NASA/CP-2004-213244

Innovative Design of Complex Engineering Systems

Compiled by
Ahmed K. Noor
Center for Advanced Engineering Environments
Old Dominion University
Langley Research Center, Hampton, Virginia

July 2004

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Phone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076-1320

NASA/CP-2004-213244

Innovative Design of Complex Engineering Systems

Compiled by
Ahmed K. Noor
Center for Advanced Engineering Environments
Old Dominion University
Langley Research Center, Hampton, Virginia

Proceedings of a workshop sponsored by the National Aeronautics and Space Administration and Center for Advanced Engineering Environments, Old Dominion University, Hampton, Virginia, and held at Peninsula Higher Education Center, Hampton, Virginia
March 23 – 24, 2004

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

July 2004

Available from:

NASA Center for AeroSpace Information (CASI)
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 605-6000

PREFACE

The document contains the proceedings of the training workshop on Innovative Design of Complex Engineering Systems. The workshop was held at the Peninsula Higher Education Center, Hampton, Virginia, March 23 and 24, 2004. The workshop was jointly sponsored by Old Dominion University and NASA. Workshop attendees came from NASA, other government agencies, industry and universities. The objectives of the workshop were to a) provide broad overviews of the diverse activities related to innovative design of high-tech engineering systems; and b) identify training needs for future aerospace work force development in the design area. The format of the workshop included fifteen, half-hour overview-type presentations, a panel discussion on how to teach and train engineers in innovative design, and three exhibits by commercial vendors.

Ahmed K. Noor
Old Dominion University
Center for Advanced Engineering Environments
Hampton, Virginia

Contents

ODU-NASA Training Workshop on Innovative Design of Complex Engineering Systems

Peninsula Higher Education Center
600 Butler farm Road, Hampton, VA 23666
March 23 – 24, 2004

Attendees List

1. George Allison
NASA Langley Research Center
Mail Stop 309
Hampton, VA 23681
phone: (757) 864-2594
email: g.d.allison@larc.nasa.gov

2. James Blair
ASRI
CD20
Marshall Space Center, AL
phone: (256) 544-6815
email: james.blair@msfc.nasa.gov

3. Patrick Biltgen
Georgia Institute of Technology
Atlanta, GA 30332-0150
phone: (404) 894-3343
email: patb@asdl.gatech.edu

4. Adel Chemaly
Technosoft, Inc
11180 Reed Hartman Highway
Cincinnati, OH 45242
phone: (513) 985-9877
email: info@technosoft.com

5. Ozgur Eris
Stanford Center for Design Research
424 Panama Street
Stanford, CA 94305
phone: (650) 725-0150
email: ozgur@stanford,edu

6. Richard Evans
George Mason University
4400 University Drive
Fairfax, VA 22030
phone: (703) 993-1000
email: revans@gmu.edu

7. Troy Frisbie
Stennis Space Center
Mail Stop MA20
Hattiesburg, MS 39529
phone: (228) 688-2211
email: troy.frisbie@ssc.nasa.gov

8. Ronnie Gillian
NASA Langley Research Center
Mail Stop 125
Hampton, VA 23681
phone: (757) 864-2918
email: r.e.gillian@larc.nasa.gov

9. Glenn Havskjold
Boeing
6633 Canoga Avenue
Canoga Park, CA 91309
phone: (818) 586-0445
email: glenn.l.havskjold@boeing.com

10. George Hazelrigg
National Science Foundation
4201 Wilson Boulevard
Arlington, VA 22230
phone: (703) 292-7068
email: ghazelri@nsf.gov

11. Jeffrey Hoffman
MIT Aero / Asto
77 Massachusetts Avenue
Cambridge, MA 02139
phone: (617) 253-1000
email: joffma1@mit.edu

12. Aaron Johns
UGS PLM
149 Connor Drive
Royersford, MO
phone: (610) 232-5180
email: aaron.johns@ugsplm.com

13. Hongman Kim
Phoenix integration
1715 Pratt Drive
Blacksburg, VA
phone: (540) 961-7215
email: hkim@phoenix-int.com

14. Barry Lazos
NASA Langley Research Center
Mail Stop 170
Hampton, VA 23681
phone: (757) 864-5731
email: b.s.lazos@larc.nasa.gov

15. Wu Li
NASA Langley Research Center
Mail Stop 132C
Hampton, VA 23681
phone: (757) 864-7091
email: w.li@larc.nasa.gov

16. Blaine Lilly
Ohio State University
1971 Neill Avenue
Columbus, OH 43210
email: lilly.2@osu.edu

17. Ade Mabogunje
Stanford Center for Design Research
424 Panama Street
Stanford, CA 94305
phone: (650) 725-0150
email: ade@stanford.edu

18. Dimitri Mavris
Georgia Institute of Technology
Atlanta, GA 30332-0150
phone: (404) 894-3343
email: dimitri.mavris@ae.gatech.edu

19. David Moorhouse
Air Force Research Laboratory
2210 Eighth Street
Wright-Patterson AFB, OH 345433
phone: (937) 255-2123
email: david.moorhouse@wpafb.af.mil

20. James Mullins
Phoenic Integration
1715 Pratt Drive
Blacksburg, VA 24060
phone: (540) 961-7215
email: mullins@phoenix-int.com

21. Ahmed Noor
Center for Advanced Engineering
Environments
Old Dominion University
Hampton, VA 23666
phone: (757) 766-5233
email: a.k.noor@larc.nasa.gov

22. James Parker
Universities Space Research
Association
10121 Dunbarton Drive SE
Huntsville, AL 35805
phone: (256) 479-4404
email: jamesparker6@comcast.net

23. Vickie Parsons
NASA Langley Research Center
Mail Stop 480
Hampton, VA 23681
phone: (757) 864-6097
email: v.s.parsons@larc.nasa.gov

24. F.G. Patterson
NASA Headquarters
300 E Street, S.W.
Washington, DC 20546
phone: (202) 358-2171
email: pat.patterson@hq.nasa.gov

25. Joe Rehder
NASA Langley Research Center
Mail Stop 125
Hampton, VA 23681
phone: (757) 864-4481
email: j.j.rehder@larc.nasa.gov

26. Robert Ryan
ASRI
CD20
Marshall Space Center, AL
phone: (256) 544-6815
email: robert.ryan@msfc.nasa.gov

27. Luke Shutzenhofer
ASRI
CD20
Marshall Space Center, AL
phone: (256) 544-6815
email: lashover@knology.net

28. Jared Sohn
25 Oakwood Drive
Yorktown, VA 23693
phone: (757) 865-6819
sohn@cs.wisc.edu

29. Lawrence Taylor
NASA Langley Research Center
Mail Stop 365
Hampton, VA 23681
phone: (757) 864-3768
email: l.w.taylor@larc.nasa.gov

30. Alex VanderVelden
Engineous Software
2957 Clairmont Road
Atlanta, GA 30329
phone: (404) 320-7283
email: velden@engineous.com

31. Ayman Wasfy
Advanced Science and Automation Corporation
20170 E. Magnolia Court
Smithfield, VA 23430
phone: (757) 816-7081
email: ayman@ascience.com

32. Tamer Wasfy
Advanced Science and Automation Corporation
20170 E. Magnolia Court
Smithfield, VA 23430
phone: (757) 469-6839
email: tamer@ascience.com

33. William Wood
University of Maryland
Baltimore, MD 21250
phone: (410) 455-3314
email: bwood@umbc.edu

Perspectives on
Innovative Design of Complex Engineering Systems

Ahmed K. Noor
Center for Advanced Engineering Environments
Old Dominion University
Hampton, Virginia 23666

Outline

Economic stresses and a very competitive market are forcing many industries to reduce cost and development time, and to insert emerging technologies into their products. Engineers are asked to design faster, ever more complex systems. They must find globally optimal designs that take uncertainties and risk into consideration.

Over the last few years, a number of methodologies and technologies have been developed and utilized to support these efforts. Also, a number of approaches have been proposed for design education and training.

An attempt is made in this presentation to give a broad overview of the activities on innovative design and to set the stage for succeeding presentations. The presentation is divided into four parts (Figure1). In the first part, examples of future aerospace systems are given, along with some of their major characteristics and enabling technologies. The second part provides a brief overview of some of the current activities on innovative design of complex engineering systems. The third part describes a vision for future innovative design along with the key components of the innovative design process. The fourth part lists the objectives of the workshop and some of the sources of information on innovative design.

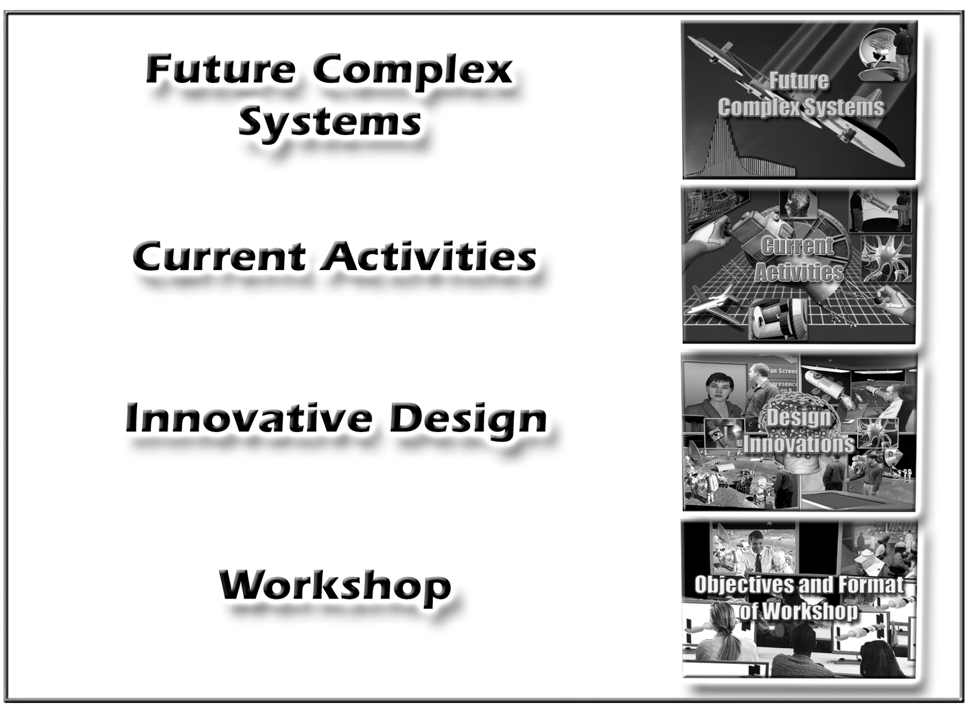


Figure 1

Examples of Future Aerospace Systems and Some of their Characteristics

The realization of NASA's ambitious space exploration initiative with the current budget constraints will require new kinds of aerospace systems and missions that use novel technologies and manage risks in new ways. Future aerospace systems must be autonomous, evoluable, resilient and highly distributed. Two examples are given in Figure 2. The first is a crew exploration vehicle. The second is a lunar outpost. Each of these is a complex system of systems.

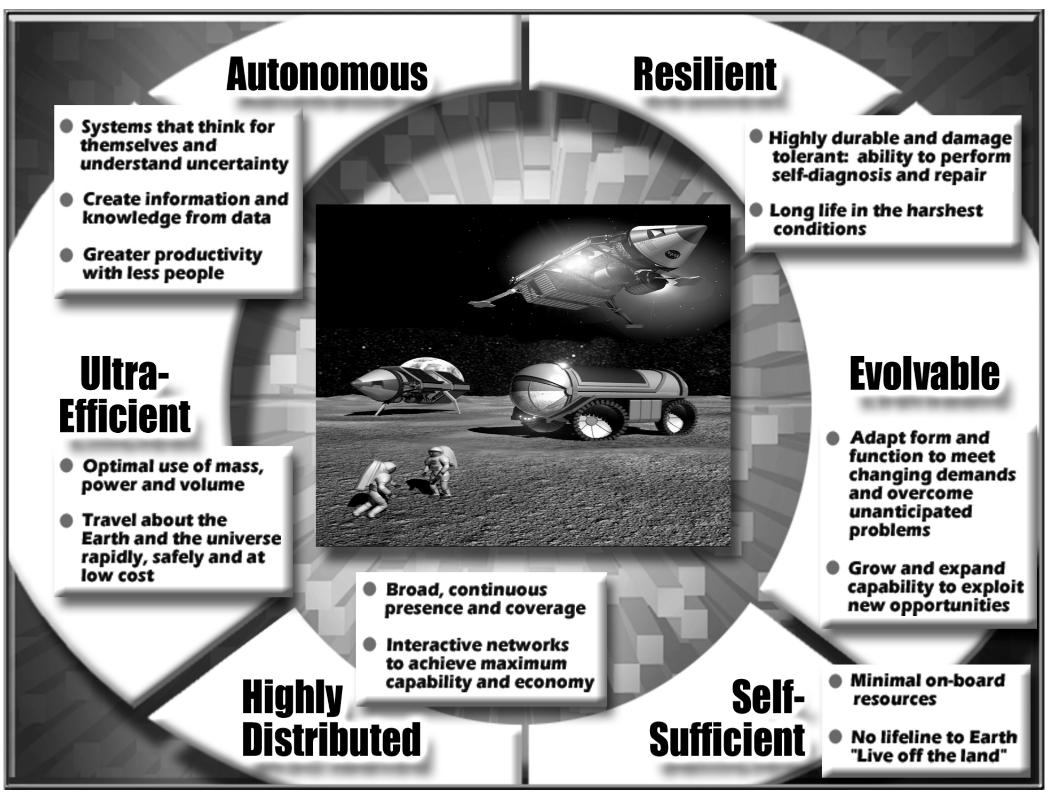


Figure 2

Enabling Technologies for Future Aerospace Systems

The characteristics of future aerospace systems identified in Figure 2 are highly coupled and their realization requires the synergistic coupling of the revolutionary and other leading-edge technologies listed in Figure 3. The four revolutionary technologies are nanotechnology, biotechnology, information / knowledge technology, and cognitive systems technology. The other leading–edge technologies are high-productivity computing; high-capacity communication; modeling, simulation and visualization; virtual product development; intelligent software agents; reliability / risk management; human-computer symbiosis; and human performance.

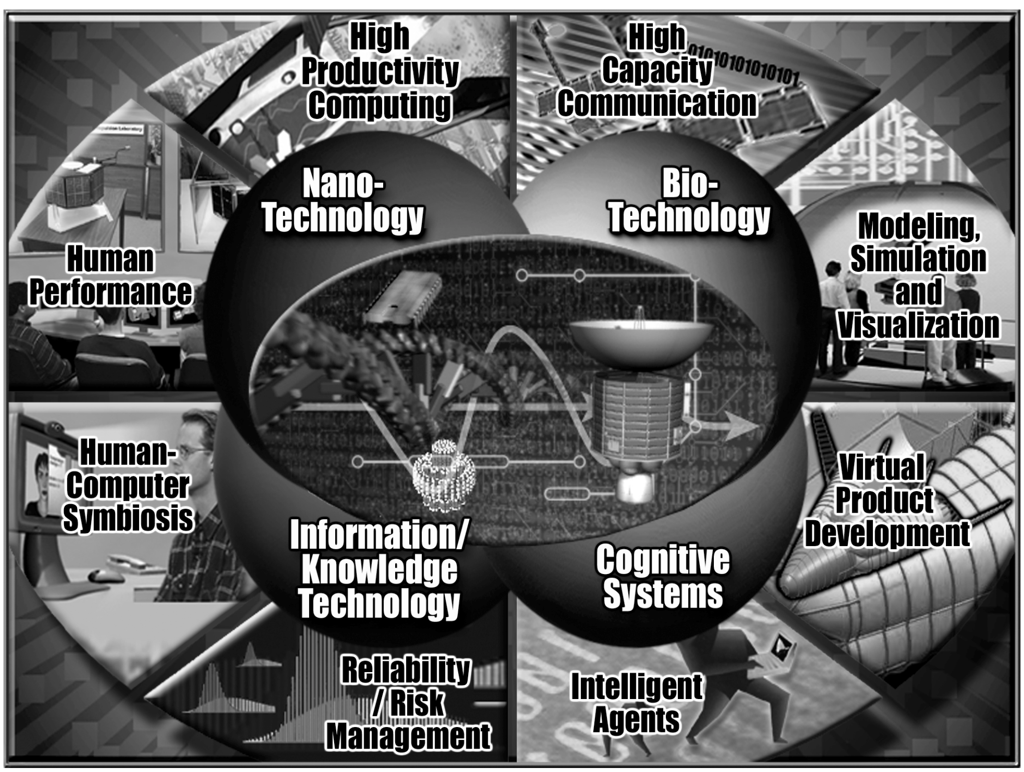


Figure 3

Definitions of Engineering Design

Although there is no single universally acceptable definition of engineering design, Figure 4 shows the definition given by the Accreditation Board for Engineering and Technology (ABET), along with four other definitions. *Design* is often equated with *Synthesis* and with the *Practice* of the engineering profession. In engineering curricula, *Design* is differentiated from *Science*, *Analysis*, and *Theory*.

Design is concerned with synthesis of information into a whole, with the everyday world of engineering practice, and with problems that cross discipline boundaries. Science, analysis, and theory achieve their power through simplifications and narrowing, through research under controlled condition, and by operating within separate disciplines.

