implement a scenario such as the following:

> Week 1: A Corporate Entrepreneur (CE) within the Global Automotive Group (GAG) submits a business plan for the manufacture of a new automobile to the company's Executive Product Development Board (EPDB). CE presents the results of preliminary modeling and simulation studies, which show that a new "chassis-less" structure invented recently by GAG's Automotive Research Products Affiliate (ARPA) can reduce manufacturing costs by about 25%. The modeling and simulation tools are integrated with technical and market analyses models that suggest that a mid-range "affordable" sports car will be the best launching point for learning about and evolving this new manufacturing approach. The EPDB votes to back the plan and release initial funding for concept development contingent on the CE establishing a financial partnership to participate as a joint venture.
>
> Week 2: CE contacts a potential financing partner, Virtual Automotive Products (VAP) with the plan. VAP's management assesses the initial concept, and its role as a product distributor, and a Joint Venture is formed. CE then accesses the **National Database of Product Realization Expertise (NDPRE)**. He (1) locates profiles on 300 potential primary subtier vendors of relevant expertise, (2) views their core areas of expertise, and (3) available capacity. From this review he solicits bids from 50 relevant firms for 10 primary subsystems. Utilizing **in-house capacity planning decision support systems** they submit bids.
>
> Week 3: CE selects 12 winners. For two of the critical subsystems — propulsion and electronic navigation — two competing firms are selected. A (virtual) planning meeting is held with the subsystem team members to refine the product definition in relation to the segment of the market they wish to attack. An IPPD is established to further define product architecture, and 12 IPTs are formed. Owing to the **standardization of process and design languages**, the design IPTs are able to connect their intra-business information systems to form an inter-business information center.
>
> Week 4: Using a **distributed architecture planning package**, an initial modularity assessment is performed. Alternative partitioning schemes are evaluated using **multi-level risk analysis tools** relative to the values of expected market segments, product portfolios that can be realized from common platforms, and the capabilities of subtier vendors. An initial **production process assessment** is formulated. Based on these analyses and IPT feedback, the IPPD decides the combine four modules into two. A decision is made to go forward with the "chassis-less" structure, but to produce the structure in-house due to the risk assessment results. One primary subtier vendors drops out as a result, while the two affected IPTs are combined into one.
>
> Week 5: IPTs define and standardize the relevant database and information system interfaces. An inter-business database is also established, allowing each IPT to review how its sub-system links into the complete product. The IPPD makes **system level trade-offs and optimization**, advising the individual IPTs on the value of various design goals and specifications and the conditions under which these goals and specifications might change due to potential discoveries later in the process. Production process simulation results lead to additional manufacturing trade-offs as the lightness and strength of the new structure permit the use of a vendor-proposed suspension system, that otherwise would have added too much weight.
>
> Week 6: The IPT leaders meet with their respective teams. Concurrently, each conducts a rapid review of subtier vendors. They are able to review core competencies, established performance in scheduling and tolerance, and realization of cost targets. A similar process of bid solicitation and selection proceeds. The standardization of process and design languages allows each to instantly establish a mutually accessible data repository. The core of the supply chain is thereby established. As each organization links into the supply chain, **an activity based costing system** links horizontal operations into a **dynamic organization management accounting system (DOMAS)**. Hence, CE is able to track the project's cost

flows, measuring sub-contractor performance, and monitor the emerging product design and supply chain.

Week 7: Preliminary analyses of the projected manufacturing orders allow the auto company to develop an **optimal supply web**. Applying various **organizational performance metrics** (e.g., life cycle cost, innovation practices, flexibility, and others), CE monitors the growth of the supply web, which is instantly connected into his DOMAS/DSS (decision support system). Based on some early feedback from suppliers and potential customers, as well as "technical intelligence" about recent R&D successes, CE facilitates the IPTs in adapting their current design concepts, including revisiting certain of the early partitioning assumptions. Using a **logistics design package**, the IPTs are able to again solicit contracts and verify credibility rapidly. A **master supply system** (MSS) automates supply scheduling. The addition of process planning and support systems allows the integration of Design, Manufacturing, and Logistics into a complete scheduling system accessible by the IPTs and by GAG.

Week 8: An **intelligent agent** in GAG's Product Planning Management Systems notices significant overlaps between the supply web for the mid-range sports car and that of a small armored personnel carrier being developed by GAG's military division. Preliminary analyses suggest that the chassis-less structure could provide key operational advantage to the armored personnel carrier and that it could also use adapted versions of five of the mid-range sports car's modules. The IPTs managing these subsystems are notified and asked to submit revised designs that optimize across the two platforms. Combined market and technical analysis generate new production schedules for five subsystems in question. The other IPTs are notified and reexamine their design strategies based on the new timetable and risk profile for the two-project portfolio.

Week 9: CE produces a complete report of the product realization organization utilizing a **vertical economic-management** (VCM) package that is integrated with DOMAS/DSS. Following review by the Joint Venture management, the project is approved for final go-ahead. All reports for taxation and government inspection are generated automatically. Likewise, all government enforced design and process requirements are validated and verified from the inter-business database from information released at the auto company and financier's discretion. The organization's product/service offerings are integrated into the NDPRE.

Week 10: The government customer for the armored personnel carrier, in performing modeling and simulation based on the chassis-less design, discovers an opportunity to integrate a new type of material that will reduce armor weight by 20%. The material, discovered by a government lab, was funded by a tank command interested in retrofitting it onto tanks. GAG negotiates with the tank command to reassign the R&D team to adapt their material for the armored personnel carrier. In exchange, CE will provide a favorable license to the tank command for design tool modules that incorporate the manufacturing properties of the new material. With an agreement in hand, CE goes back to NDPRE to find a software house to develop design tool modules. He notifies the marketing manager of GAG's military division about the potential opportunity to bid on the potential upcoming tank upgrade program.

Week 11: Based on **Virtual Qualification Analyses** of the new material and input from the IPTs, the exterior of the armored personnel carrier is redesigned. One of the propulsion system suppliers, owing to the superior training of their engineers and management, is able to take advantage of the new material to create a clearly superior life cycle product concept than their competition. In response, the IPPD dissolves the second propulsion system IPT and refocuses their resources on helping two of the other module producers accelerate their process to meet the new development schedule. One of the supplier companies to the losing propulsion system integrator, having retooled inflexibly, announces that it will file for bankruptcy. An offer for purchase the flagging firm is made by one of the companies supplying the winning propulsion system integrator. However, an Intelligent Agent in GAG's industrial affairs office notices the emerging market power of this supplier and notifies CE. CE runs his multi-level risk analysis tools and determines that it is in GAG's long term interest to maintain this supplier as a possible

> competitor for future contracts. Based on this analysis, CE lets an R&D contract to the losing supplier for upgrade work on the propulsion system.
>
> Week 12: CE searches and efficiently locates distributors, sales units, and overhead specialists. Because of the zero-overhead connectivity of the Internet, many companies now specialize in providing services typically considered an intrinsic component of corporate bureaucracy. He contracts information bandwidth and information storage capacity. Operations such as payroll, advertising, market analysis, and other services are solicited and contracted in hours, and on an hourly basis. Owing to the distributed nature of the organization no large-scale acquisition of permanent support are needed. Only the kernel of his own organization need be locally and permanently supported. The auto company is thereby able to focus on the development of its own core competencies.
>
> Week 13: The CE and IPT chairs go to the mountains for their quarterly Enterprise Development Retreat. They contemplate the demise of the “keyboard” and the “mouse” and lament their decision not to invest in the hot new virtual reality company, The Matrix. Castro celebrates his 100th birthday. CE donates his PT Cruiser to the museum of gasoline powered automobiles.

Key elements in this scenario beyond the current state of the art can be delineated. They are summarized here and described in more detail in Section 3.