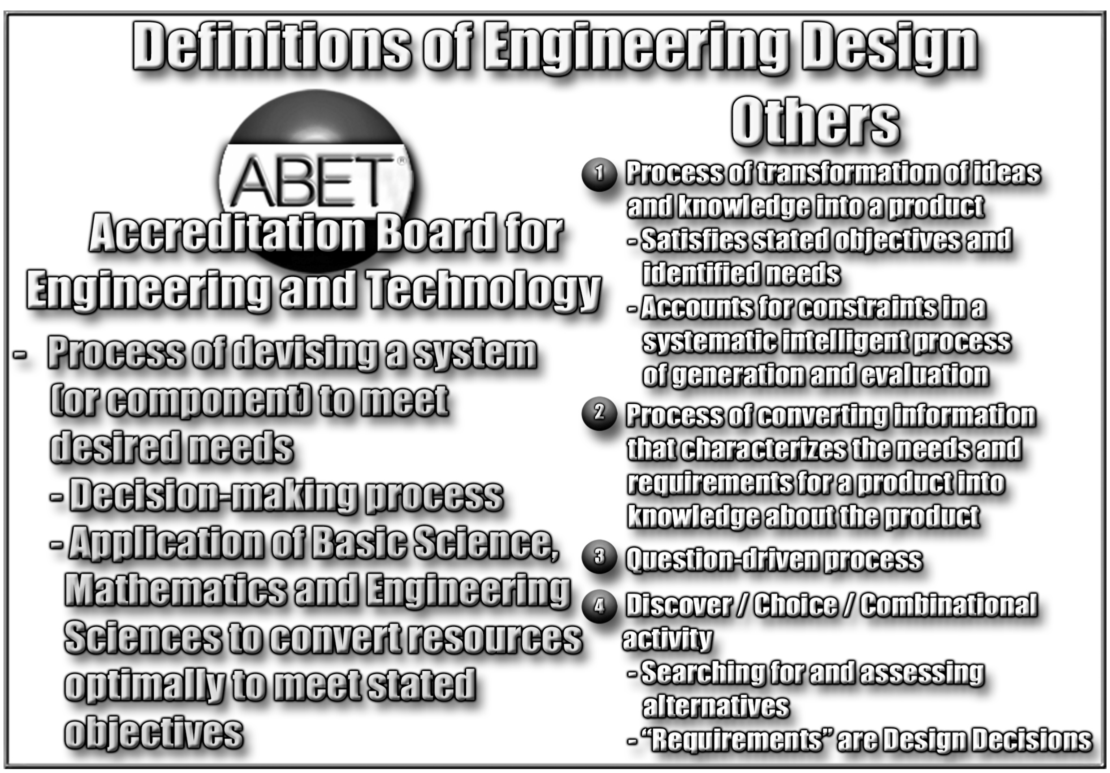


Figure 4

Design Paradigms

A number of different design paradigms are currently being used, including the four shown in Figure 5 and described subsequently. These are:

• *Design for Safety*

Intended to mitigate risk by improving the resilience of the system to unforeseen events. It aims at making the system smart to adapt to changes and self-heal from damage. It provides a final barrier against any system degradation and rare unforeseen events.

• *Design for Cost and Quality*

This includes Taguchi's robust design approach. It aims at determining the optimum configuration of design parameters for performance, quality and cost.

• *Design for the Life Cycle*

Based on early consideration of several life cycle factors in the design process, including testability / inspectability, reliability / availability, maintainability / serviceability, upgradeability, safety, and human factors.

• *Design for manufacturing*

Covers all aspects of design and manufacturing integration, including integrated assembly design and planning, part design and process planning integration, and robust design and variation management. It encompasses design for mass customization, layered manufacturing, and remanufacture.

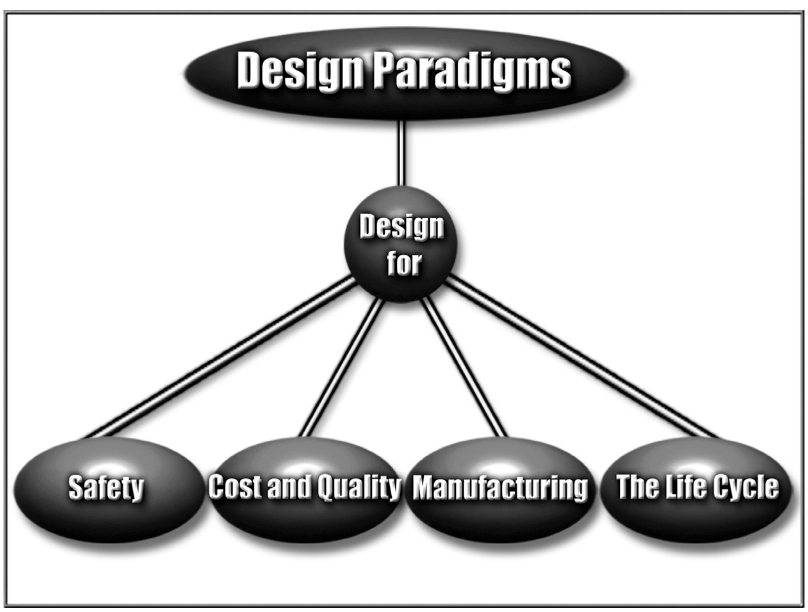


Figure 5

Enhancing Design Performance

Traditionally, the evaluation of design performance has focused on the outcome of the design process, the product. Recently, the human dimensions of designing, namely design cognition and human-centered perspective have been added to the design performance (Figure 6).

The design process involves understanding, synthesizing and applying principles associated with basic and engineering science for creating new technologies that enable new products which satisfy and delight users.

Design cognition refers to design thinking, i.e., the thought process employed in the design.

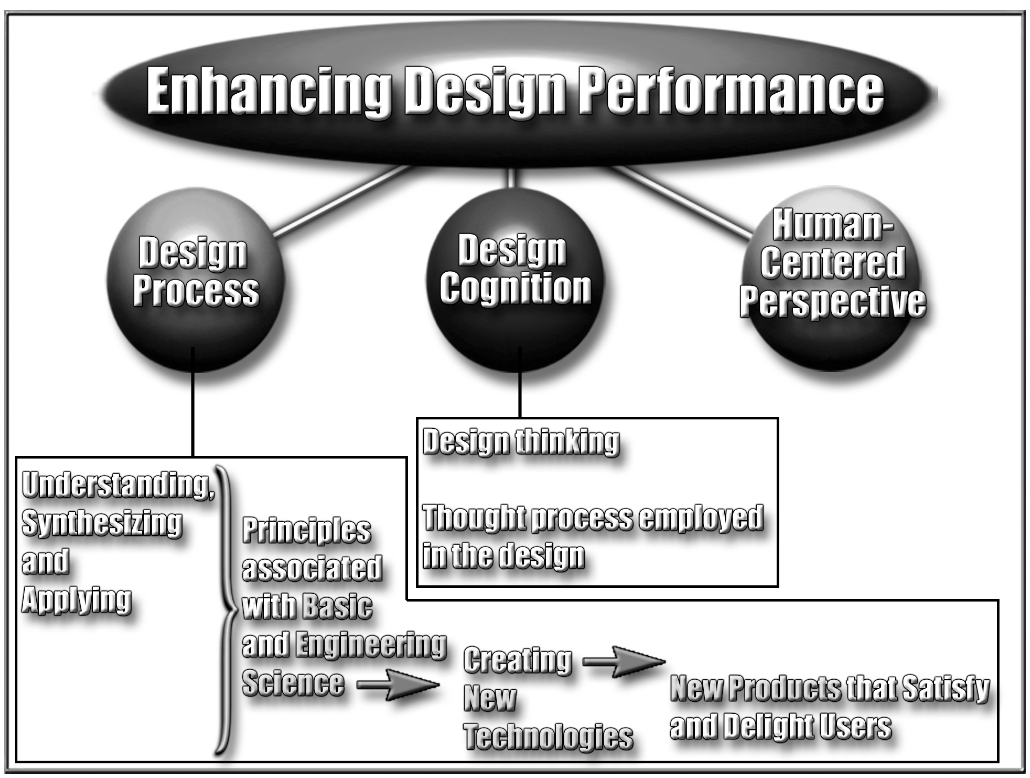


Figure 6

Activities on Innovative Design

The need for developing new approaches to design, analysis, testing and manufacturing of complex engineering systems have been recognized by government agencies, industry, and Academia. Examples of projects initiated by these organizations are given in Figure 7.

Among the government projects are the NASA Engineering Training (NET) innovative design project, NIST design repository project, DARPA's Rapid Design Exploration and Optimization (RaDEO) project, and the two NSF Projects—Engineering Design, and Transferable Integrated Design Engineering Education (TIDEE) projects. Several innovative design projects have been initiated by industry groups, including Boeing Phantom Works, Lockheed Skunk Works, General Motors (Virtual Vehicle Project) and IBM (virtual product innovation project).

Universities have developed new approaches, laboratories and centers for design research and education. Examples include MIT's Conceive-Design-Implement-Operate (CDIO); Georgia Tech Aerospace Systems Design Lab (ASDL); Stanford Center for Design Education.

Also, consortia of universities and other organizations have been formed. An example is the Space Systems, Policy and Architecture Research Consortium (SSPARC).

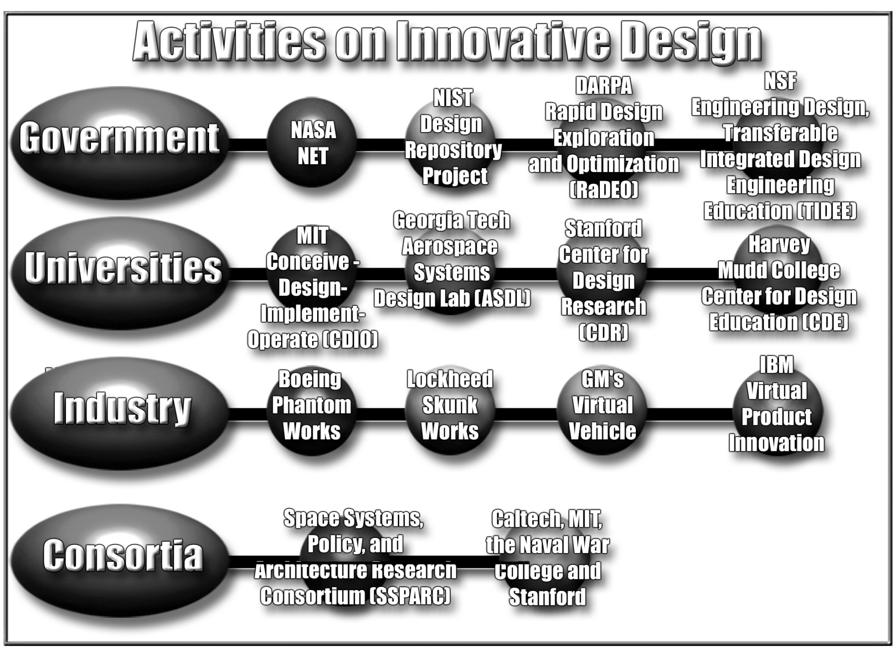


Figure 7

Forces Driving a Change in the Design of Complex Systems

After decades of evolutionary change, revolutionary changes are both needed and possible in the design of complex engineering systems. The changes are driven by four categories of forces (Figure 8):

-- *Changes in High-Tech Organizations.*
Quality was the focus of high-tech organizations in the 1980s. In the 1990s, the move from the industrial to the knowledge era shifted the focus to re-engineering and streamlining the processes, and then to managing knowledge and creation of high-performance workplaces. In the future there is likely to be a move to the biological and advanced materials era (referred to as the bioterials era). The focus of high-tech organizations will shift to explorations in the cellular and subatomic universe - architecting matter. Facilities will be developed for temporal compression and global diffusion.

-- *Economic and Business Pressures.*
Economic stresses and customer demands for cheaper, better, faster products have driven high tech organizations from mass production to mass customization, and to the adoption of lean production system concepts. They have integrated simulation and design tools with other tools and facilities for lean engineering, manufacturing and supplier management.

-- *Paradigm Change in Human / Machine / Network Interaction.*
Ubiquitous / pervasive computing and wireless connectivity among diverse teams and embedded devices, including thousands of embedded nanodevices per person, will become the norm. Consequently, there is a move from human-centered (interactive) computing to human-supervised (proactive) computing. Multimodal perceptual, neural and other advanced interfaces, which integrate adaptive interfaces with intelligent agents, will become available.

-- *Impact of Advances in Technology*.
The synergistic coupling of several leading edge technologies will have a significant impact on future products and engineering systems. To realize the potential of this syngerism, high-tech organizations will have to provide effective diverse team collaboration facilities and interdisciplinary research and development networks (VPD hubs). Modeling, simulation and visualization tools will be thought of as network services.

Forces Driving a Change in the Design of Complex Systems (cont'd)

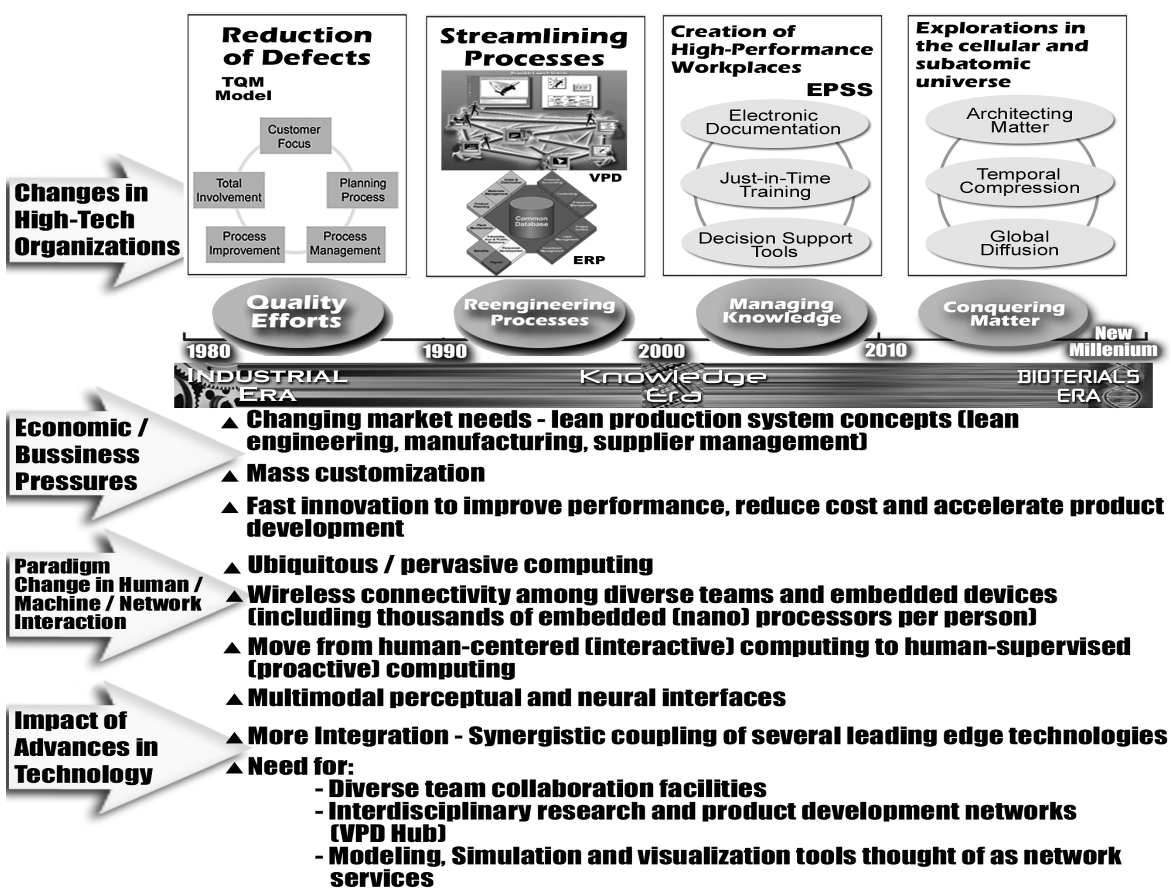


Figure 8

Innovation and Creativity

Creativity refers to coming up with new ideas. Innovation equals creativity plus successful implementation, or putting ideas into practice, which includes idea selection, development, and commercialization (Figure 9). Achieving implementation involves development of processes, procedures and structures that allow timely and effective execution of projects.

Alliance of technology and creative practices can lead to innovative product design. This includes providing new tools and media for designers, and providing opportunities to develop creative critical thinking skills.

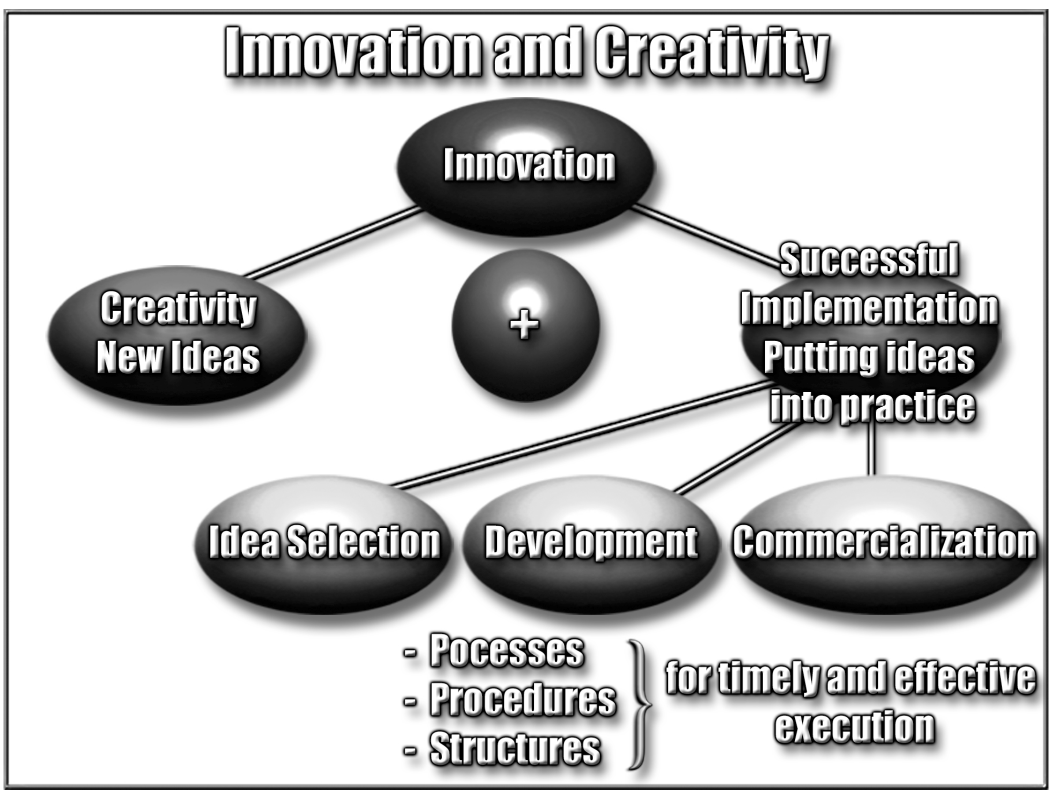


Figure 9

Key Components of Innovative Design Process

The essential components of the innovative design process can be grouped into three categories: virtual product hub, intelligent integrated networked design environments, and tools for managing complexities and uncertainties (Figure 10). The three categories are described subsequently.

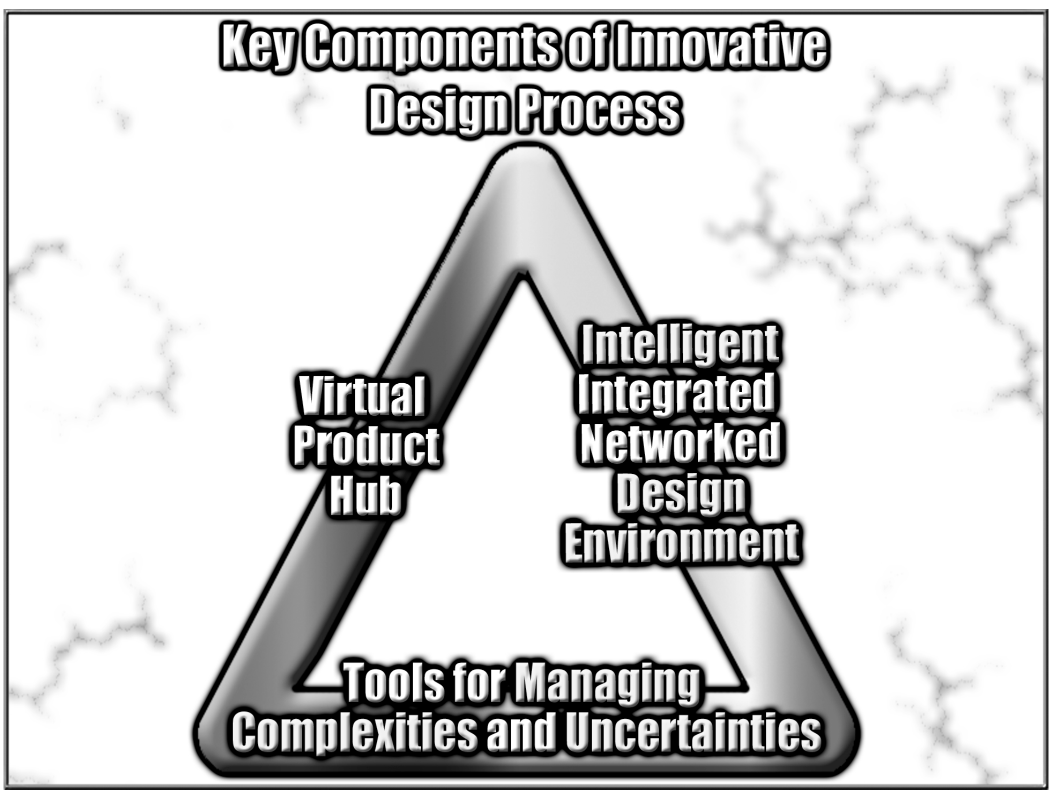


Figure 10

Virtual Product Hub

Product innovation requires a unique blend of people, processes and technologies. All rely on a common capability to collaborate, integrate and innovate: the pervasive use of a virtual product hub (Figure 11). The hub incorporates a product life cycle management (PLM) system. Modeling, simulation, visualization and optimization tools will be thought of as network services.

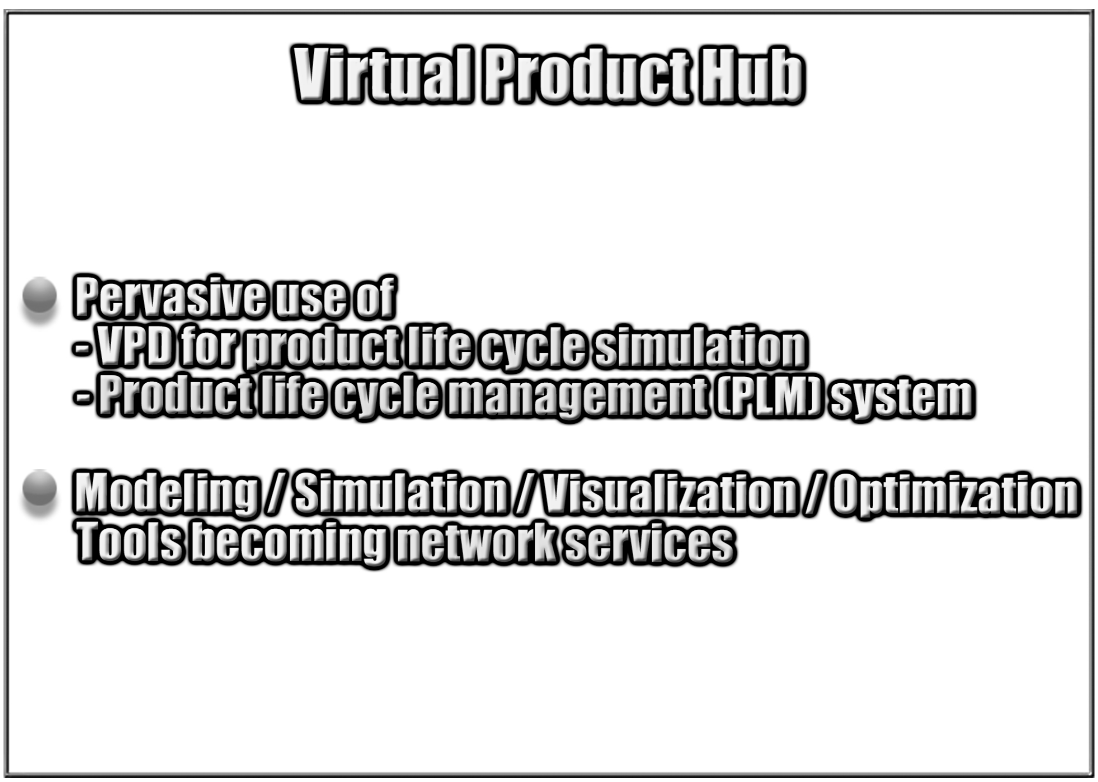


Figure 11

Intelligent Integrated Networked Design Environment

Future design environment will provide multidisciplinary and interdisciplinary teams with flexible dynamic information devices, novel multiuser displays, intelligent software agents, telepresence and other distributed collaboration facilities and multimodal interfaces.

It will exploit information / knowledge and other leading edge technologies to facilitate simultaneous collaborative design (across disciplines, tools and organizations); automate non-creative tasks; and enable informed design decisions early in the design cycle using elaborate knowledge repository, lessons learned and inverse engineering (Figure 12).

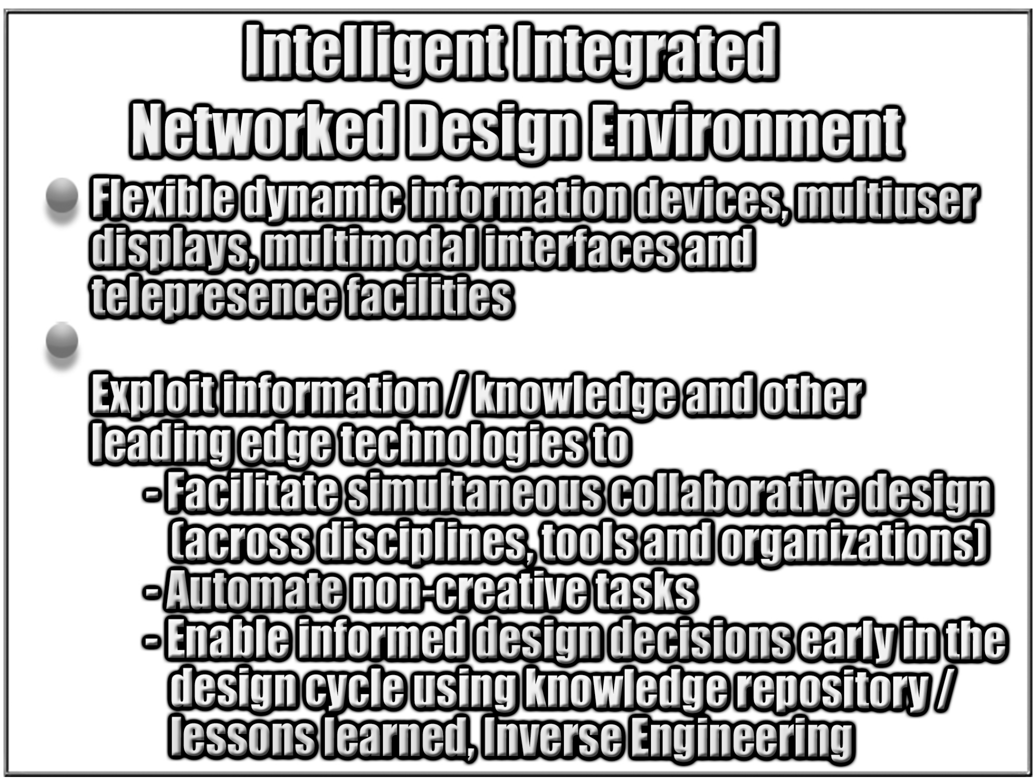


Figure 12

Tools for Managing Complexities and Uncertainties

Variety of tools can help designers in managing the complexities and uncertainties of future high-tech engineering systems, involving large number of interactions among components. These include (Figure 13):

-- Tools for handling complex multiphysics data and varying degrees of model fidelity

-- Tools for computational steering (interactively controlling the computational process during its execution), inverse steering (where the user specifies the desired simulation result, and the system searches for the simulation parameters that achieve this result).

-- Emergent synthesis tools for handling hierarchical complexity. These are interdisciplinary tools with strong connection to the fields of artificial life, artificial intelligence, evolutionary and emergent computation, soft computing, complex adaptive systems, reinforcement learning, self organization and others.

Figure 13

Innovative Design Network

The realization of the full potential of design innovations in the development of future complex systems requires, among other things, the establishment of innovative design networks. The networks connect diverse, geographically dispersed teams from NASA, other government labs, university consortia, industry, technology providers, and professional societies (Figure 14).

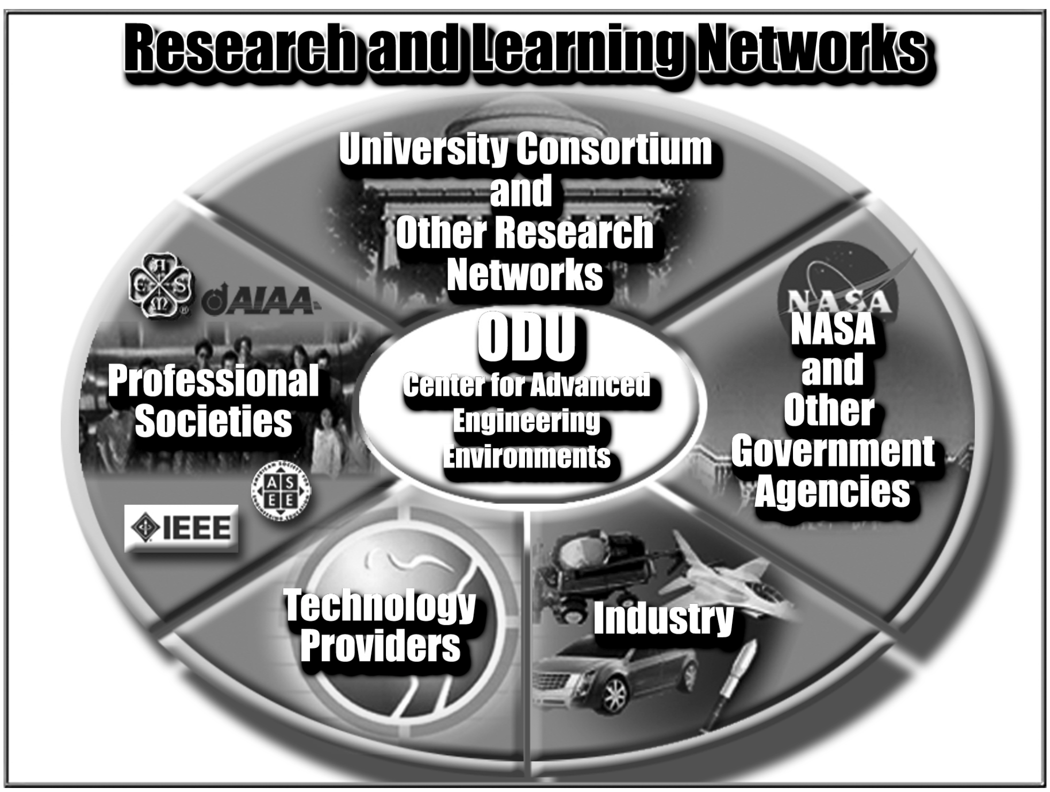


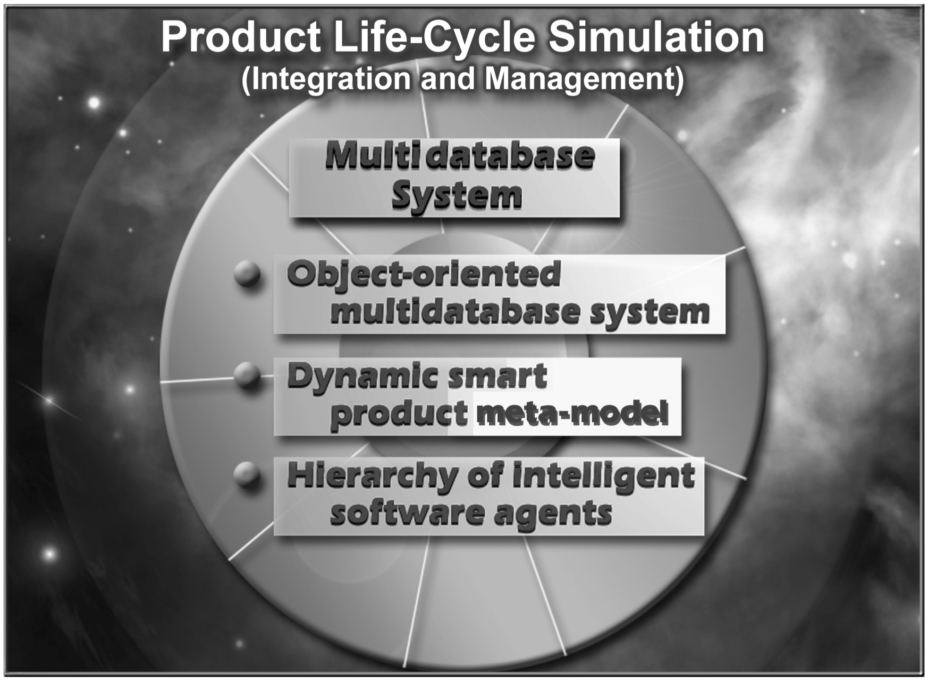
Figure 14

Product Life-Cycle Simulation

There is a pressing need to be able to optimize complex engineering systems for all aspects of life-cycle performance—including factors such as maintenance, reliability, training, and end-of-life disposition (e.g., recycle and disposal). By providing the capability to accurately model and simulate all aspects of the product life cycle from the earliest stages of mission requirements and concept selection to manufacturing, assembly planning and prototyping, testing, operations, maintenance and repairs, organizations can significantly reduce costs of acquisition and ownership, and dramatically improve operational performances and efficiency (Figure 15). Current development in this area is focused largely on CAD-based product life cycle management (PLM) tools.

Current efforts aim at having integrated models for driving, enabling and supporting all phases of the product life cycle. All activities in the life-cycle simulation apply and support a central product "meta-model" that is linked to analytical simulation tools for design, systems engineering, and decision support; and to all processes, systems, and participants in the product life cycle.

Product Life-Cycle Simulation (cont'd)



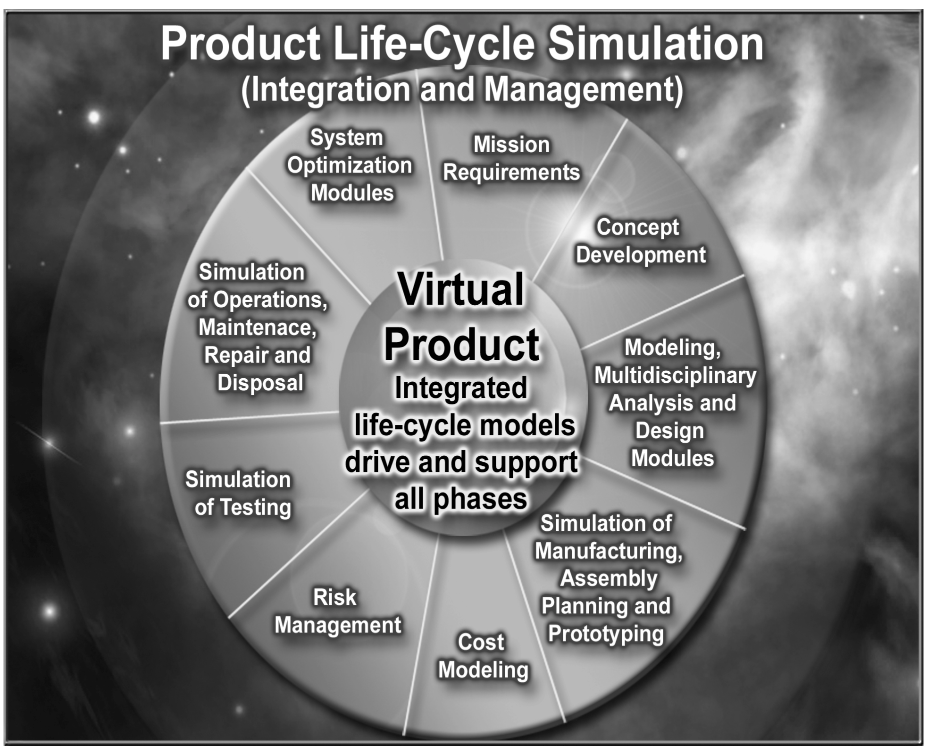


Figure 15

Virtual Product Development Hub

Figure 16 shows the major components of a virtual product hub. These are:

-- *Blended virtual product development* environment consisting of modeling, life-cycle simulation, visualization, and optimization tools (network facilities)

-- *Product life cycle management system,* incorporating model management, product data management, and simulation management

-- *Knowledge repository* incorporating information about previous projects performed by the enterprise

-- *Collaboration infrastructure* for synchronous and asynchronous communication, information sharing and group distributed developments

-- *Multimodal and advanced interfaces*

-- *VPD adviser* (intelligent software agents)
The latter three are described subsequently

Virtual Product Development Hub

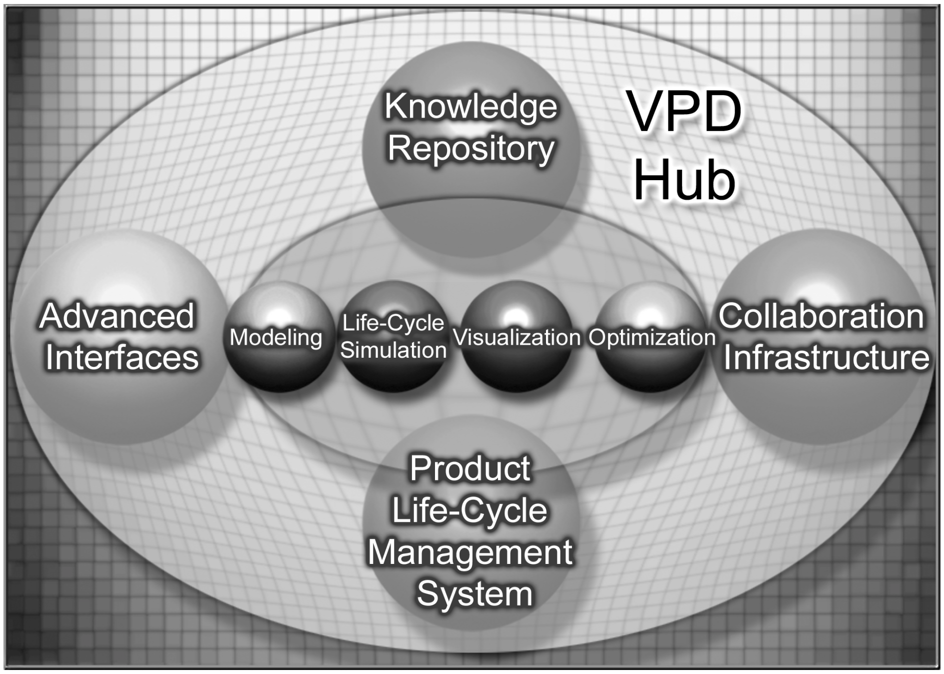


Figure 16

Collaboration Infrastructure

Intelligent software agents (human-like avatars) are used to carry out all the routine tasks that can be automated for distributed group collaboration (Figure 17). These include scheduling and starting a group meetings; query and display of information; and recording the session for the team members who cannot join the meeting.