Knowledge Management and Decision Support

Radical advances in Knowledge Management (KM) and Decision Support (DS) are central to this product realization vision. For instance, the players in this scenario are able to call upon and navigate a variety of knowledge bases. Building, maintaining and *securing* such disparate knowledge bases is a key challenge beyond the current state of the art. Beyond this foundation, the ability to transition among different levels of knowledge abstraction requires a means of representing changing information contexts, as well as evolving data standards to support the interoperability of product realization tools. Embedded in this scenario are capabilities for organizing and visualizing multi-dimensional, cross-disciplinary design optimization problems and developing management metrics based on the results. Finally, intelligent agents help the product realization team discover and exploit global technology developments.

Business Process Re-Engineering

The design teams in the scenario above had at their disposal tools that allowed them to recognize the key elements of the product domain and quickly match their design strategies to it. Embedded within the various tools was a capability to rapidly optimize product architecture, negotiate its partitioning among suppliers, and communicate design needs sufficiently clearly to allow the global, multi-cultural supply chain to self-organize. Project management also had at their disposal tools to conceptualize and analyze the proposed architecture in terms of a wider product family. Designers throughout this chain had the training necessary to rapidly understand their role within the larger design team and keep up with the intricacies of the evolving design, despite the presence of various new technologies (with which they were unfamiliar) and suppliers (with whom they had never worked before).

Characterization and Communication of User Needs

A “requirements definition language” was used by the team to coordinate thousands of design engineers located around the globe around evolving customer needs. The language included mathematical representations of user value, life cycle cost, and risk, as well as qualitative information that conveys context and a hierarchy of user objectives. This language was translated into value-based contracts and integrated into the variety of product realization tools.

New Frontiers

The design team overcame perhaps the greatest challenges to future product realization: the incorporation of new technologies, processes and interfaces. Also touched upon in this scenario was the way in which developments in novel materials, nanotechnology, microelectromechanical systems (MEMS) and biotechnology, could engender entirely new manufacturing regimes. New materials and extremely accurate materials shaping technologies may revolutionize the production of solid structures. Nanotechnologies may enable immensely complicated control systems to be realized. MEMS will integrate mechanical and electrical design domains, and will usher in a world in which an entire system is realized on a chip, which itself is just a small component of a much larger system. Integration of biotechnology may lead to many new products being "grown" rather than manufactured in the conventional sense. Designing and validating such "systems of systems" embodying numerous new technologies and then managing their production across a distributed supply chain raises the product realization problem to an entirely new level.

2 State of the Art and Current Research

2.1 Philosophy

Figure 1 depicts what one academic observer believes to be a typical distribution of an engineer's time today. The implication is that so much time is consumed with communication and documentation that the engineer's time actually using his design skills represents a relatively small percentage of his time. One interpretation of this chart is that improved product realization tools should focus on reducing the burden of communication and documentation, freeing the engineer to do what he is trained to do.

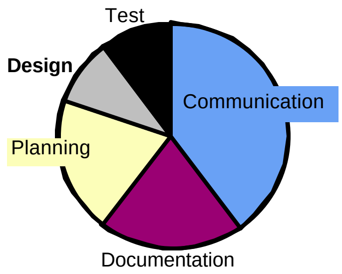

Figure 1. A Typical Design Engineer's Time Allocation?[1]

However, there are other interpretations. One could view communication and documentation not as "bad" things to be eliminated, but rather as *critical parts of the design process*. Indeed, the product realization vision for 2020 conceives of a design environment in which much broader communication would take place, in part to take advantage of the greater efficiency promised by future product realization tools. So the amount of time spent on communication could increase by 2020.

There is no one "right" way for engineers to allocate their time and attention.

One important potential contribution of advanced product realization tools will be to help design teams to manage their communication as part of a deliberate design strategy. For instance, in cases where market and technology evaluations suggest the need to develop a radically innovative product, then communication and cycle time should increase to facilitate that. The design team would explicitly decide to experiment with relatively high-risk approaches. In another domain, the optimal design strategy could be to minimize the time to market, in which case less risky approaches would be pursued. In both cases, customers' values and the expected longevity of the product would argue for more or less modular

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[1] Peter Will, University of Southern California, presentation to Product Realization Workshop at the Institute for Defense Analyses, Alexandria, VA, 9/9/99.

approaches.

And in all cases the optimal design strategy might change as new information enters the system. A successful product realization effort is at best only a temporary solution. A new product usually does not completely satisfy the market at which it is aimed. Rather, it causes the market to change shape. In the aftermath of product realization, the world contains a new set of product realization problems. One of the key goals embedded in our product realization vision in 2020 is maintaining the type of situational awareness and adaptability that allows design teams to move efficiently through a series of product realization challenges. There is no one “right” way for engineers to allocate their time and attention.

2.2 Leading-Edge Practices Today

Dramatic improvements in product realization over the past decade have been triggered by an emphasis on total quality management (TQM). In TQM, decisions are reached through a concurrent process that seeks to bring all information, analyses, and viewpoints to bear. These decisions are aided by team decision-making processes, computerized tools and databases.

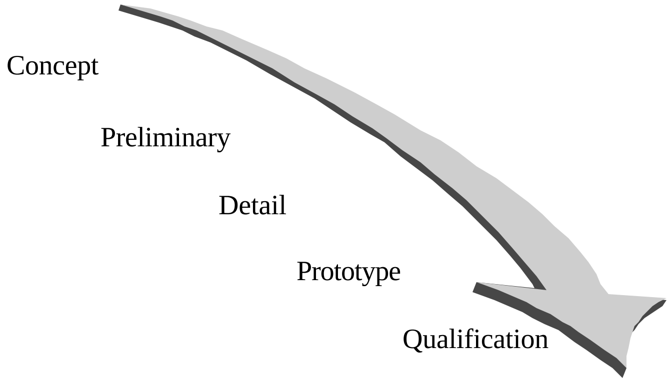

Figure 2: Product Development Activities

Although TQM and associated concurrent engineering concepts have emphasized overlapping product realization activities, the development part of the process is still traditionally viewed as a set of phases—conceptual design, preliminary design, detailed design, prototyping, and qualification—as depicted in Figure 2. Each phase has defined activities with deliverables and criteria for judging the satisfactory completion of the deliverables. These criteria are applied in phase reviews at the end of each phase.

Across time and projects, technology transfer is accomplished by the transfer of people and via the technology embedded in computer models and databases. In leading edge companies, networks of subject matter experts populate multimedia training materials. More typically, learning is accomplished via centralized training and deployment models, with content delivered in classroom settings.

2.2.1 Conceptual Design

The first activity is conceptual design, which encompasses the union of customer needs with technological capability to create a functional representation of a product and an outline of how it will be realized technically. The conceptual design phase is widely regarded as the most critical in terms of defining the future product’s long-term performance and cost profile. By some estimates, 75% of life cycle costs are determined at this initial stage. The direction and affordability of upgrades is also largely determined. *Hence, improving conceptual design is a large part of improving product realization.*

The state of the art in conceptual design incorporates at least 4 main processes:

❐ **Understanding customer needs**

Five to ten years ago, the state of the art was Quality Function Deployment, a Japanese technique that provided a semi-numerical ranking of needs based largely on surveys and focus groups. Currently, the benchmark method is value modeling, which quantitatively describes customer wants, usually as an equation that estimates price as a function of product performance measures. For example, a commercial aircraft value model might calculate aircraft price based on range, payload, fuel burn, reliability, noise level, and so on. Value models have been used for major commercial aircraft systems and have been proposed for the design of automobiles and military aircraft.

- ☐ **Formulating competitive strategy**

While satisfying the customer, the successful product must also acquire an advantageous position with respect to competitors. The state of the art here incorporates rules of thumb and some game theory, but is not as quantitatively developed as customer analysis.

- ☐ **Optimizing the product design**

True optimization requires a way to measure the "goodness" of design and a way to search through the space of possible designs. One major advantage of value modeling over quality function deployment is that a value model in concert with a cost model yields an objective function that represents "goodness." Because the space of possible designs for a complex system is huge, the search problem can be daunting. Thus, conceptual design environments that perform formal optimization often incorporate automatic design generators. For each design generated—expressed as a set of engineering parameters—the design tool estimates the performance of the design in terms which can be evaluated by the objective function or value model.