Figure 17

Multimodal and Advanced Interfaces

Although the WIMP (windows, icons, menus, pointing devices) paradigm has provided a stable and global interface, it will not scale to match the myriad form factors and uses of platforms in the future collaborative distributed environments. The combination of neural, affective, perceptual interfaces and handheld devices will enable the interaction with the virtual product hub in more human-like ways (Figure 18).

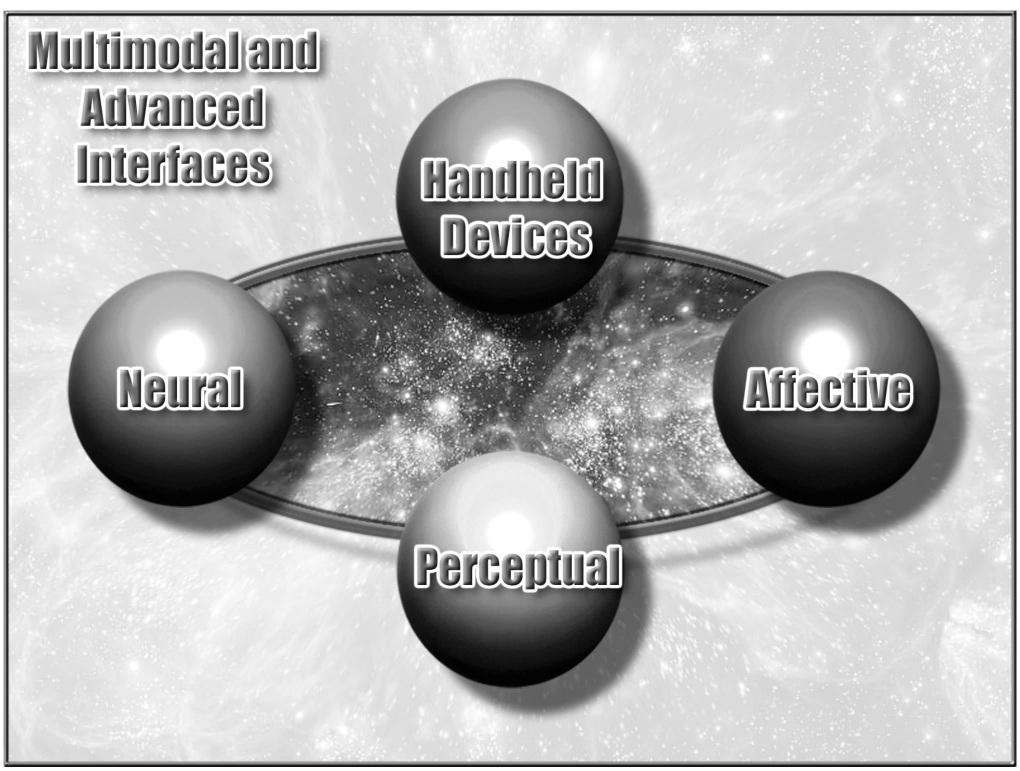


Figure 18

Virtual Product Development Advisor

Intelligent software agents (human-like avatars) are used in the VPD hub as virtual technical assistants. They provide assistance in the use of the different tools and facilities of the hub. This is accomplished by coupling natural language processing, and rule-based expert systems with the avatars (Figure 19).

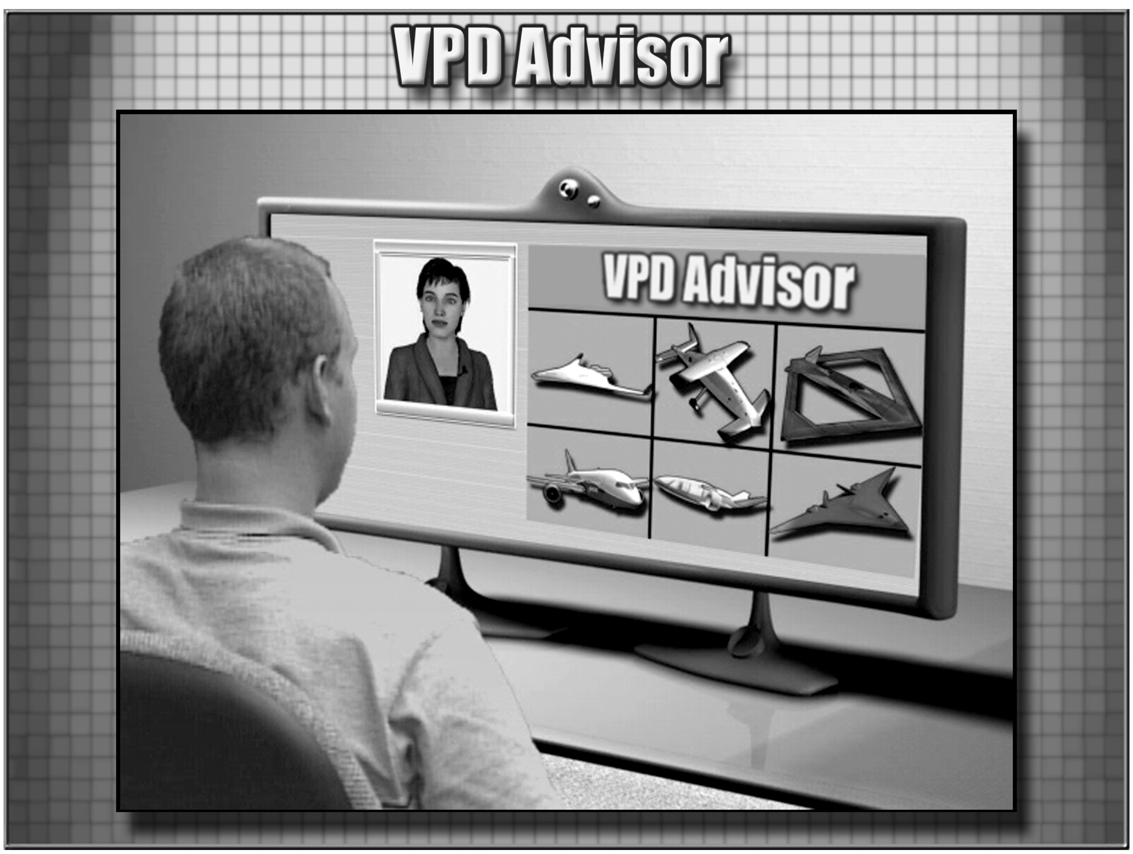


Figure 19

Intelligent Design Environment

The future design environment will enable collaborative distributed synthesis to be performed by geographically dispersed interdisciplinary / multidisciplinary teams. It will include flexible and dynamic roomware (active spaces / collaboration landscape) facilities consisting of (Figure 20):

-- Portable and stationary information devices

-- Novel multiuser smart displays

-- Telepresence and other distributed collaboration facilities

-- Novel forms of multimodal human / network interfaces

-- Middleware infrastructures and intelligent software agents

Intelligent Design Environment (con't)

Figure 20

Objectives and Format of Workshop

The objectives of the workshop are to (Figure 21): a) provide a broad overview of the diverse activities related to innovative design of complex engineering systems; and b) identify training needs for the future aerospace workforce development in the design area.

The format included 15 presentations in six sessions. A panel session was devoted to "how to teach and train engineers in innovative design." Three exhibits were also organized by technology providers at the meeting.

Figure 21

INFORMATION ON INNOVATIVE DESIGN OF COMPLEX ENGINEERING SYSTEMS

A short list of books, monographs, conference proceedings, survey papers and websites on innovative design of complex engineering systems is given subsequently.

Books, Monographs, and Conference Proceedings:

[1] Eris, Ozgur, *Effective Inquiry for Innovative Engineering Design*, Kluwer Academic Publishers, 2004.

[2] Antonsson, Erik K., and Cagan, Jonathan (editors), *Formal Engineering Design Synthesis*, Cambridge University Press, 2001.

[3] Kroll, Ehud, Jansson, David G., Condoor, Sridhar, S., *Innovative Conceptual Design: Theory and Application of Parameter Analysis*, Cambridge University Press, 2001.

[4] Tong, Christopher, and Sriram, Duvvuru (editors), *Artificial Intelligence in Engineering Design: Models of Innovative Design, Reasoning about Physical Systems, and Reasoning about Geometry*, Academic Press, 2000.

[5] Pugh, Stuart, *Creating Innovative Products Using Total Design,* Prentice Hall, 1996.

Survey Papers and Articles:

[1] Eris, Ozgur, Leifer, Larry, "Facilitating Product Development Knowledge Acquisition: Interaction between the Expert and the Team," *International Journal of Engineering Education*, Vol 19, No. 1, pp. 142-152, 2003.

[2] Klein, Mark, Faratin, Peyman, Sayama, Hiroki, and Bar-Mar, Yaneer, "What Complex Systems Research Can Teach Us about Collaborative Design," Proceedings of the Sixth International Conference on Computer Supported Cooperative Work Design (CSCWD-2001), IEEE Press, pp. 5-12, 2001.

[3] Raju, P.K., Sankar, Chetan S., Halpin, Gerald, Halpin, Glennelle, "An Innovative Teaching Method to Improve Engineering Design Education," *American Society for Engineering Education*, St. Louis, MO, June 2000.

[4] Cowan, F. Scott, Allen, Janet K., and Mistree, Farrokh, "Exploring Perspectives with Livings Systems Theory in the Design of Complex Engineering Systems," Proceedings of the 44th Annual Conference of the International Society for the Systems Sciences, (Allen, J. K., and Wilby, J., eds.), ISSS, July 16 - 22, 2000, Toronto, Canada, Paper No. 20138

[5] Szykman, Simon, Sriram Ram D., Bochenel, Christophe, Racz, Janusz, "The NIST Design Repository," *Soft Computing Engineering Design and Manufacturing*, July, pp. 5-19, 1998.

Websites:
1. Aerospace System Design Lab, Georgia Tech
http://www.asdl.gatech.edu

2. Center for Design Research, Department of Mechanical Engineering, Stanford University
http://www-cdr.stanford.edu

3. Conceive-Design-Implement-Operate, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology
http://www.cdio.org/index.html

4. Center for Design Education, Harvey Mudd College
http://www2.hmc.edu/~dym/CDE_index.html

5. Chalmers Innovative Design
http://www.design.chalmers.se/about_us/idsummary.html

6. The Institute of Systems Research, University of Maryland
http://www.isr.umd.edu/ISR/about/definese.html

7. Rapid Design Exploration and Optimization (RaDEO)
http://www.darpa.mil/dso/trans/swo.htm

8. National Institute Standards and Technology Design Repository (Virtual Library)
http://nvl.nist.gov/

9. National Science Foundation Engineering Design
http://www.nsf.gov/home/eng/

10. National Science Foundation, Transferable Integrated Design Engineering Education (TIDEE)
http://www.tidee.cea.wsu.edu

11. IBM Virtual Product Innovation
http://www1.ibm.com/industries/automotive/doc/content/component/services/283660108.html

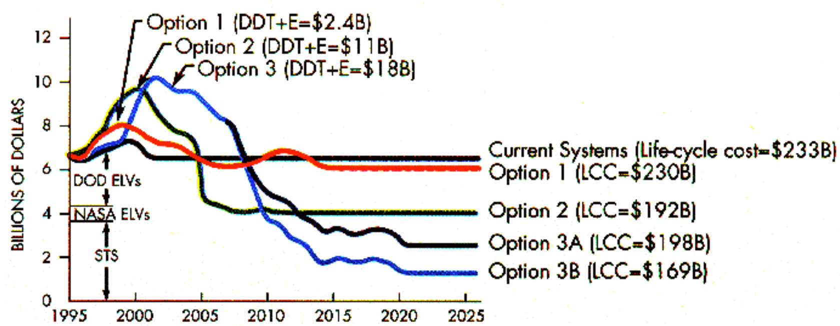
The Product Development Imperative: Business Case for the Robust Design Computational System (RDCS) and the Acceleration Insertion of Materials (AIM) Technologies

Glenn Havskjold
Advanced Technology Programs
Boeing
Canoga Park, CA

To develop an advanced technology aerospace product on budget and on schedule, data indicates that what I am labeling a “Product Development Imperative” exists. This presentation discusses that imperative and shows how critical capabilities have been developed in the Robust Design Computational System and are being developed in the Accelerated Insertion of Materials program.

A chart from a NASA study, published in Aerospace America, illustrates the economic issues in deciding to invest in an access to space capability. For each option shown, an up-front investment is required to achieve a desired benefit. Generally, the greater the desired benefit, the more investment is required. In the private sector, a financial analyst would compute a return on investment or an internal rate of return to assess the worth of the investment. Government agencies may or may not use such an analysis, but to justify investing, at some point a decision is made that the benefit of some option is worth the investment. If the size of the required cost increases, if the schedule increases, or if the benefit is smaller than planned, the cost-benefit analysis associated with the investment may be compromised. For development programs, the issue is how to develop an advanced technology product on a planned budget, on a planned schedule, and achieve the targeted goals.

NASA Study Illustrates Economic Basis of Access to Space Decisions

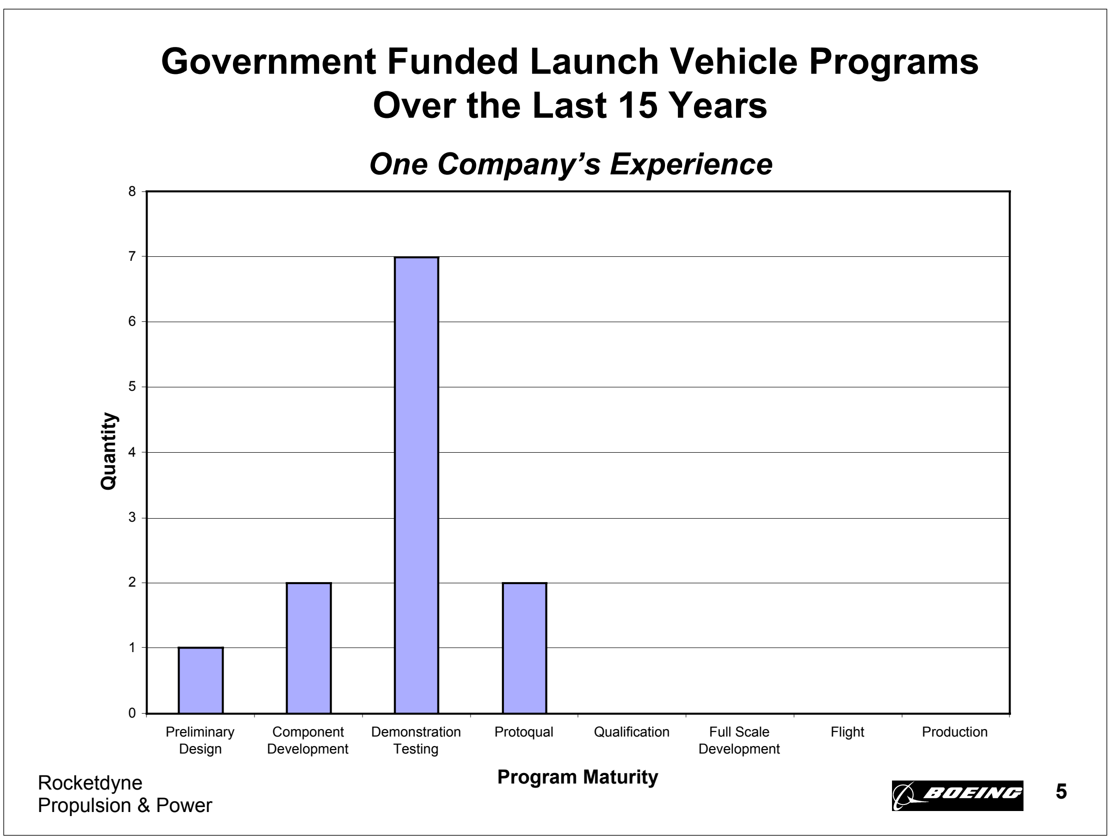


Bekey, Ivan: Powell, Richard; Austin, Robert. "NASA studies access to space." Aerospace America, May, 1994. PP 38 - 43

Rocketdyne
Propulsion & Power

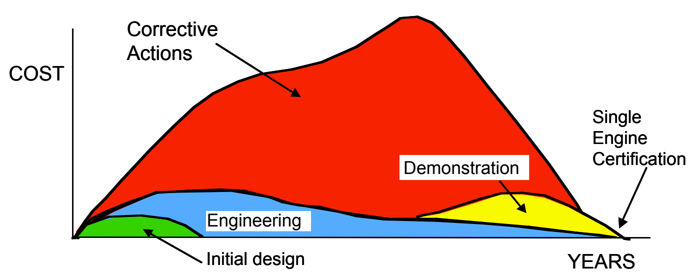
BOEING 4

Often the consequence of exceeding the budget or schedule or not achieving the planned goal on a government funded program is that the program is cancelled. Shown in one company's (not Boeing, although the Boeing experience would be similar) experience in government-funded launch vehicle programs over the last 15 years. Note that none of the programs over the last 15 years ever reached flight status. What has been the return on the government investment in these programs?