- ☐ **Designing a product family**

The best products are not designed alone. Rather, each is conceived as a member of a family of products. The family will share a common set of features, called the product platform. Commonality of platform parts increases production volume, driving these parts further down learning curves and thereby reducing manufacturing cost. By the same token, common parts means common spares, which reduces logistics burdens. Low volume products can realize particular benefits from platform design, because, after the first product, much of the nonrecurring costs for upgraded future products are eliminated, and technical risk is reduced as the platform builds experience in service.

Using this design philosophy, some of the best design organizations are able to realize radically new products through a series of incremental modifications to existing products. In this "radical incrementalism" approach, the initial design challenge can be great, but the risk associated with each incremental release is much less. Furthermore, as each product is released, the market reacts, providing valuable customer feedback and guidance.

2.2.2 Preliminary Design

The principle activity in preliminary design is fixing and defining product partitions and modules. Once module boundaries are defined, different groups or suppliers can design different modules. Module boundaries are chosen based on supplier experience, organizational history, or balancing workload with resources. User needs are then decomposed and translated into detailed specifications for each module. First, the product outline generated in conceptual design is characterized, and each key characteristic is said to be a product requirement. Certain requirements are specific to a single module. Others, like weight and cost, are budgeted among all the modules to which they apply.

2.2.3 Detailed Design and Prototyping

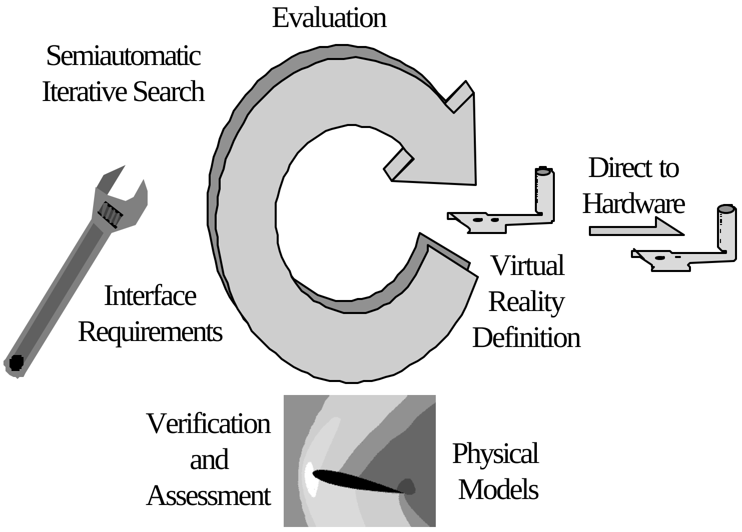

Figure 3. Cutting Edge Detailed Design

Detailed design is the activity during which individual parts are defined with sufficient specificity to allow manufacturing processes to be devised. There has been substantial progress recently in the development of tools to aid with the detailed design, as shown in Figure 3. Cutting edge digital environments allow engineers to search multi-dimensional design spaces using physical models from many engineering disciplines. Cost and manufacturing process models are embedded in the design tool to aid in the search process. The resulting part can be visualized as a three-dimensional, solid geometric object within a "virtual reality" environment. These design objects may be transmitted digitally to other design groups and embedded in system-level design tools that check for conflicts (such as geometric interference, material incompatibility) among designs. For many standard part types, this virtual part definition can also be directly translated into instructions for a numerically controlled machine tool that creates a prototype physical part.

At its best, these detailed design environments improve productivity enormously by allowing very rapid design realizations, better coordination among design groups, reduced training overhead, and large improvements in quality. Although it has been observed that CAD models do not work in all circumstances, and interoperability is poor, the experienced designer comes to recognize errant results and understand which code to select for particular jobs. The integration and interoperability of design tools are likely to be solved through continuous improvement by users and tool developers, aided by industry standards organizations.

2.2.4 Qualification

Qualification of complex products serves two purposes. One is the technical validation that the product performs as intended. The other is a demonstration to nontechnical stakeholders that the product is effective in meeting the demand of the marketplace. While the latter seems to necessitate a physical test, the former purpose is accomplished more and more by analysis. Many performance metrics such as reliability can only be practically demonstrated through statistical simulation. The emerging validation paradigm is illustrated in Figure 4. In this process, physical tests are only used to validate simulation codes. The

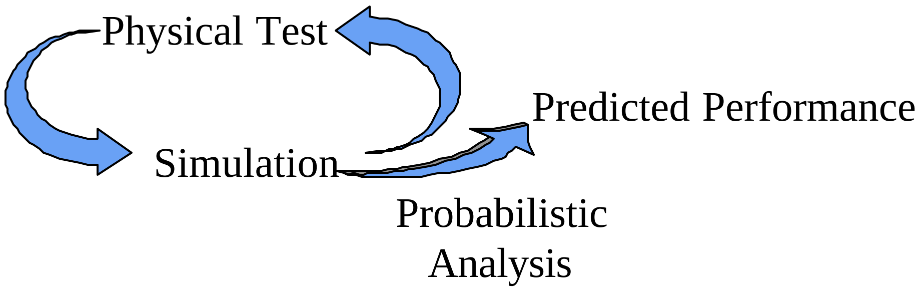

Figure 4. The Emerging Validation Paradigm

simulation is used to validate the product, yet while doing so this allows a larger number of alternative designs to be explored. Today, the need for prototypes has not been eliminated.

2.2.5 Manufacturing

Advanced manufacturing is a broad topic that has received significant attention in recent years.[2] For the purposes of this report, the most significant aspect of this work is in the area of automatic, flexible manufacturing technologies.

Push button production of individual machined parts from completed CAD definitions is on the horizon. There have been numerous demonstrations that numerically controlled machine programs can be generated directly from CAD definitions, downloaded into the machines, and immediately utilized to cut metal and form the part. Analogs exist for cast and molded parts and deposition processes. The CAD program generates a definition of the mold, die or master from the part definition, programs the code to machine the mold or master, it is cut, and the part is cast. Several shops now use automatic, CAD-based manufacturing as their basic method.

Conceivably, this automatic manufacturing approach renders obsolete traditional notions of a learning curve. Design organizations already talk about “learning in manufacturing process simulation” before any metal is cut. The effect is reinforced by a reduction in tooling. Converting a CAD definition to a program for a sophisticated five axis milling machine is generally simpler and more trouble free than trying to automatically generate code to machine the tooling necessary to make the part on a series of less capable machines.

Versatile mills and lathes now can machine to such accuracy that many finishing steps are eliminated. Various other applications of information technology promise to automate other aspects of the manufacturing process (e.g., material handling, part tracking, and equipment maintenance), enable on-line problem diagnosis, and provide self-correcting capabilities at the enterprise level. This will allow for real-time tracking of manufacturing flows across the enterprise, making current “batch and queue” operations more like continuous process control situations. The ultimate result could be single setup tool-less manufacturing, with much less economy of scale than traditional machining.

Single unit manufacturing should be especially advantageous to weapon systems, which are generally built in small volumes relative to commercial products and are built at low rates in an environment where needs change rapidly. Single unit manufacturing could facilitate rapid reconfiguration of a design to accommodate changes in the political and military environment, followed by a quick small production run of the modified system. Such a change would warrants a fundamental re-thinking of how parts are designed. Part by part customization would become much more practical than before. Replacing complex, assembled units with large machined castings may be more attractive than before.

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[2] National Research Council, *Visionary Manufacturing Challenges for 2020*, (National Academy Press, Washington, DC, 1998). See also *Integrated Manufacturing Technology Roadmapping Project: Manufacturing Processes & Equipment* (IMTR Project Office, Oak Ridge Centers for Manufacturing Technology Oak Ridge, Tennessee), 21 May 1999.

3 Key Issue Areas in Product Realization

The background material in Section 2 highlighted the current state of the art in complex product realization and identified general problems beyond the agenda of current research. In this section, these problems are consolidated into four key issue areas and analyzed. The four issue areas are as follows:

- **Knowledge Management and Decision Support**
- **Business Process Re-engineering**
- **Characterization and Communication of User Needs**
- **New Frontiers**

Interwoven within these issue areas are the following key technology research challenges:

- **Logic of knowledge abstraction**
- **Distributed, Adaptive Algorithms for Optimization of Multi-Dimensional Designs**
- **Mathematics and Science of Product Architecture and Modularity**
- **Virtual Characterization and Qualification of "System of Systems"**

3.1 Knowledge Management and Decision Support

Radical advances in Knowledge Management (KM) and Decision Support (DS) are central to achieving the product realization vision for 2020. Knowledge Management (KM) refers to the way an organization stores, organizes, accesses, uses and amends internal and external information. It is the baseline for effective information sharing and "organizational memory" and hence a critical enabler of collaborative work. Section 3.1.1 Data, Information and Knowledge highlights some foundational KM issues and their relevance to the product realization problem. Section 3.1.2 Optimization focuses on the problem of optimization in the context of product realization.

3.1.1 Data, Information and Knowledge

In order to explore the types of KM and DS issues beyond current trends, it is important to clarify the distinctions among data, information and knowledge. In large databases the structure of how data is stored and relationships among data are key considerations. Different data structures support different types of activities. The database structure appropriate for distributed product realization, for instance, would likely not be well suited to on-line transaction processing. Building and maintaining accurate, timely and secure product realization data is one of the key challenges associated with the KM/DS issue area.

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Data becomes information through selection, transformation and consolidation in a particular context. The selection process involves segmenting and filtering the data according to some criteria, so that subsets of the data can be identified. Transformations are key when data from different sources are to be consolidated. "Data mining" is one form of a data consolidation process. Efforts such as NIST's Standard for the Exchange of Product (STEP) model aim to simplify data consolidation from different design tools. One of the challenges for the future will be to devise a process by which data standards can evolve along with advances in product realization technology.

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Information becomes knowledge when patterns identified during data mining are evaluated and interpreted within a certain context toward the fulfillment of an objective. These interpretations can be in the form of summaries, explanations, predictions, insights, solutions, better questions, etc. Simply sharing information is not KM. The information must reflect an organization's business and decision processes. Knowledge is information that has been converted into a form suitable for human decision making.

KM represents a new means of managing an organization's knowledge assets, much in the same way that physical assets are managed: successful practices must be identified and reused. This means that KM must become more than simply moving information from one person's head to another's. Rather, it must facilitate the embedding of new knowledge in evolving organizational routines. Only in this way can an organization become more competitive in whatever ways that are important for its particular environment, be it through efficiency, innovation, or responsiveness.

The essential property of complex products, which shapes the process by which they are designed, is that they are far too complex for any one individual to understand all the parts to the depth necessary to competently design them. This property necessitates that such products be designed by organizations. The state of the art solution is to use separate computer representations of the part versus a system of parts, and a separate representation again for the whole product. This leads to problems of consistency and synchronization. Thus, there is a need for a product definition strategy that can represent the product in fine detail for parts designers, less detail for systems engineers, and even less detail for the chief engineer's perspective. Engineers will want to be able to navigate among these levels, so that part designer can occasionally consider the whole product perspective, or so the chief engineer, trouble shooting a product problem, can study the details of individual parts. A key challenge for the future will be the ability to draw accurate conclusions efficiently while moving among different levels of knowledge.

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The ability to move among different levels of design abstractions is particularly important to facilitate the type of adaptability envisioned for 2020. Architectural decisions for systems in which component technologies are changing rapidly can be very complex due to uncertainty as to the timing, scope and direction of the changes. Technological limitations are often only discovered during detailed design or prototyping activities, and external sources might discover new technological possibilities at any time during the design process. The ability to move among levels of design abstractions could help capture and communicate to detailed designers the intent of system architects, as well as making technological opportunities more visible throughout the supply chain. By capturing design intent, tradeoffs based on discoveries at the subsystem and component level can better reflect overall system-level priorities.

A similar problem arises in optimization techniques used for design. For complex systems, optimization of even relatively simple components can present designers with a multi-dimensional, cross-disciplinary problem rife with discontinuities. Detailed physical models are difficult to use in optimization systems because they realistically represent discontinuities and singularities. Optimization search algorithms perform better in smooth spaces. A more abstract model derived from a detailed physical model is likely to be smoother and therefore much easier to search. A systematic approach to deriving more abstract, general representations from more detailed representations would therefore be of great use to optimization-based design strategies. We explore these aspects of the optimization problem in the following subsection.

3.1.2 Optimization, Visualization and Intelligent Agents

Optimization means finding the best. Formal optimization processes and tools generate and evaluate many designs searching for the best design in some set. Mathematically, the set of possible designs is usually represented as a Cartesian space. The coordinates of the space are a set of parameters that collectively define the design. For a simple part, such as a bracket, the parameters would be dimensions and angles. A discrete parameter could be material.

For each design, there must be a function, called the objective function, which for each point in the design space yields a comparative measure of goodness. If the design space contained only a finite number of points, it might be possible to evaluate them all and choose the best. However, most design spaces have an infinite number of points in many dimensions. Thus, the art of optimization is to search the design space. Often, the only guide in this search is the objective function value of the points already encountered. From the value of past points, a search must infer good directions or good areas for future search. Unless something is known beforehand about the shape of the objective function in the design space, there is never a guarantee that the best design found to date is the best design in the entire space. Moreover, there is no single search strategy that works best for all spaces. Thus, optimization remains a challenging exercise, even for experts.

Design spaces with singularities and discontinuities are particularly difficult to search. As an example, a multistage axial turbine optimization may find a relatively good three-stage design, but the search has generated no useful information for finding good two-stage or four-stage turbines, or even whether it is worth searching those parts of the design space. Common search strategies tend to converge to singularities and discontinuities. Designs located along discontinuities (as well as designs located along boundaries) tend to be far less robust than the designs that search engines find in the interior of the space. Robust in this context means that small changes in design parameters (coordinates) have very small impact on overall performance. Performance prediction is uncertain, especially in conceptual and preliminary design. Physical models used in design optimization have inherent inaccuracies that contribute to uncertainty in the design space. For this reason, robustness is a very desirable characteristic of the design optimization process, yet the irregularities of typical design spaces and the over use of constraints lead classical search techniques to especially non-robust designs that, in general, are not even optimal.

The very fact that design spaces tend to be particularly discontinuous and ill conditioned suggest that there may be mathematical properties that are characteristic of these spaces, and that a search algorithm might be created which could exploit these characteristics to yield more optimal and more robust solutions.

Over the past fifty years, operations research and artificial intelligence have developed a rich library of optimization search strategies. Tools vary in the number of points they must evaluate, use of derivatives, computational burden, confidence in finding the best solution, and their ability to perform in ill-conditioned spaces. When applied to design problems, these search tools are often slow and fragile. They are slow, because the evaluation of individual designs requires execution of physical models, which take minutes or hours to run; they are fragile because methods that perform well on one problem may fail to converge or return poor designs on another problem. Today, this means that optimization tools, like computational fluid dynamics models, can only be used effectively by experts, generally PhDs. This is a major barrier to widespread use, especially since the same engineers often need doctorate-level expertise in the underlying physical models.

Another common difficulty in using optimization tools for engineering designs is the “winners curse” phenomenon. A typical physical model (CFD, NASTRAN, CATIA, and so on) may be very accurate over a large area, but will have regions where it is not so accurate. In some of these regions it is pessimistic and in others it is optimistic. A good search tool using such a model is naturally drawn to the areas where the model has the greatest errors on the optimistic side. The state of the art approach for coping with this problem is to rule out inaccurate regions with constraints. However, it is hard to surgically excise such regions, and, when constraints are in place, the true best design might be located beyond a constraint and thus will never be found. Successful management of optimization search tools will require assistance in selecting the best tool, accommodating the tool’s weaknesses, and coping with limitations of physical models, especially as search tools exacerbate these limitations.