To understand what is happening, we start with the initial investment phase. The cost profile shown is taken from a NASA-funded cost estimation contract which looked at the historical experience of advanced technology rocket engines. What stands out clearly is that 73 percent of the cost of developing an engine to the point of single engine certification was absorbed in corrective actions on full-scale hardware after it had been designed and installed in the test stand. The large cost for corrective actions represents a cost overrun. A second set of data characterizing both advanced technology rocket engines and advanced technology jet engines shows a different breakout. To see how these two sets of data help understand what is happening in the product development process, we start with a simple depiction of a development process.

Development Cost Dominated by Rework Cycles After Full Scale Engine Testing Begins



Corrective Actions Largest Development Cost	
Initial Design	2 percent
Engineering	15 percent
Demonstration	10 percent
Corrective Actions on Test Stand	73 percent

NASA cost analysis contract for rocket engines

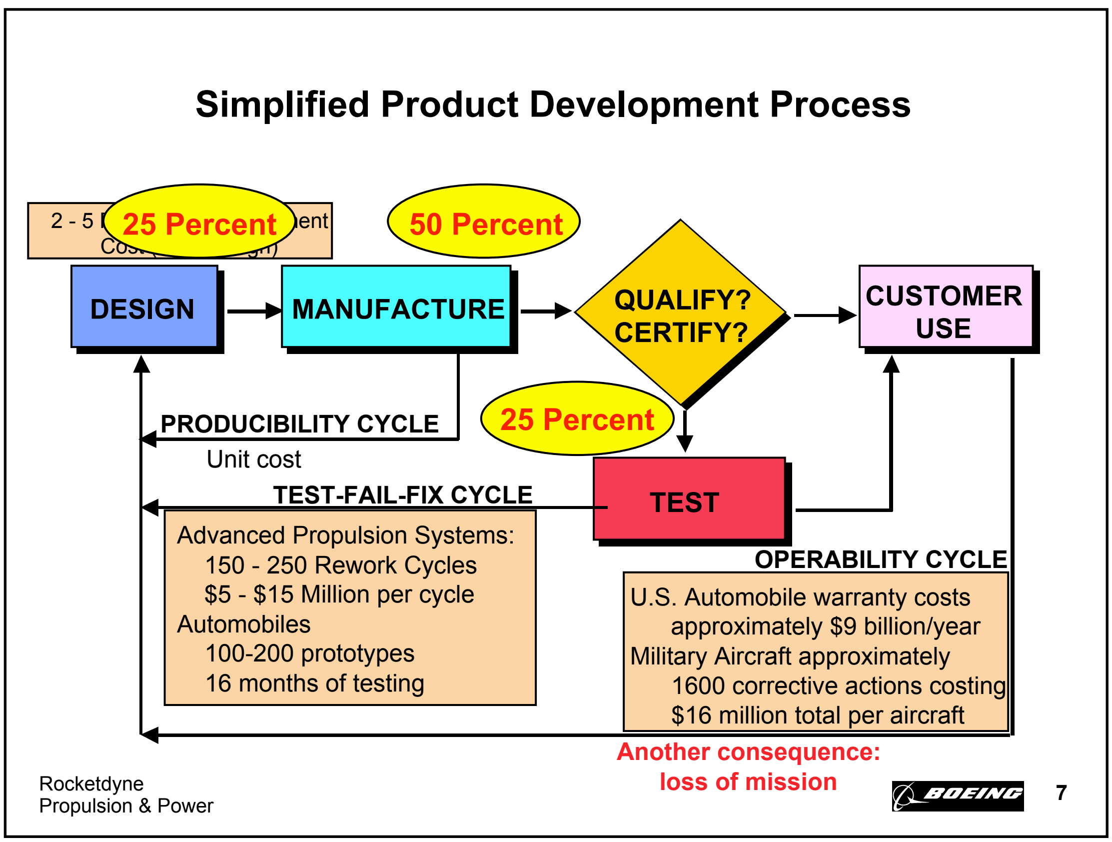
Development Costs by Discipline	
Engineering & Mgmt	25 percent
Test	20-25 percent
Hardware	50-55 percent

NASA consortium data for jet and rocket engines

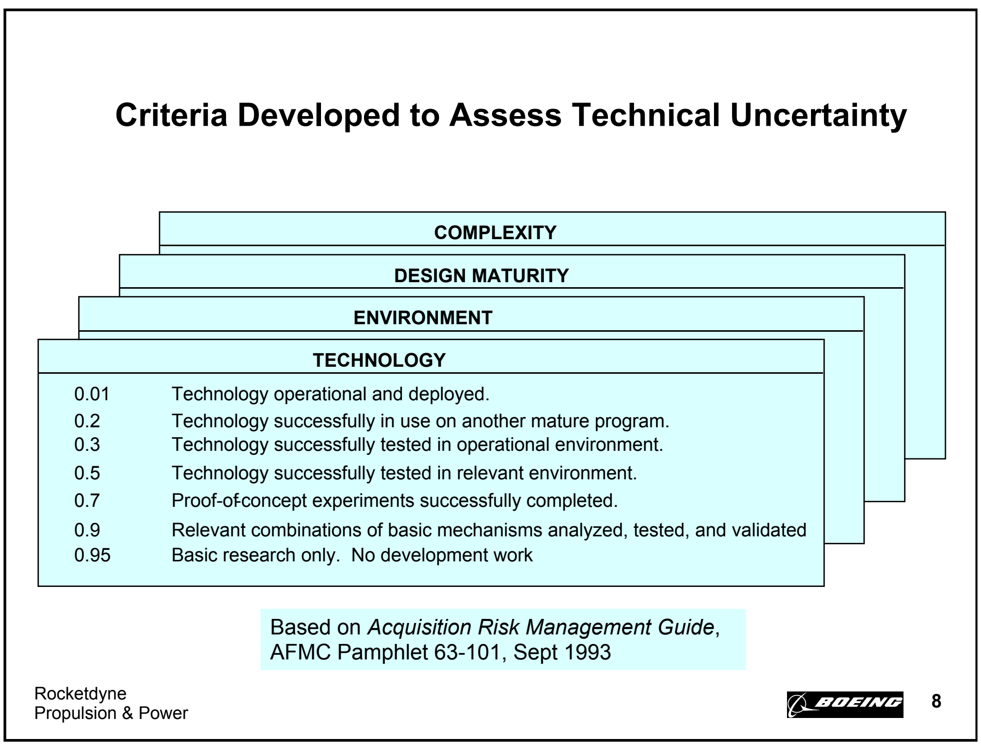
Rocketdyne
Propulsion & Power

BOEING 6

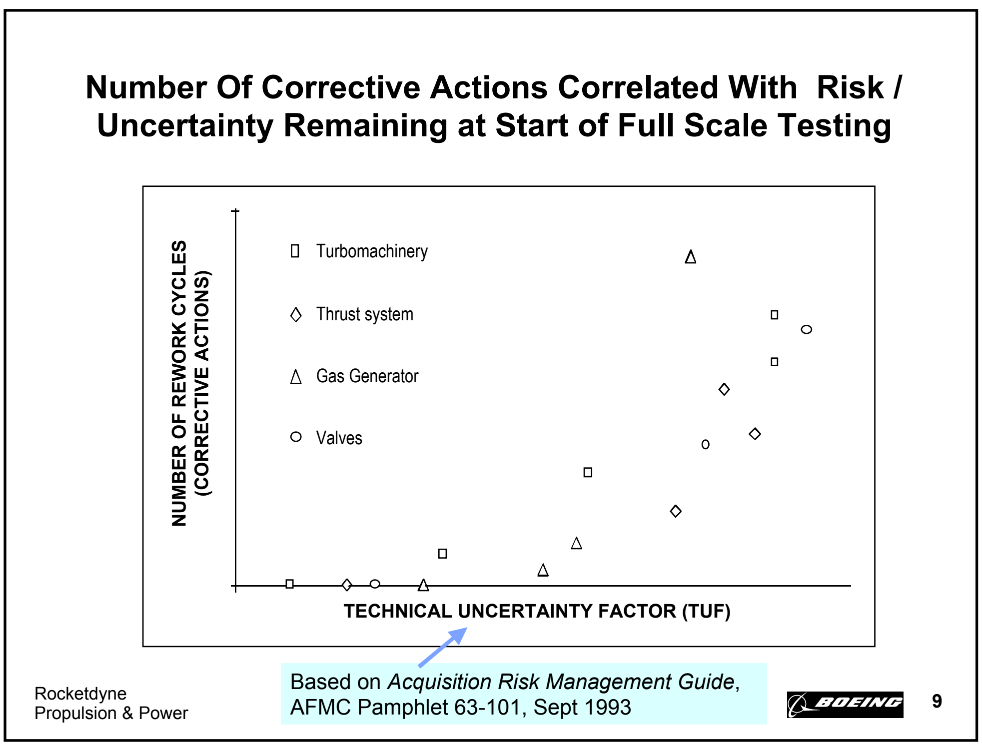
A simplified product development process is shown consisting of design, manufacture, test (if necessary) and customer use. If problems with the design are found in manufacturing, changes may be made to the product to resolve the manufacturing problems. This is the famous "throw it over the wall" problem, and one measure appropriate for this "Producibility" cycle is the unit cost. If problems with the design are found during tests of the full scale product, then the "Test-Fail-Fix" cycle occurs. For advanced technology propulsion systems, both jet engine and rocket engine, the typical number of rework cycles and the cost of a single rework cycle are shown. Taking the midpoints, 200 rework cycles and $10 million per rework cycle, gives a $2 billion result. Clearly, the Test-Fail-Fix cycle has been a major cost element in development programs. If a problem is found when the product is in customer use, the Operabilty Cycle could occur to solve the problem with a design change. Change at this stage is so expensive, however, that when it occurs, it occurs in blocks (groups) of changes. Often, the consequence is increased maintenance costs or limitations on product use rather that incur the costs of the Operability Cycle.



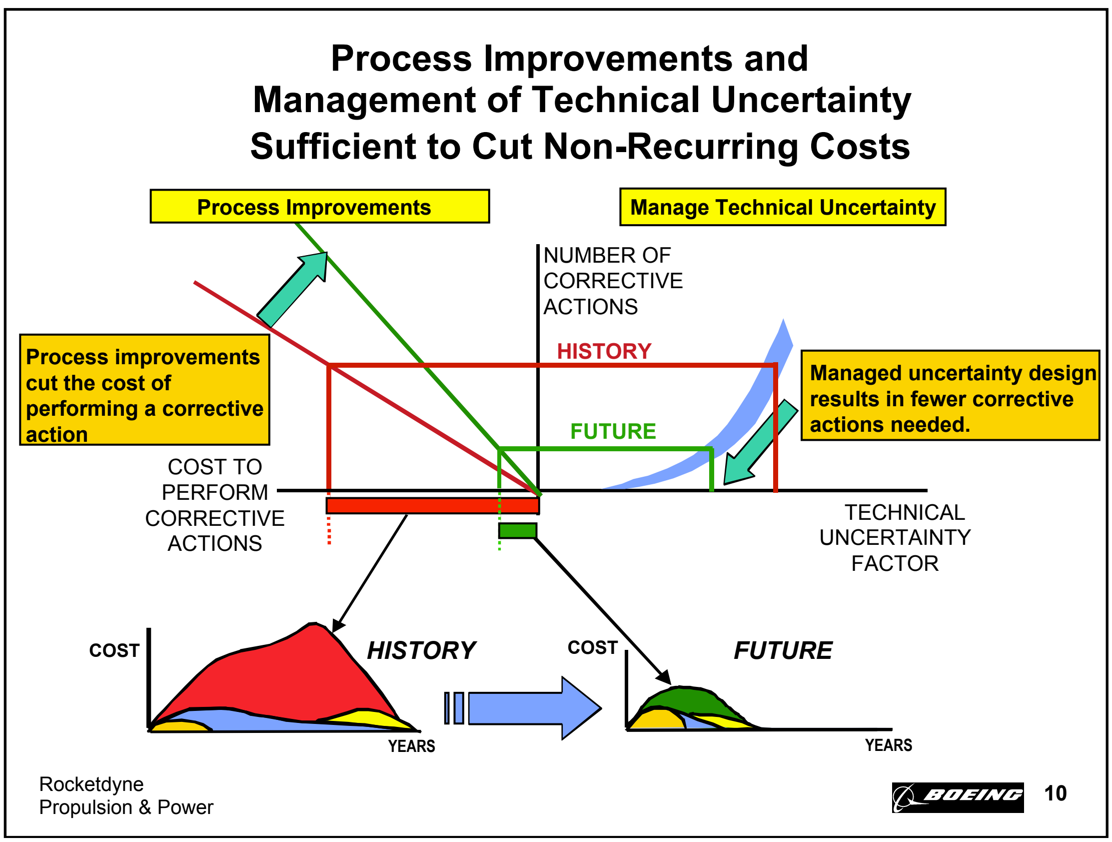
To meet the time limit for this presentation, several steps have been skipped. When it became clear that the cost of rework cycles dominated development costs for advanced technology propulsion systems, further investigations suggested that rework cycles were in turn possibly determined by the level of risk assumed when the decision was made to design the hardware. Accordingly, some criteria, based on an Air Force risk assessment guide, were developed to assess the level of risk assumed on some heritage products. Note that the criteria are similar to the NASA Technology Readiness Level scale for the case shown, but the numbers are two decimal place numbers between 0 and 1 rather than the levels of 1 to 9.



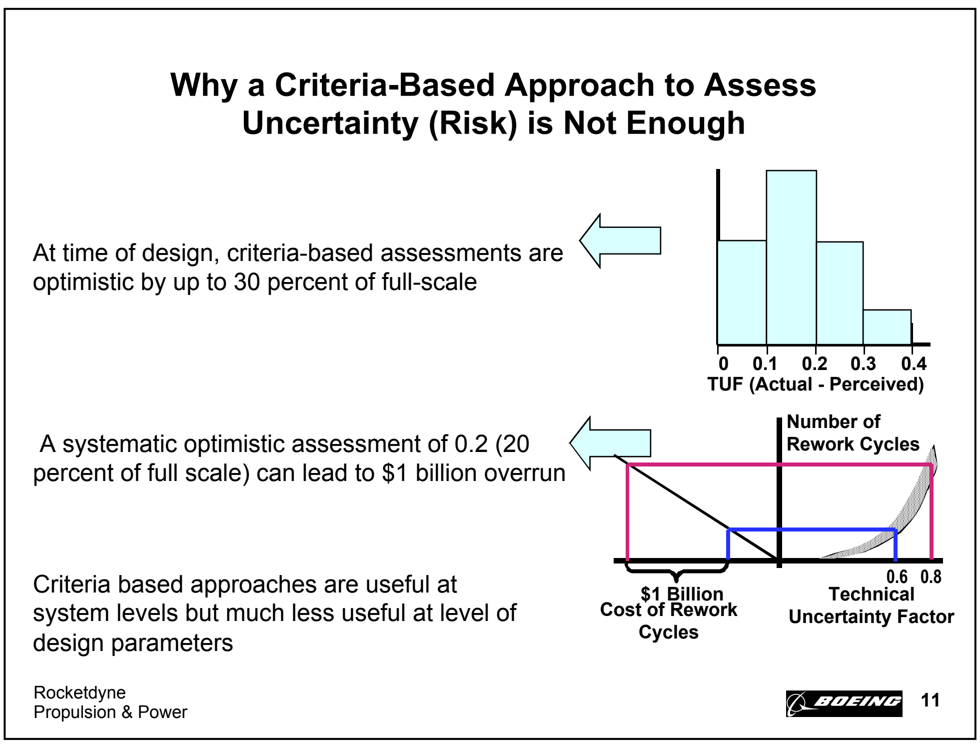
A group was assembled consisting of people who had been involved in the development of several heritage propulsion systems. The group used the criteria just discussed to look back in "20-20 hindsight" and assess each component of those heritage engines. For each component, the four assessments (one for each criteria) were averaged and plotted against the number of rework cycles that had actually been experienced. The data were plotted to give the graph shown where the Technical Uncertainty Factor (TUF) is the average of the four ratings. For each component, there is a clear relationship between TUF and the number of rework cycles. Note that the graph also combines the ratings from four different propulsion systems.



There are two levers in product development-- the efficiency of processes and the management of technical uncertainty -- that are sufficient to control and minimize nonrecurring product development costs. The right quadrant in the figure is simply the relationship already shown between the Technical Uncertainty Factor and the number of rework cycles (corrective actions). The individual points are now covered with a blue colored band. The left quadrant is simply the relationship between the number of corrective actions and the total cost to perform those corrective actions. The slope of the line is the average cost of a corrective action. The horizontal axis labeled Cost to Perform Corrective Actions is a measure of the portion of development costs absorbed by performing corrective actions. As is apparent from the figure, decreasing the Technical Uncertainty Factor before designing the full scale product combined with reducing the average cost to perform a corrective action results in a dramatic reduction in the cost of the development program.