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Complex products are designed by organizations, not individuals. The vision for product realization in 2020 emphasizes the wide distribution of design tasks across a supply chain. Full use of optimization requires that different design groups be able to optimize their components independently in a way that produces a globally optimal result. That is, design optimization must be distributed. Demonstrations have shown savings of over 20% can be achieved on an entire product through coordinated distributed optimization versus state of the art techniques. This was a commercial demonstration on a product where the cost had already been driven down significantly by competition—the impact on military systems should be much greater.

Today, it is not generally possible to link optimization performed at different levels so that the cumulative result is global optimization. Instead, for example, efforts in one component to save weight are frequently canceled out by optimizations of other components to reduce cost. Distributed optimization algorithms have been developed, but no design organization surveyed in this study is close to employing a distributed optimization method for design. Barriers to the use of distributed optimization include

- The lack of rigorous, customer-focused objective functions at the product level
- Overuse of requirements, weight budgets, and target costing
- Lack of incentives in supplier contracts, particularly during design

A satisfactory design process must not only produce a design, it must also deliver the rationale for choosing the design so as to gain the support of stakeholders in the business, and to guide future adjustments, enhancements and elaborating the design. Especially because optimization processes are not guaranteed to select the optimal design, and the results tend not to be robust, there is a vital need to critique the output. Engineers familiar with optimization usually express this as a need to visualize the design space in the vicinity of the selected design. Specifically, they wish to see the objective function hypersurface in the design space to check for flatness (robustness) and note nearby discontinuities and boundaries. A straightforward solution requires projection in a space one dimension greater than the design space. Thus, the plot of an objective function for a two-dimensional design space is a two dimensional surface embedded in three dimensions.

Virtual reality can represent three dimensions with stereo viewing, or four dimensions adding animation, where time is the fourth axis. Projections, colors, and cross sections can be of some use for visualizing one or two additional dimensions. However, design spaces frequently have ten or more dimensions. No currently available technique comes close to providing useful information about the local space around a selected design in such a space. Consequently, the promise of design optimization tools is seldom realized. Results unsupported by contextual information inspire little confidence in the engineers who use the tools, and less in their managers and other members of the design team.

Some hold out hope that intelligent agents — i.e., proactive, autonomous software tools — could bridge this gap. A design agent could observe the dynamics of design process and, based on information and values supplied by the designer or system architect, highlight known opportunities or pitfalls. For example, an agent could make designers aware of global technology developments that could solve a pending design problem. However, intelligent agents still are a distant dream in KM. Classical algorithmic approaches and even rule-based (expert systems) approaches are not often flexible enough to address search and pattern analysis problems often faced in large-scale, semi-structured collections. A truly *adaptive* agent system would automatically change methods of analysis or emphasis of key information elements and adjust outputs consistent with the changing problem focus. This capability is well beyond the current state of the art.

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The implications of overcoming the KM/DS challenges outlined here could be staggering: A massive database of organized, machine-readable design knowledge that can be navigated and optimized at various levels of abstraction and is searchable by intelligent agents. This is one part of the vision of product realization in 2020.

3.2 Business Process Re-Engineering

Just as information does not imply knowledge, knowledge does not imply capability. It is expected that future product realization organizations will need to find ways to turn massive amounts of accessible information into useful knowledge and, more importantly, into products that meet users' changing needs. Customers will increasingly demand the type of highly tailored (but affordable) products made possible by tight coordination. A functional hierarchy will not be fast enough or adaptable enough. There will no longer be time for a large chain of decision making. Weekly or monthly reports will be too slow to keep up with changing market conditions. Hence, organizational resources will increasingly need to be deployed dynamically in pursuit of short-lived opportunities. To coordinate thousands of dispersed stakeholders rapidly, the business architectures of the future are likely to become highly organic, flexible network structures.

The challenge will be to develop tools that help organizations match their design strategy to their chosen domain and, more importantly, adapt to surprises.

The phenomenal success of Enterprise Resource Planning systems is a testament to the strategic advantage conveyed by having information transparency among customers and suppliers. Some organizations have developed a new executive position, the Chief Knowledge Officer to help the organization quickly and effectively exploit the broad array of information available to help make decisions. In the product realization domain, the challenge will be to develop tools that help organizations match their design strategy to their chosen domain and, more importantly, adapt to surprises. Like the adaptive agents mentioned earlier, organizations will require the capacity to automatically change methods of analysis consistent with a changing problem focus. Managers will need to facilitate such changes across organizations in the supply web. It will be particularly important to highlight key technical and market risks, evaluate the value of architectural flexibility, and estimate costs of options.[3] Product realization engineers in 2020 will need consistently to be expanding and upgrading their skills. Hence, the treatment of the business process re-engineering issue area will focus on four aspects:

❒ Architectural Planning and the Self-Organizing Supply Chain
❒ Risk Management and the Value of Flexibility
❒ Cost Estimation
❒ Training

3.2.1 Architectural Planning and the Self-Organizing Supply Chain

High development cost and low production volumes often plague complex systems, particularly in defense. A technique to combat both these ills is the design of product families instead of individual products. In the DoD, the Joint Strike Fighter is a prime example. Instead of three separate development programs with production volumes ranging from three hundred to sixteen hundred aircraft, one program is planned with three thousand aircraft. Although the missions of the three variants are quite different, large portions of the aircraft are common. These parts need only be designed once and can be produced in relatively high volumes. Furthermore, if the program is successful, designers are leaving room for additions to the family. It might be possible, therefore, to create high-performance, high-cost and lower-performance, lower-cost systems that share many components.

The power of the product family approach is clear, in a qualitative sense, but there is no rigorous theory to guide decisions as to when the concept should be applied and what degree of commonality is best. There is no objective methodology for selecting a portfolio of products to cover a varied market with different sized niches, whether or not this portfolio employs the family strategy. Similarly, organizations could use better guidance toward selecting the mix of products or technologies in development.

As discussed in Section 2.2.2 Preliminary Design, the central activity in preliminary design is the partitioning of the product into modules and eventually into parts that can be designed and produced separately. The choice of modules and the precise boundaries between modules is the central activity in architectural planning. Modularization choices impact:

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[3] As discussed in Section 2.2.1 Conceptual Design, architectural decisions can have a particular impact on the affordability of complex systems that are to be manufactured in low volumes.

❒ Communication burdens during detailed design

❒ How design changes propagate, a principle driver of development cost and schedule

❒ Manufacturing options—make vs. buy decisions

❒ Assembly tolerances, cost and quality

❒ Maintainability, including fault isolation

❒ Upgradeability

❒ The ease of incorporating new, "off the shelf" technologies

There is a multitude of ways to partition a system. For instance, in order to achieve the highest possible performance for particular design parameters, a set of key components can be optimized along the desired dimensions by tightly linking their operations. Achieving high performance can be a slow and painstaking process because it unclear how to design any one component "optimally." Furthermore, tight coupling means that changes in one component can create a ripple effect, requiring many others to be adjusted in order to restore the desired performance. Because the components are linked tightly, there is little margin for error. On the other hand, if the designers' goal is to build a system that can be upgraded rapidly, then they will want to employ a system architecture that is highly modular and that has larger margins for performance variance at the interfaces. Doing so means that initial performance is typically lower than it could be. Initial performance is sacrificed for the benefit of simplifying the process of making improvements over time.

At some point in a product's evolution, interfaces can become a performance or cost bottleneck. The system architect will require tools that help him resolve partitioning issues. Important work has been done in the theory of software modularization, but it is not clear the extent to which these approach apply to mechanical systems. At present, there is no "science of interface design" on which he can call to guide the distributed design process.[4] The "distributed architecture planning package" described in the scenario does not yet exist nor is it likely come about as a result of current research. Nor could such a system exist in isolation from the organizations using it. Product architecture is a nexus of technology management, as product platform decisions require a tightly interwoven consideration of both technical and market concerns.

There is no "science of interface design" on which he can call to guide the distributed design process.