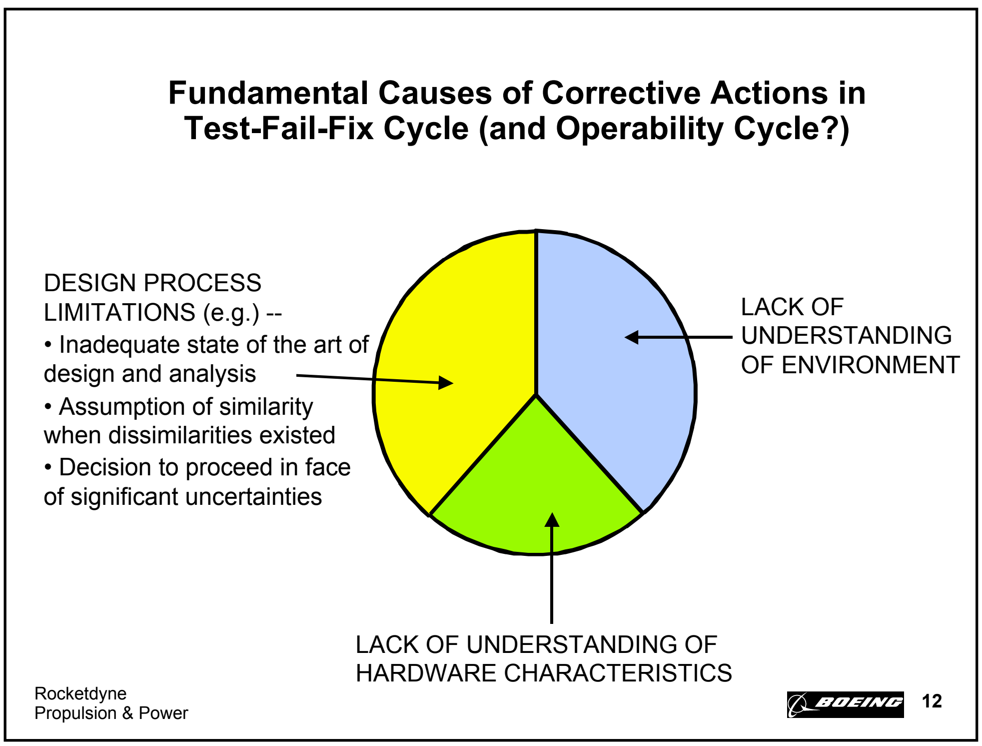


In the upper part of the figure, a distribution shows the difference between using the uncertainty evaluation criteria to evaluate the uncertainty in 20-20 hindsight (labeled “Actual”) and, for a limited number of cases, the results that would have been obtained if the criteria had been used to evaluate technical uncertainty at the time the design initiated (labeled “Perceived”). In all cases, the technical uncertainty in 20-20 hindsight is higher than would have estimated at the time of design. In the middle of the figure, it is shown that a systematic mis-estimate in technical uncertainty of 0.2 would lead to a $1 billion difference in the size of the development program. The consequences are severe and dictate that more accurate techniques be developed.

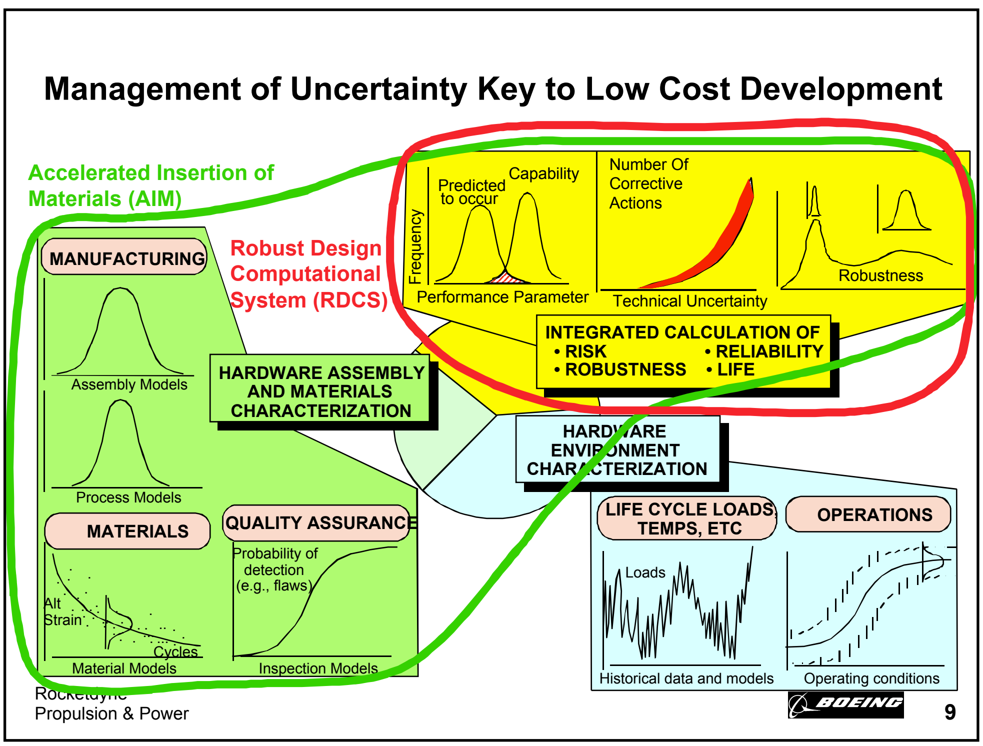


At the time that the moon landings were coming to an end, NASA awarded a contract to go back and look at the development programs for two of the primary rocket engines to see what could have been done to make development more efficient. One of the results from that study is shown in this slide. There are three major fundamental causes of trips through the Test-Fail-Fix cycle. First, lack of understanding (or, uncertainty) of the environment. Second, lack of understanding (or, uncertainty) of the hardware that was being built. Third, limitations in the design process.

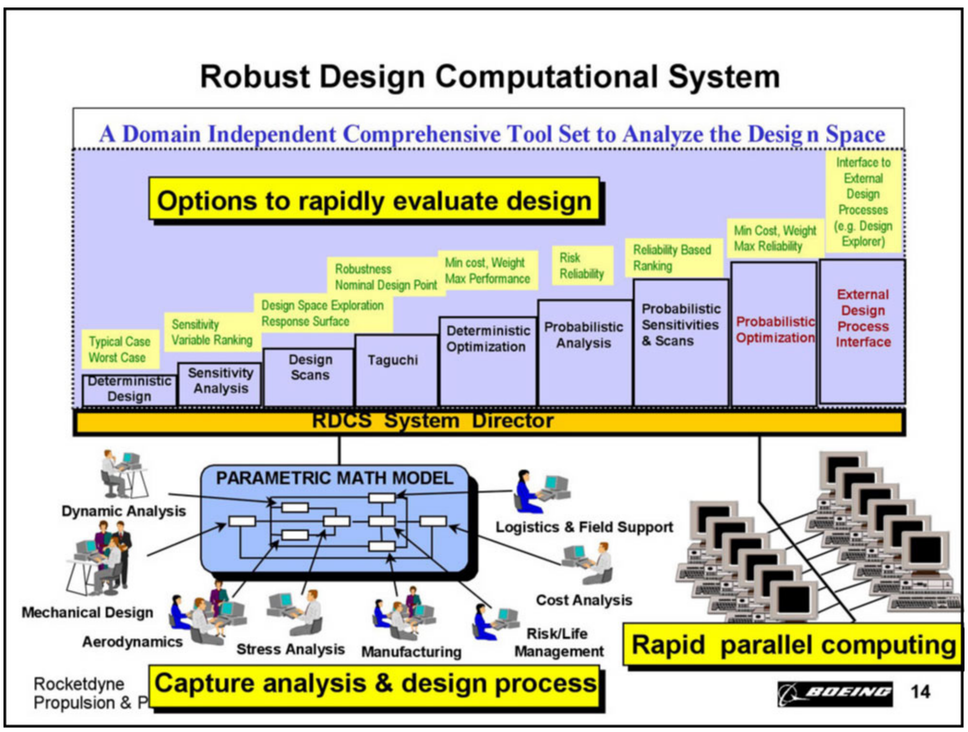
THESE ARE THE FUNDAMENTAL CAUSES. THESE MUST BE ADDRESSED IF ONE INTENDS TO MAKE ANY SIGNIFICANT DIFFERENCE IN DEVELOPMENT PROGRAMS. RDCS WAS DESIGNED TO ENABLE DESIGN TEAMS TO ATTACK THESE CAUSES DURING DESIGN.



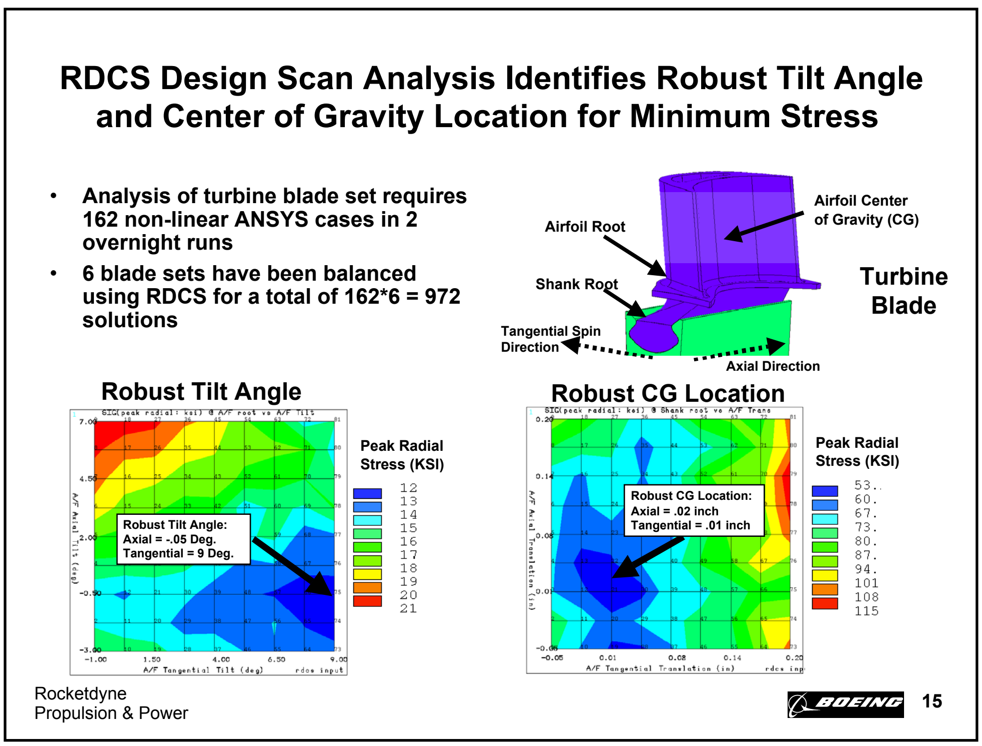
In this figure, descriptions are provided of the various segments of the pie chart from the previous figure. Characterization of the hardware includes material properties as well as the manufacturing and quality control processes used to convert the raw material form into the actual hardware. Environment characterization includes the operation duty cycle and the loads associated with each portion of the duty cycle. The portion corresponding to design limitations processes the uncertainty information from the hardware characterization and from the environment characterization to provide an integrated calculation of life, risk, robustness, and reliability. The DARPA-funded Robust Design Computational System (RDCS) was designed and developed to provide the integrated calculation capability. RDCS is the only system in existence which was designed and developed for this purpose, and it is the only system designed and developed by engineers who actually work in product design. Subsequently, the Accelerated Insertion of Materials program, also DARPA funded, developed the capability for materials characterization and linked it to RDCS.



The Robust Design Computational System (RDCS) provides three major services to a design team: (1) a facility to capture the analysis and design process, (2) options to rapidly evaluate the design, and (3) a capability to process large numbers of jobs in parallel over a network of workstations or on a high performance computing system. A multidisciplinary team must define an integrated set of executable modules (one or many) that evaluate the some aspect of the design. This integrated set of modules is linked to the RDCS System Director which provides a large number of options to automatically create design evaluation instances including deterministic and probabilistic effects. RDCS then sends these jobs out to be processed and retrieves and displays the results.



The RDCS full factorial design scan feature allows a design team to evaluate the design for a systematically generated set of points. In this case a set of evaluations was performed for systematic variations in tilt angle, and a second set of evaluations was performed for systematic variations in the location of the center of gravity. In each case, the selection of design value was based on which design values would result in the stresses being well within a low stress region. Robustness is achieved because stresses will continue to be low even with variations (such as manufacturing variations) in the tilt angle and location of the center of gravity. Note that nearly 1000 lengthy nonlinear ANSYS solutions were required for this design activity.



This and the next two charts illustrates applications of RDCS to actual large scale design cases. Specific details have been removed to enable these charts to be presented in an open forum. This chart shows the application of RDCS to help select appropriate values for the design parameters characterizing the cross section of the fuselage of a large aircraft. As in the turbine blade design case, factorial design space explorations were combined with sensitivity analyses. Determining the appropriate values required 158 large scale finite element solutions. Without the ability of RDCS to rapidly generate and process evaluation cases, only a few cases would have been run.

RDCS Application to Fuselage Concept Design

Application Objective

- To aid in the selection of appropriate values for fuselage and barrel design variables
- An optimum weight design meeting constraints of body bending, ultimate internal pressure, decompression and forward and downward "g" loads

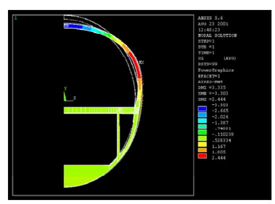
High Level Description

- **Design variables:** Barrel and frame geometry parameters
- **Response Variables**: Weight
- **Solvers:** RDCS and ANSYS

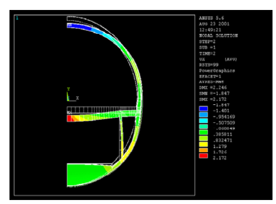
Solution Scope

- **RDCS:** Sensitivity analysis and Factorial Design Space Explorations
- **ANSYS**: Static analysis and Optimization
- **Solution Cases**: 158 Large Scale FEM Solutions

Typical Results



Internal Pressure



Decompression

RDCS Application Benefits

- **Significant insight into the behavior of the structure that would otherwise been lacking**
- **Rational design decisions**
- **Better and optimal design**
- **Automated design process**
- **Significant design cycle time reduction even for the first application. With RDCS models and projects (templates) set up, further similar application study can be performed automatically in a day or less with engineers time totally devoted to design improvement**

Rocketdyne
Propulsion & Power

BOEING 16

RDCS has also been used to investigate the effect of skin-stringer panel geometric parameters on maximum moment at the flange and the margin of safety for stringer pull-off. The percent contribution pie chart is one representation of the results of a sensitivity analysis, and the pull-off margin of safety was evaluated using a factorial design space exploration. For this case, 81 large scale finite element solutions were required. In the Accelerated Insertion of Materials program, a similar problem was analyzed for sheet and stringer composed of composite materials. In this case, material processing modules were included so that the design variables included, for example, cure cycle parameters. Each cure cycle run would take about an hour to run, but hundreds of cases could be run overnight due to the parallel processing capability of RDCS.

RDCS Application to Fuselage Concept Design

Application Objective

- To aid in the selection of appropriate frame spacing and fuselage cross-section parameters
- Investigate the effect of skin-stringer panel geometric parameters on maximum moment at the flange and margin of safety for stringer pull-off

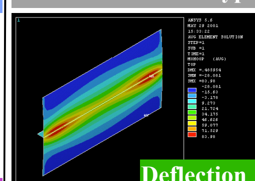
High Level Description

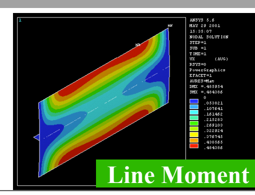
- **Design variables:** Skin Thickness, Flange Thickness, Stiffner Height, Total Flange Width, Cap Width (Hats Only)
- **Response Variables**: Maximum Flange Moment, Pull-off Margin
- **Solvers:** RDCS and ANSYS

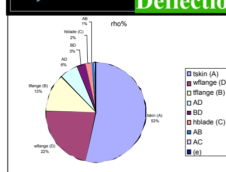
Solution Scope

- **RDCS:** Sensitivity analysis, Factorial Design Space Explorations
- **ANSYS**: Static non-linear large deflection analysis
- **Solution Cases**: 81 Large Scale FEM Solutions

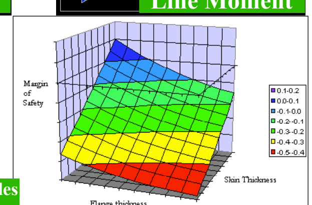
Typical Results


Deflection


Line Moment



Percent Contribution: Variables



Response Surface: Pull-off Margin of Safety

RDCS Application Benefits

- **Rapid factorial design calculations for external ANOVA study and response surface with significant cycle time reduction**
- **ANOVA helps identify critical factors and interactions**
- **Accurate surrogate response surface model helps simplify the design process**

Rocketdyne
Propulsion & Power

BOEING 17

Turbine power is sensitive to the turbine pressure ratio which is in turn is sensitive to turbine nozzle area. Because turbine nozzle area varies with each build, analyses were performed to assess the effect of component uncertainties on engine performance and to select design parameters such that the performance sensitivity is minimized. In this case several components of the propulsion system were modeled, variabilities estimated, and 1000 solutions were obtained via the Monte Carlo simulation feature available in RDCS. The analyses were quickly completed in time to influence a design change.

RDCS Application to Engine System

Application Objective

- Optimize Staged Combustion Cycle Engine to meet vehicle requirements
- Incorporate design solutions to component variations for robust engine design

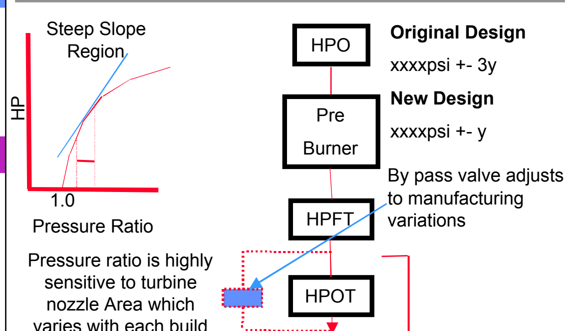
High Level Description

- **Design variables:** Component uncertainties on turbopump/turbine efficiencies, turbine nozzle flow areas, injector/cooling jacket flow resistances, etc.
- **Response Variables**: Turbopump speeds and dis pressures, PB temp, engine perfo, etc.
- **Solvers:** RDCS, SSODO and SSOD

Solution Scope

- **RDCS:** Min/Max Design Condition (MDC) Variation Study
- **SSODO:** Steady-State On-Design & Optimizer
- **SSOD:** Steady-State Off-Design Eng Bal Code
- **Solution Cases**: 1000 Solutions

The Design Change Based on Robustness



RDCS Application Benefits

- **RDCS Provided the necessary variability effect to make a design change**
- **Incorporated the oxidizer turbine bypass valve (OTBV) to minimize MDC**
- **Significant design cycle time reduction (approx. 3 instead of 30 hours of run time) for the 1000 engine balance predictions.**

Rocketdyne
Propulsion & Power

BOEING 18

DARPA's Accelerated Insertion of Materials program is a very well conceived program which targets the accelerated development of confidence in hardware characterization such that the technical justification is developed for government certifying agents to certify that the product can be used.

Accelerated Insertion of Materials - Composites

DARPA

NAVAIR

Jointly accomplished by a BOEING Led Team and the U.S. Government under the guidance of NAST

Work funded by DARPA/DSO and administered by NAST through TIA N00421-01-3-0098

Dr. Raymond J. Meilunas, Government Agent/Technical Monitor, NAVAIR

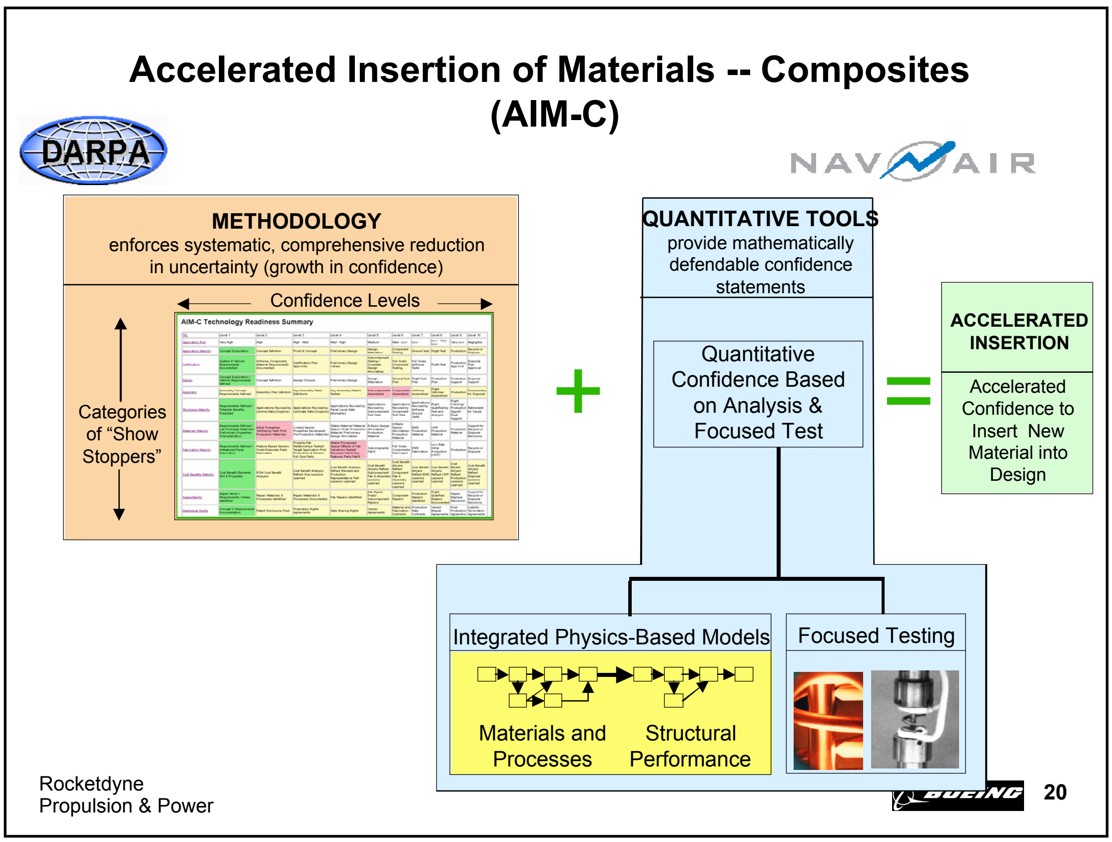
Dr. Leo Christodoulou, DARPA/DSO Program Manager

Dr. Steve Wax, Director, DARPA DSO

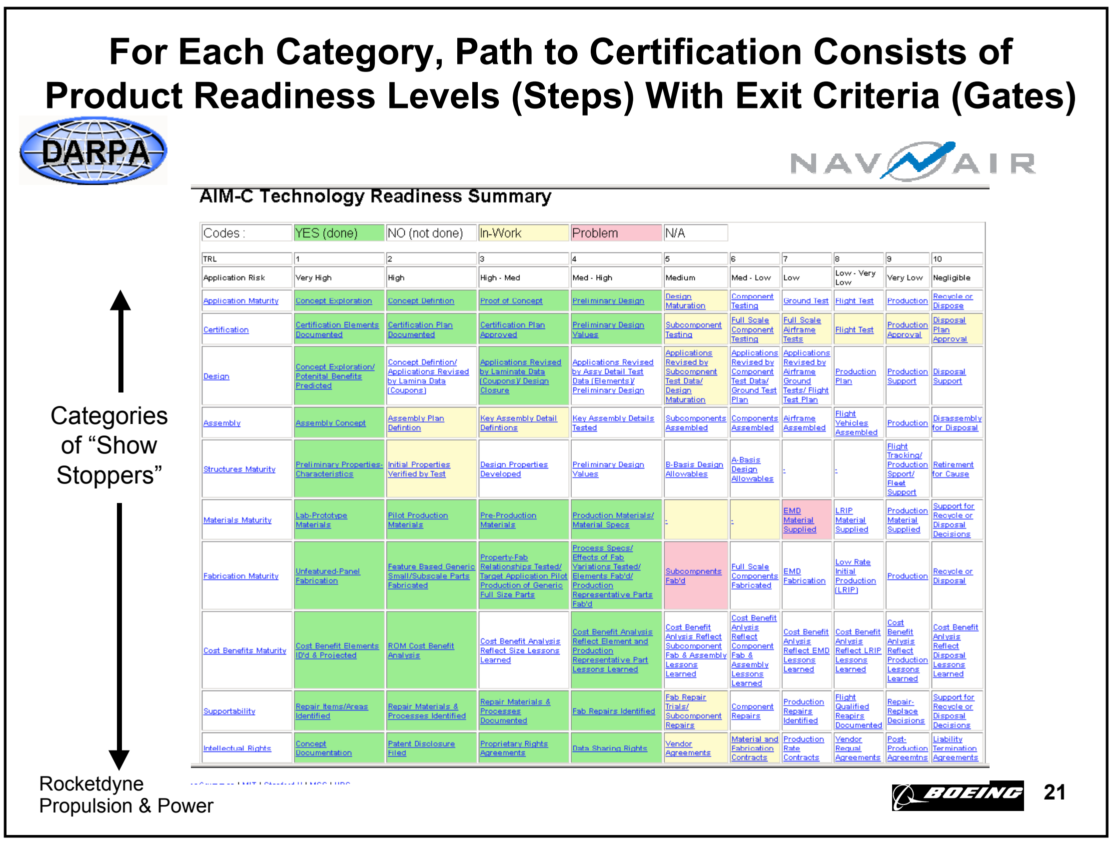
Rocketdyne
Propulsion & Power

BOEING 19

There are two major elements of the Accelerated Insertion of Materials program which result in accelerating the development of confidence in a new material to the point where it can be inserted into a design. First is a tool set which integrates physics-based models, helps focus testing to validate models and fill in the gaps in knowledge, and then fuses the analytical and test information to produce mathematically defendable statements of confidence. The second element is a methodology which guides the use of the tools, provides a framework for the interaction of the various disciplines involved in the design, and ensures a broad consideration of all factors which might become "show stoppers." RDCS is used as the framework for integration and computation.

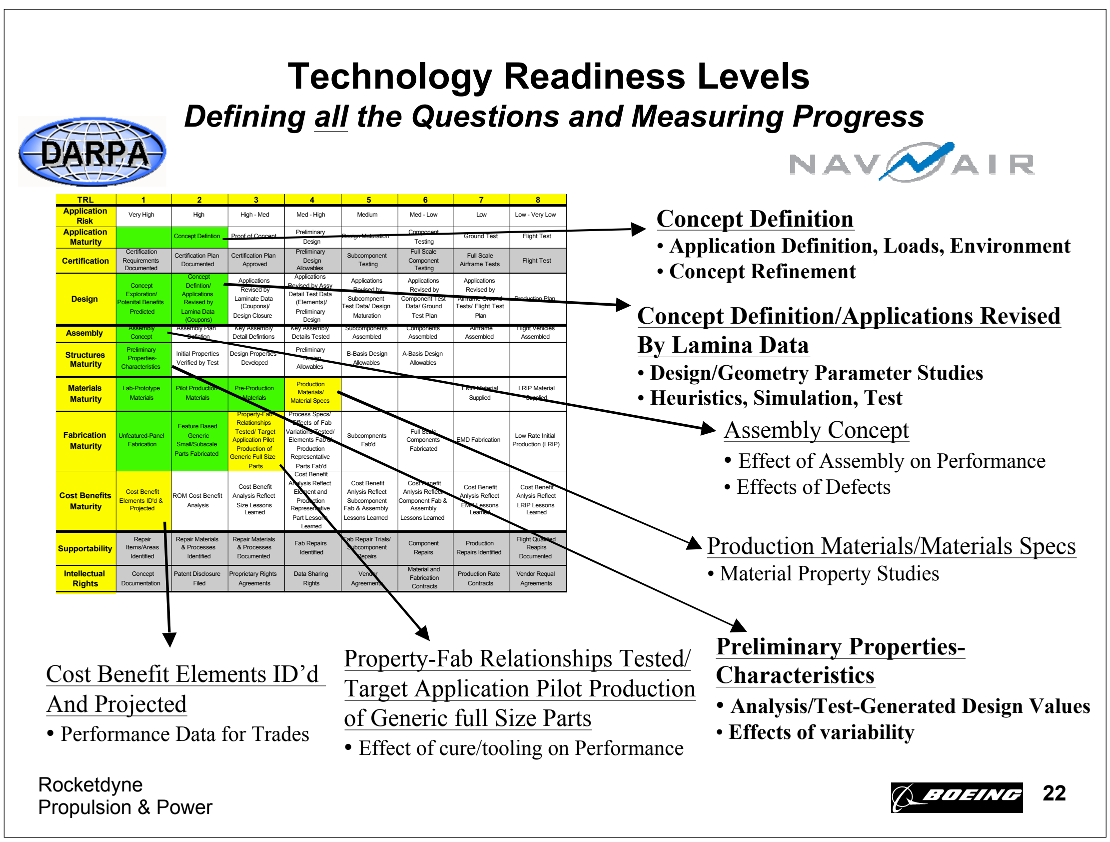


At the top level, the methodology looks like several TRL (Technology Readiness Level) scales each for a different category of "Show Stopper." The categories of show stoppers were developed from a brainstorming session with materials development experts who listed all the factors that could potentially be showstoppers in inserting materials. The factors were then affinitized into the categories shown, and top-level TRL criteria were developed for the various levels.

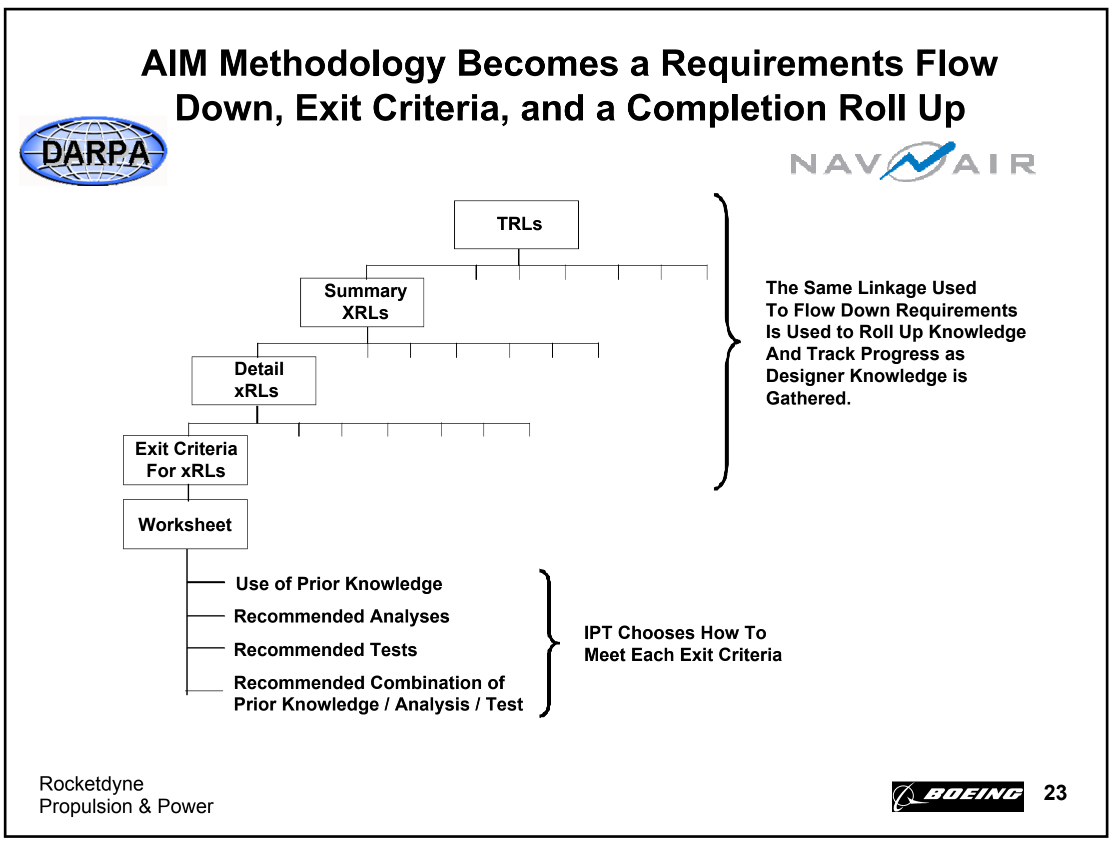


Codes :	YES (done)	NO (not done)	In-Work	Problem	N/A					
TRL	1	2	3	4	5	6	7	8	9	10
Application Risk	Very High	High	High - Med	Med - High	Medium	Med - Low	Low	Low - Very Low	Very Low	Negligible
Application Maturity	Concept Exploration	Concept Defintion	Proof of Concept	Preliminary Design	Design Maturation	Component Testing	Ground Test	Flight Test	Production	Recycle or Dispose
Certification	Certification Elements Documented	Certification Plan Documented	Certification Plan Approved	Preliminary Design Values	Subcomponent Testing	Full Scale Component Testing	Full Scale Airframe Tests	Flight Test	Production Approval	Disposal Plan Approval
Design	Concept Exploration/ Potenital Benefits Predicted	Concept Defintion/ Applications Revised by Lamina Data (Coupons)	Applications Revised by Laminate Data (Coupons)/ Design Closure	Applications Revised by Assy Detail Test Data (Elements)/ Preliminary Design	Applications Revised by Subcompnent Test Data/ Design Maturation	Applications Revised by Component Test Data/ Ground Test Plan	Applications Revised by Airframe Ground Tests/ Flight Test Plan	Production Plan	Production Support	Disposal Support
Assembly	Assembly Concept	Assembly Plan Defintion	Key Assembly Detail Defintions	Key Assembly Details Tested	Subcomponents Assembled	Components Assembled	Airframe Assembled	Flight Vehicles Assembled	Production	Disassembly for Disposal
Structures Maturity	Preliminary Properties-Characteristics	Initial Properties Verified by Test	Design Properties Developed	Preliminary Design Values	B-Basis Design Allowables	A-Basis Design Allowables	-	-	Flight Tracking/ Production Spport/ Fleet Support	Retirement for Cause
Materials Maturity	Lab-Prototype Materials	Pilot Production Materials	Pre-Production Materials	Production Materials/ Material Specs	-	-	EMD Material Supplied	LRIP Material Supplied	Production Material Supplied	Support for Recycle or Disposal Decisions
Fabrication Maturity	Unfeatured-Panel Fabrication	Feature Based Generic Small/Subscale Parts Fabricated	Property-Fab Relationships Tested/ Target Application Pilot Production of Generic Full Size Parts	Process Specs/ Effects of Fab Variations Tested/ Elements Fab'd/ Production Representative Parts Fab'd	Subcompnents Fab'd	Full Scale Components Fabricated	EMD Fabrication	Low Rate Initial Production (LRIP)	Production	Recycle or Disposal
Cost Benefits Maturity	Cost Benefit Elements ID'd & Projected	ROM Cost Benefit Analysis	Cost Benefit Analysis Reflect Size Lessons Learned	Cost Benefit Analysis Reflect Element and Production Representative Part Lessons Learned	Cost Benefit Anlysis Reflect Subcomponent Fab & Assembly Lessons Learned	Cost Benefit Anlysis Reflect Component Fab & Assembly Lessons Learned	Cost Benefit Anlysis Reflect EMD Lessons Learned	Cost Benefit Anlysis Reflect LRIP Lessons Learned	Cost Benefit Anlysis Reflect Production Lessons Learned	Cost Benefit Anlysis Reflect Disposal Lessons Learned
Supportability	Repair Items/Areas Identified	Repair Materials & Processes Identified	Repair Materials & Processes Documented	Fab Repairs Identified	Fab Repair Trials/ Subcomponent Repairs	Component Repairs	Production Repairs Identified	Flight Qualified Reapirs Documented	Repair-Replace Decisions	Support for Recycle or Disposal Decisions
Intellectual Rights	Concept Documentation	Patent Disclosure Filed	Proprietary Rights Agreements	Data Sharing Rights	Vendor Agreements	Material and Fabrication Contracts	Production Rate Contracts	Vendor Requal Agreements	Post-Production Agreemtns	Liability Termination Agreements