One of the hopes for product realization in 2020 is that the process of complex system partitioning will be accomplished through self-organization of supply chains. At the most basic level, the choice of a particular system architecture imposes structure on the tasks required to complete the design. The chosen architecture embodies the relationships among tasks—i.e., which tasks take as input the output of some previous tasks—and hence suggests a logical decomposition of design activities. If a design is truly modular, these design activities can proceed relatively independently. The only requirement is that the resulting products continue to adhere to the interface standards and design rules that originally defined the

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[4] Edsger Dijkstra summed up the problem well in "Programming Considered as a Human Activity" (*Proceedings of the 1965 IFIP Congress*, North-Holland, Amsterdam, 1965, pp. 213-217.):

The technique of mastering complexity has been known since ancient times: *Divide et impera* (Divide and conquer)….Some people might think the dissection technique…(is) a rather indirect and tortuous way of reaching one's goals. My own feelings are perhaps best described by saying that I am perfectly aware that there is no Royal Road to Mathematics, in other words, that I only have a very small head and must learn to live with it.

modules. In this respect, the process of partitioning modules generally corresponds to partitioning among module suppliers.[5]

Hence, in the case of the virtual organization, the process of improving the overall system can be distributed over many different companies. As long as the module interfaces remain stable, competing companies with different core competencies are free to seek improvements in module performance. The entire supply chain can participate in the evolution of a complex system by improving the design of modular pieces of it, without central control.[6]

This being said, the interaction of many stakeholders in a virtual design organization will inevitably give rise to negotiations with respect to the division of work, risk and rewards. The key to making these negotiations constructive rather than destructive is to share a common set of values throughout the distributed organization. Where the organization spans the supply chain, contract incentives, similar to warranties, can be developed to propagate values from one corporation to another. The problem of value modeling will be covered in Section 3.3 Characterization and Communication of User Needs.

Value modeling can be used to establish the more tangible values, but there may always be some values that defy economic analysis. These too must be declared and shared through the team. Thus, it is hard to imagine that even the most virtual organization of the future will not require a leader to establish and communicate a vision and a set of guiding values to facilitate cooperation among the team.

3.2.2 Risk Management and the Value of Flexibility

The development of complex products is fraught with uncertainty concerning performance, schedule, manufacturing cost and development cost.[7] These uncertainties may be described as technical risks or as program risks, but both notions are strongly interrelated. When performance falls well below expectation, the product or component can be redesigned, trading development cost and schedule for performance. Often the redesign will recover the performance shortfall through the use of exotic material or additional parts, trading manufacturing cost for performance. The net result tends to be a less desirable product, in terms of performance and cost, than was originally planned.

Worse yet, design changes in one component to solve one problem often necessitate changes in other components, even those that do not directly interface with the changed component. State of the art product realization processes are fragile. They do not tolerate uncertainty or evolution in component technologies, change in design tools and methods, or change in the market (for commercial products) or military/political environment (for weapon systems). If many shortfalls materialize in different components, changes

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[5] Carliss Y. Baldwin and Kim B. Clark, “The Microstructure of Designs,” Harvard Business School Working Paper 98-031, 1997. Ron Sanchez and Joseph T. Mahoney, “Modularity, Flexibility, and Knowledge Management in Product and Organization Design,” *IEEE Engineering Management Review*, Winter 1997, pp. 50-61. Stepfan H. Thomke, “The Role of Flexibility in the Design of New Products: An Empirical Study,” Harvard Business School Working Paper 96-066, May 1996.

[6] Carliss Y. Baldwin and Kim B. Clark, “Sun Wars: Competition within a Modular Cluster,” in David B. Yoffie, *Competing in the Age of Digital Convergence*, Harvard Business School Press, Boston, MA, 1997.

[7] Examples are the market failure of the MD-11, which was largely due to a shortfall in range so that many trans-Pacific city pairs could not be served; the redesign of the F-119 turbine in the midst of the F-22 development program; schedule delays and cost overruns that brought about the cancellation of the A-12 program; and delays and high manufacturing cost that caused Boeing to lose money during the first production year of the new generation 737.

propagating from component to component can run rampant, throwing schedules and budgets into disarray. There is virtually no technology for anticipating the propagation of change.

A core problem initiative for the enabling the product realization vision for 2020 must therefore include the development of cohesive risk management strategies and methods. In particular, such an initiative will need to include:

- Technical tools for doing risk management
- Administrative processes for supporting risk management
- Methods of capturing and analyzing results

The state of the art in risk management tools aim at the minimization of risk. However, it is the very features that are technically risky that can offer significant innovations. Eliminating risk entirely will therefore relegate a product to second rate performance. There is a need for a method of quantifying uncertainties and the consequences of redesigns so that risks can be accepted or avoided in a rational manner. More importantly, given that complex product realization will increasingly involve integrating “system of systems,” it will be important to identify interdependent risk drivers and manage total risk posture across entire platforms and across time.

There is no general method for economically assessing flexibility. What we do know is that designs that seem more flexible tend to also be higher in cost and lower in performance. Some designs have successfully adapted to changes, and product platforms have been designed to accommodate specific variations, such as the Joint Strike Fighter aircraft family. In general, however, our products and processes lack flexibility, largely because we do not know to talk about flexibility in a quantitative way. Consequently, some research has begun to economically assess the value of upgradability, particularly with regard to electronic packages within weapon systems. However, there is no general theory that establishes a quantitative measure of flexibility or even a broadly usable definition of flexibility of a product, much less of a design process.

Ultimately, in the context of a modular architecture, the system architect must decide where to spend funds to protect against risk. Systems may be modularized, with more or less flexibility in the interface. Engineers are reluctant to pay the price for flexibility when they cannot quantify the payoff. Typically the returns to such investments are nonlinear and decreasing in returns. It is therefore critical to determine how the impacts of technology change on discrete systems are correlated, in order to assess the true value of a risk management strategy at the program and system-of-systems levels.

In addition to understanding the intra- and cross- platform correlation of risk, a second critical dimension must be integrated with our current risk management strategies—time. While it is well known that changes made late in program development cost far more than those made early, the work on this subject is limited. This shortcoming will be magnified by a change to a system-of-systems approach for risk management, where technical change will impact early in some programs and late in others. A rigorous set of metrics is necessary to allow for the standardization and valuation of risk across non-concurrent programs.

3.2.3 Cost Estimation

Predicting manufacturing costs based on design is improving, and predictive models are used more frequently in all phases of design. However, without exception, these models lack any rigorous theoretical foundation. Consequently, they inspire little confidence in the engineers who use them. The methodology of most models traces to the Rand Corporation studies from the 1960’s. Parameters that (are believed to) strongly affect cost are selected, and statistical regression is used to fit cost data to the parameters. The result is a Cost Estimating Relationship (CER). The standard cost model in the aerospace industry, Price-H, employs this strategy throughout. Among the serious theoretical and practice problems with this approach are the following:

- Causality is never established between the parameters and cost.
- The validity of predicting of future cost based on regression fits to historical costs is questionable, particularly given the rapid evolution of manufacturing technology and efforts such as continuous improvement. There are no traceable standards, such as the ones on which physical models are based.
- No accounting is made of the pricing behavior of manufacturing firms. Prices for purchased parts are (optimistically) believed to be tied to the cost of the parts as opposed to being determined by demand, competition and strategic business choices.
- Cost predictions during design can set expectations, and these expectations can impact the eventual actual cost.
- Cost models are generally constructed to conform to accounting systems rather than to support design decisions made by engineers.

The solution to these shortfalls is basic research in the quantitative and causal relationship between engineering designs and manufacturing cost.[8] When engineering cost models use regression, it should be because causality has been established. Models should rigorously incorporate economic market representations. The effect of cost predictions on designs should be estimated and corrections should be applied. Finally, engineering cost models must meet the needs of engineering even if that means a break with accounting.

3.2.4 Training

Designers are and will be challenged to keep up with increasing numbers of specialized design tools and models. Today the only solution is training. There have been significant advances recently in Internet-based training.[9] One of the key advantages of Internet-based training is that it is not limited by scale, as is a traditional classroom, for which more instructors are required as there are more students. Stanford University is the first educational institution to offer a master's degree for courses taken solely over the Internet. The on-line program employs audiovisual streaming with synchronized slide shows and electronically distributed class notes. But even this advanced technology for training may not meet the needs of this workforce, especially given the constant change in the design environment and therefore the ever-increasing need for retraining.

According to MIT researchers, "current practice for enterprise learning focuses on fairly centralized training and deployment models, with central groups both developing the content and delivering the content in classroom settings. These solutions often are one-size-fits-all, and do not adequately address the unique

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[8] An example of research in this area, with a literature review, is "Cost Comparison of Alternate Designs: An Information Based Method," by David P. Hoult and Stuart W. Muter, The Manufacturing Institute, MIT, 1993.

[9] Forrester Research anticipates that web-based training could reach $6 billion in two years. Technical companies drive the demand, as keeping content up to date is critical for them. For example, DigitalThink Inc., backed by Intel and Texas Instruments, already has 20,000 registered users worldwide for engineering training courses. They offer more than 50 courses in embedded design and programming.

needs of workgroups….”[10] The MIT research area is developing both theory and “an integrated system of strategies and technologies for enterprise learning. In place of central control, the learning system is organized around local needs and is connected more with product program work practices than with the state of the art. Training will be integrated with case examples and learning-by-doing through distributed means (for example, web-based pedagogy and distributed expertise). Knowledge sharing support will address practice-level issues of knowing ‘how’ to do something, rather than just process level issues of knowing ‘what’ to do.”[11]

Efforts are also currently underway to create the type of technical professionals who will be competent to manage simultaneously the type of intertwined technology and business concerns described in the previous subsections of this Business Process Re-engineering issue area. The Center for Innovation in Product Development (CIPD) at MIT focuses on basic research in product development with a balance between organizational and technical issues. The type of research done at CIPD is only possible with faculty grounded in engineering and business. The scarcity of such interdisciplinary researchers is likely the reason that there is so little rigorous research in this field. One suggestion for jump starting academic research in product realization is to employ the strategy used by NASA in the Space Grant program and by the Navy in the Sea Grant program: Allocate funds to establish one university in every state as a research leader in product realization. Universities would propose research programs in a competition to see which fifty schools are selected. Thus, the research funds are distributed in a competitive manner.

3.3 Characterization and Communication of User Needs

Successful products allow continuous matching of technological capability to changing user needs. Deep understanding of evolving user needs is critical to conceptual design. Simply interrogating the user is a useful step, but it is usually not adequate. Firstly, users (and designers) are often uncomfortable with directly discussing needs, which seem abstract, so they attempt to refocus discussion on design alternatives. Secondly, users are generally not familiar enough with the relevant technology to understand what design alternatives are possible, and thus they may not think to ask for the features that they really want.

If enough alternatives are compared, some sense of user wants can be inferred. Economists call these “revealed preferences,” and this approach has been used to construct quantitative descriptions of consumers’ relative desires for different automobile features. Traditional systems engineering methods focus on asking users to define overall requirements. The systems engineer then attempts to guess the optimal design region for individual components. Any design that falls within the region will be acceptable. It is hoped that the region contains the optimal feasible design. To drive designers toward the optimal design, the intersection between requirements and the feasible region is as small as possible. Phrases like “challenge” and “stretch goals” refer to pulling the requirements out to shrink or even eliminate the intersection with the feasible region.

In practice, at the time requirements are defined, no one is certain exactly where the edge of the feasible region is, so that often no product can be made to meet challenging requirements. Traditionally, cost was not a hard requirement and shortfalls in performance could be made up with overruns in cost. Now, with cost as an independent variable, designers are more often left with no possible way to design a product

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[10] CIPD 1998 Annual Report.

[11] *Ibid*.

inside the box, so that requirements must be renegotiated midway through development. Thus, requirements definition becomes a game of pulling the design along a direction in the design space.

A more formal method of capturing user needs is to represent them as an objective function. For instance, instead of asking a squadron commander what range is required for a new strike fighter, the question is how many dollars of unit cost are worth one mile of range. This defines a gradient in the objective function that can be used to identify the most desirable directions for design improvement.

Research in the automotive industry has shown that consumers' objective functions can be constructed from revealed preferences. An alternative approach is to model the customer as a rational economic actor; e.g., a simple profit maximizer, in the case of commercial firms. Customers view product acquisition as a financial investment decision, weighing the net present value of revenues against life cycle costs. Risk is quantified by its expected cost.

For the DoD the concept of value-based acquisition is just emerging. At present, weapon system price more often reflects cost plus a fee, rather than value to the customer. If user value can be quantitatively defined, then price should be anchored to user value, not to cost. (Other factors might be considered by the seller in setting the price, such as sales to future customers or the use of the technology in other products). Although this would require a major shift in the thinking of program managers and sourcing personnel at prime contractors, and entails many thorny issues that need to be worked out, the potential benefit is tremendous, as can be seen in commercial markets. Free markets tend to bring price variations into line with value variations. For example, a consumer will only pay $800 extra for a sunroof on a car if she believes that the sunroof brings at least $800 more value. On the other hand, the carmaker will not price the option less than $800 if it believes that most people place that much value or more on a sunroof. Thus, the price of a feature converges to the value that most customers place on the feature.

An aspect of free markets is that as manufacturers attempt to earn as much profit as they can, they incidentally optimize their product to maximize value to the customer and minimize manufacturing cost. Specifically, maximizing profit effectively maximizes customer value minus cost. The design that maximizes value minus cost is the best design for society as a whole (that is, it is the most effective allocation of manufacturing resources).

Government programs or sole source contracts can also create the incentive for contractors to develop the best design for whole systems or components simply by mimicking the free market. Contractors want to maximize profit (price less cost), so if a contract price is structured such that price varies dollar for dollar with value, contractors will incidentally maximize value minus cost as they maximize profit, just as in the free market. Such a value incentive in a contract is an extension of performance warranty clauses that are already widely used.

An open issue is how to express product or component value in dollars so that a simple formula can be developed to calculate price as a function of performance. Also, in government acquisitions that do not have a price nexus, it is not clear who the customer is. Warfighters, system program offices, logistics, and others are impacted by weapon system design. Whose values are relevant? Some work has scratched the surface in this area, suggesting that these problems are tractable, but generally, value assessment in government systems is unexplored territory.

3.4 New Frontiers

State of the art complex product realization is heavily dependent on physical models, such as finite element stress/strain models, thermal conductivity models and computational fluid dynamics models. Every model is based on assumptions, and a quality model can be trusted to represent the regime where its assumptions hold. However, the nature of new technology is to frequently break out of customary operating regimes into new areas. This often entails violations of physical model assumptions, so that the results of the models are no longer applicable. Designers unwittingly use these models and create part or systems that do not function as predicted or as desired. Currently, the burden is on individual designers to understand the assumptions made by models that they use, and how assumptions correspond to the operating regime of their part. As the number and sophistication of models proliferate, this challenge will grow.

When modern design methodology is compared to manufacturing methodology, it is clear that designers have not benefited from statistical management of quality and uncertainty to the same extent as manufacturers. For example, manufacturing would avoid grinding a surface to a tolerance of 0.1 thousandths of an inch unless such accuracy were necessary. Yet an aerodynamicist will regularly use a computational fluid dynamics grid so fine that an analysis requires several hours to run. The aerodynamicist cannot adjust the accuracy of his model to the needs of the design or analysis because he can neither quantify the accuracy requirements of his design, nor assess the uncertainty of the results of his model.

Neither of these issues is well understood. The first depends on an uncertainty analysis chaining through the design process similar to the key characteristic methods used to establish manufacturing tolerances under the six sigma process. Large increases in the quality and productivity of design processes could be realized if they could be brought under the same kind of statistical control that continuous improvement and six sigma initiatives have brought to manufacturing. The second issue is an analytical issue that requires a deeper understanding of the physical models, particularly of the numerical computations involved.

Ultimately, developers and users of product realization tools will have to cope with new and exotic technologies on the horizon that will require entirely new types of design tools. Emerging technologies, such as MEMS, bio-mechatronics, and nano- technology, will require entirely new manufacturing processes. For instance, some envision aircraft wings “grown” from “nano-bio” components and employing MEMS-base controls. How will we design systems of systems that, for instance, have a MEMS-based system-on-a-chip — e.g., a sensor, actuator and processor — integrated with conventional mechanical and electronic systems?

4 Toward 2020

This report has traversed a number of concepts, from currently exploited industrial practices to creative visions about a near-perfect world of product realization. It has proposed four overarching issue areas for categorizing the advances deemed necessary to reach this happy state: Knowledge Management & Decision Support, Business Process Re-Engineering, Characterization and Communication of User Needs, and New Frontiers.

Common threads through these issue areas include:

- The role of converging information technologies in altering the overall business landscape
- The importance of adaptability in coping with the surprises embedded in this new world
- The impact on design strategy of potentially radical changes to contemporary production functions

Within these issue areas the following basic research areas have been identified which, if not pursued, may cause product realization improvement to plateau long before reaching desirable levels of quality and cycle time:

❒ **Logic of knowledge abstraction**

There is a need for a product definition strategy that can represent the product in fine detail for parts designers, less detail for systems engineers, and even less detail for the chief engineer's perspective. This research challenges includes subchallenges in areas such as data structures and intelligent agents.

❒ **Distributed, Adaptive Algorithms for Optimization of Multi-Dimensional Designs**

The different levels of the design space means that tradeoff problems tend to be discontinuous and ill conditioned. This suggests that there may be mathematical properties that are characteristic of these spaces, and that search algorithms might be created which could exploit these characteristics to yield more optimal and more robust solutions. Subchallenges include visualization technology and, again, intelligent agents.

❒ **Mathematics and Science of Product Architecture and Modularity**

The interconnection of design challenges means that complex product realization will increasingly involve integrating "system of systems." To do so, it will be important to identify interdependent risk drivers and manage total risk posture across entire platforms and across time. Key subchallenges include representing and valuing flexibility, structuring supply chains, and cost modeling.

❒ **Virtual Characterization and Qualification of "system of systems" products and processes**

The physical models that underlie current product realization systems will need to keep up with new technologies, which frequently exceed customary operating regimes. Emerging technologies, such as MEMS, bio-mechatronics, and nano-technology, will require entirely new manufacturing processes and process characterizations.

Deeper study and continued interaction with state of the art practitioners could refine this set of research areas into a detailed and focused research agenda, addressing quantum advances. In addition to identifying these research areas more specifically, future work in projecting trends in complex product realization should delve into how particular aspects of the ultimate vision might happen. Key questions to be addressed would include the following:

❒ **How and where are advances in complex product realization happening now?**

❒ **What are expected improvements along the commercial evolutionary path?**

❒ **In what ways might government funding facilitate leapfrog improvements, infrastructure development, and advances, particularly those that lead to US defense advantage?**

It will also be critical to extract and question much more deeply the assumptions underlying the ultimate vision. An example is the 6th grade science teacher who began the year by declaring, “half of what I am going to teach this year is wrong; but no one knows which half!” If we take this intellectual modesty seriously, it will be important to make a fuller effort to identify common assumptions and expectations about complex product realization and consider how the field might proceed if, for instance, we were to learn that some of number of these are false. For instance, our complex product realization vision places much confidence in our ability to create models that represent reality well enough to dispense with processes that today require physical prototypes. But recent findings in aerospace modeling give some cause for concern (see box below), and we are embarking on fundamentally new manufacturing regimes—such as bio-molecular approaches where our experience is negligible.

Despite our best efforts, we have no doubt failed to break free of the current paradigm in design and production. Many of the future directions identified in this report represent greater understanding and control of existing processes and methods. But the challenges in product realization in 2020 will likely be beyond things that are currently uncertain. Rather, they are unknown. Learning how to embrace the unknown, as opposed to minimizing uncertainty, may be a key part of technological innovation and leadership in the future.

Sunday October 10, 1999 *The (Champaign-Urbana) News Gazette*

"Researchers Find Flaw in Aerodynamics Laws," *Dallas Morning News*

Dallas - Two California researchers have found a hole in a law of aerodynamics big enough to fly an airliner through. A mathematical equation that has been drilled into the heads of every aspiring airplane designer since 1938 as one of the Ten Commandments of aviation is wrong, the two mathematicians say. The equation, know as the Law of the Wall, helps engineers predict how turbulent air will flow over solid objects. It has been used to help streamline the designs of airplanes ranging from single-engine Cessnas to the space shuttle. "When we came to the conclusion again and again that this law was wrong, we couldn't believe it," said Grigory Barenblatt, 72, a professor at the Department of Energy's Lawrence Berkeley Laboratory. "We were astonished. We asked ourselves, 'How could this be?'"

In simple language, Barenblatt and his colleague Alexandre Chorin, 61, combined the experiences of their mathematical careers to discover a formula that — unlike the old equation — accurately predicts what will happen in wind-tunnel experiments that try to mimic actual flight conditions. In the past, wind-tunnel results often disagreed with predictions from the Law of the Wall, causing engineers to scratch their heads and wonder where they had failed. Ultimately, many of their questions had to be answered on test flights. Test pilots routinely put their lives — and expensive prototypes of airplanes — on the line.

The fall of the Law of the Wall has not been heard around the engineering world. And where it has been, airplane designers have been skeptical. "Is this an 'Aha!' moment? I doubt it," said Bob Kelley-Wickemeyer, chief engineer of aerodynamics for Boeing Commercial Airplane Co. "Most likely, it's a 'hmmm.'" Kelley-Wickemeyer, a 1967 Berkeley graduate, helped design the Boeing 777, one of the largest, most efficient airplanes ever built. Yet, he is among the first to volunteer that the science of aerodynamics is comparable to predicting the weather. "At every turn, we are faced with a pack of lies that we have to make sense of," Kelley-Wickemeyer said. At least until now, the most accurate mathematical theories available to airplane designers gave researchers incorrect answers to eight significant questions. Theories are tested in wind-tunnel experiments. But even those don't truly mimic reality, in part because normal-sized air molecules are traveling over scaled-down airplane models. The result: wrong answers to five more key design questions. "Then we have to rely on Mother Nature to set us straight," Kelley-Wickemeyer said. Legendary engineer and test pilot Scott Crossfield, the first pilot to fly twice the speed of sound and one of the designers of the X-15 rocket plane, said he doubted that the new theory would make a huge difference. Barenblatt thinks it will take time for engineers to realize the significance of the new formula.

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Workshop Agenda

Product Realization 2020: Trends, Issue Areas and Potential Leverage Points

0800-0815	Welcome and Opening Remarks	***Kevin Lyons, DARPA***
0815-0830	Workshop Overview: Agenda & objectives, IDA research team, & invited participants	***Richard Van Atta, IDA***
0830-1000	Visions for advanced design process/tools Each invited participant will have the floor for 5-10 minutes to outline his or her perspective on the future of design processes, tools, and critical implementation issues	***All invited participants***
1000-1015	Break	
1015-1115	State of the art, current trends, & potential paradigm shifts	***Paul Collopy & Noah Richmond, IDA***
1115-1145	Presentation: “Change state in design for components and subsystems”	***Dave Japikse, CETI***
1145-1215	Presentation: “Creating the engineers for a new design paradigm”	***Mike Kelly, CSLA***
1215-1315	Lunch — Open forum	
1315-1345	Presentation: “Key areas beyond the next generation”	***Warren Seering, MIT***
1345-1630	Facilitated discussion: Issue areas	***Brad Hartfield & Richard Van Atta, IDA***
1630-1730	Facilitated discussion: Synthesis Defining issues for future needs in product realization	***Kevin Lyons & Richard Van Atta***

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