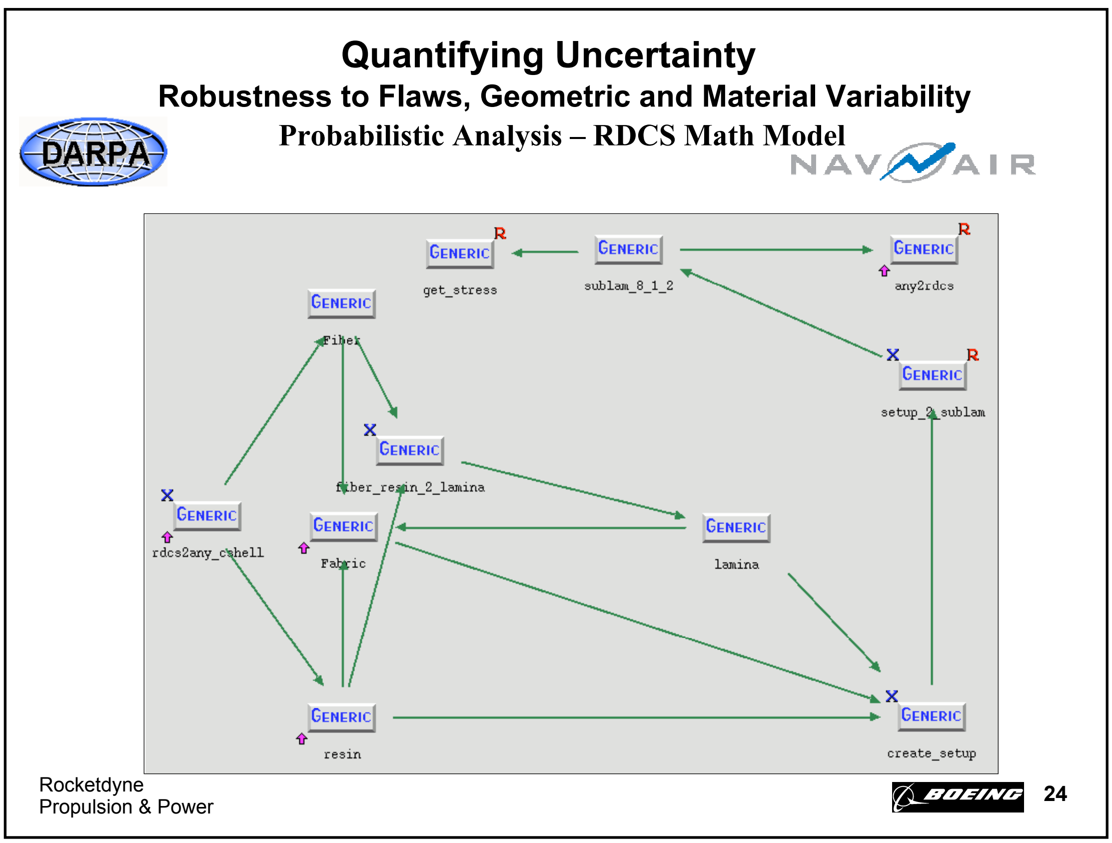
The matrix described in the previous chart is the mechanism which ensures that all factors that might impede insertion of the material are addressed in a timely manner. The chart gives examples of the kinds of issues that are addressed in several categories at selected TRL levels.



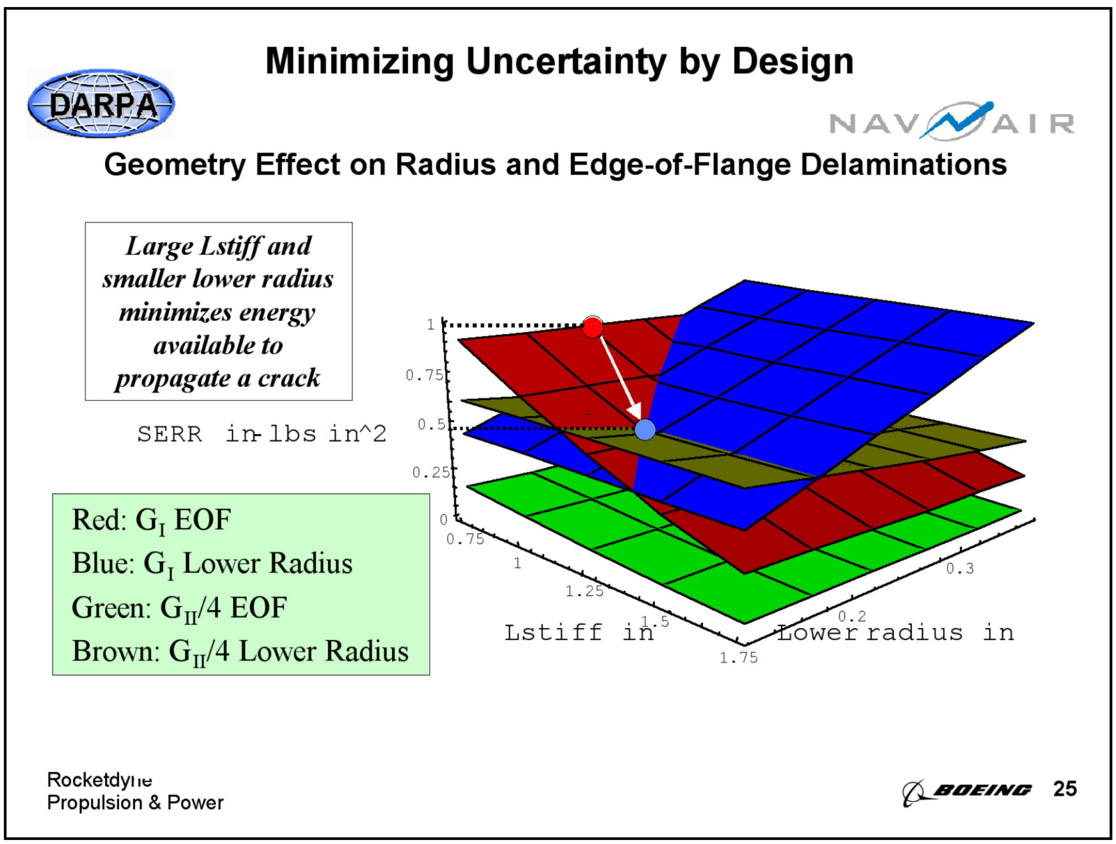
What is unique about the Accelerated Insertion of Materials program, however, is that a series of "xRLs" have been defined beneath each of the TRL categories shown on the matrix. These xRLs are basically a decomposition of the top level criteria down to associated criteria for each individual discipline involved in design. At the very bottom are exit criteria which must be met to move to the next TRL level. When these exit criteria are quantitative, then the qualitative TRL criteria at the top level have been converted to quantitative criteria. The conversion of qualitative criteria to quantitative criteria is apparently unique to the Accelerated Insertion of Materials program. The combination of physics-based models and focused testing is then used to establish that the exit criteria have been met.



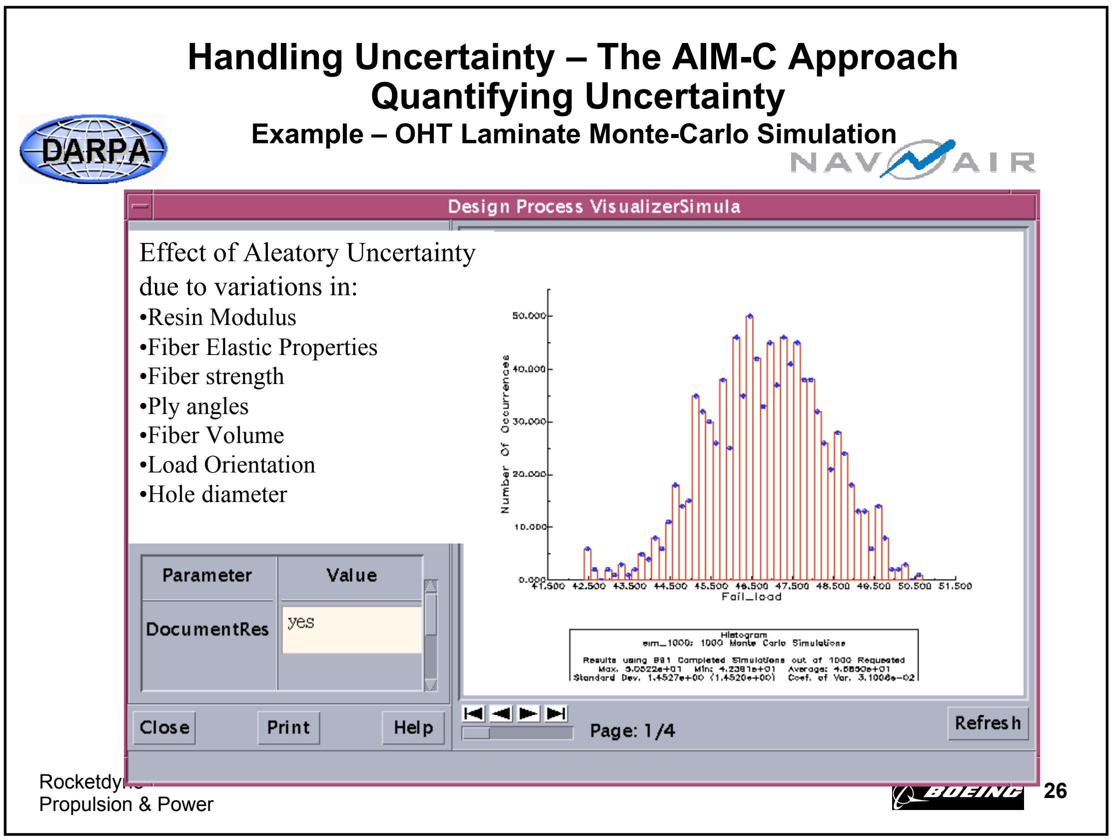
This chart gives a sense of how many physics-based models actually get involved in establishing confidence in a material property. The effects of variability are included via the RDCS capability to perform probabilistic analyses using models which were developed deterministically.



Similarly to the case of selecting design values for the turbine blade discussed earlier, this chart is the result of a design space scan to determine parameter values (Lstiff and Lower radius) which minimize the energy available to propagate a crack. What is different here is that underlying the results are physics-based models for the constituents and the processing of composite materials along with the geometric parameters associated with the structure itself.



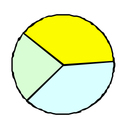
This chart shows the results of using a Monte Carlo approach to predict the distribution of failure load for a composite structure given uncertainties in the constituent properties, processing parameters, and geometric parameters. Although the cure cycle simulations could take up to an hour to run, the parallel processing capability of RDCS was able to process 1000 instances overnight.



Over the last 14 years, studies of aerospace development programs have identified a Product Development Imperative, management of uncertainty, and the dominant drivers of uncertainty. DARPA investments in the Robust Design Computational System and in the Accelerated Insertion of Materials program have matured the relevant technologies sufficiently that it is now feasible to demonstrate the technologies in a controlled pilot project in parallel to an ongoing program.

Summary

1. **Product Development Imperative – Developing advanced technology products on budget and schedule requires effective management of uncertainty**
   - **Classical risk management practices are inadequate**
2. **Uncertainty the primary driver in program cost and schedule overruns**
   - **Hardware characterization**
   - **Environment characterization**
   - **Design process limitations**



3. **RDCS designed to eliminate design process limitations driver by providing framework for quantitative assessment and management of uncertainty**
4. **AIM technologies accelerating technology insertion (attacking hardware characterization driver) by linking quantitative characterization of materials and processes with RDCS**
5. **AIM technology sufficiently mature to**
   - **Generalize to include environment characterization**
   - **Evaluate in controlled pilot project working in parallel to ongoing program**

Rocketdyne
Propulsion & Power

BOEING 27

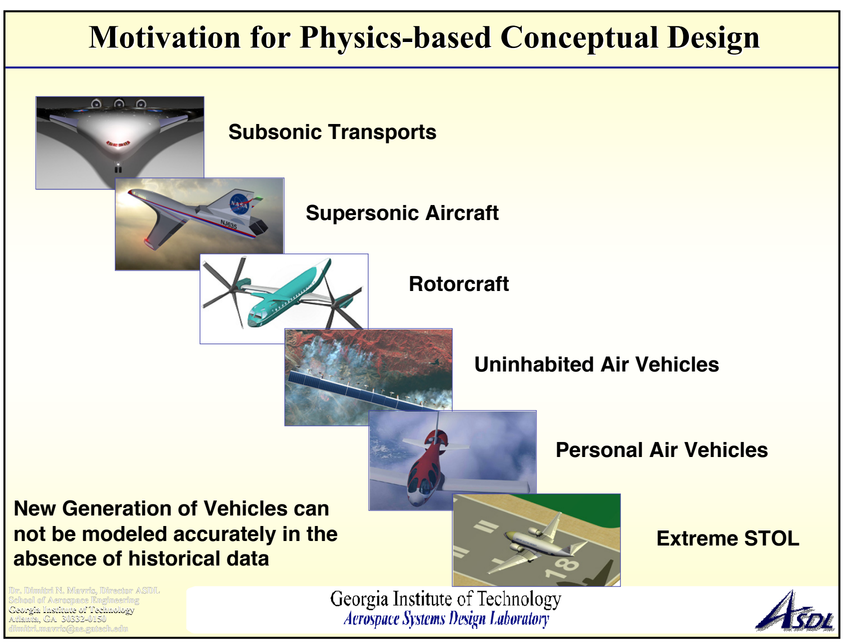
**Physics-based Conceptual Design of Revolutionary Concepts:
A "Paradigm Shift" in Complex System Design**

Dimitri Mavris
Aerospace Systems Design Laboratory
Georgia Institute of Technology
Atlanta, GA

Dr. Dimitri Mavris is an Associate Professor in the School of Aerospace Engineering at Georgia Tech. He is also the director of the Aerospace Systems Design Laboratory: the largest research lab in the School of Aerospace Engineering. Dr. Mavris advises 128 masters' and Ph.D. students engaged in relevant research in the field of complex systems design. His current research focus includes efforts in the design of unconventional systems and high-fidelity physics-based design methodologies.

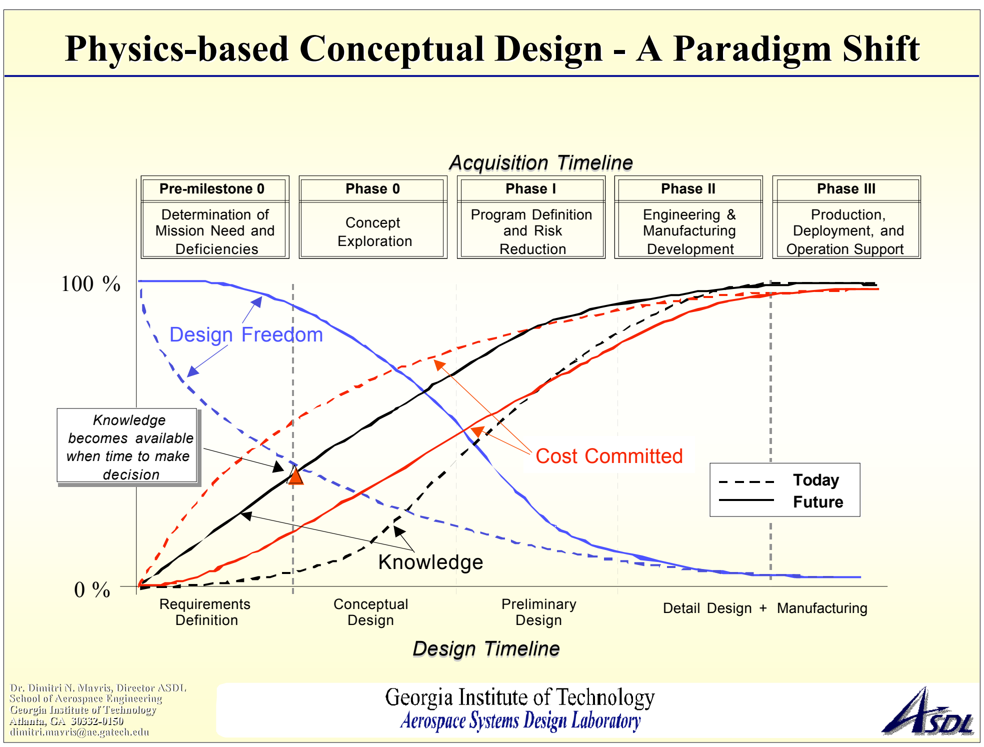
The main motivation behind a physics-based conceptual design approach is the focus on unconventional systems for which no “canned” design programs exist. Currently, NASA has identified several classes of unconventional systems that it wishes to examine over the next several years. Some of those configurations are highlighted here. Unfortunately, since these systems are extremely unconventional, reliance upon historical data is often inappropriate. As such, efforts are underway at Georgia Tech to more fully understand these systems and model them in a variable-fidelity physics-based design environment.

By physics-based, we mean that aircraft drag polars will be more accurately calculated using a panel method or CFD code. The propulsion systems will be analyzed from a cycle standpoint for both design and off design operation. The performance of the aircraft over many flight regimes will likely involve an energy or exergy-based approach to tracking the various performance constraints imposed upon the vehicle by the mission requirements. Structural analysis will require some sort of higher-level modeling than traditional zeroth order design codes that focus only on historical mass estimation relationships.



This chart shows the paradigm shift in design that must occur. This is the pre-2001 acquisition timeline for military acquisition programs. The milestones have shifted slightly but the basic concepts are the same. This chart indicates the "today" state of affairs as a dashed line and the future goals as a solid line. Essentially, it has been discovered that a majority of the cost of the program is committed at the early stage of the design process, when the knowledge about the design process is very low. Furthermore, early in the design process, since little is fixed, the design freedom is much greater than after the configuration has been specified and heavily analyzed.

Through the infusion of physics-based conceptual design methods, more information about the design (knowledge) is moved forward in the design process. As a result, design freedom increases because more designs can be examined in the conceptual design phase. As a result, the cost committed curve shifts to the right, because major design decisions do not fix the design early in the process due to the increase in freedom.



A traditional point-design philosophy is a deterministic analysis that is usually driven by historical data and disciplinary-centric design organizations. In these designs, almost all the requirements and assumptions are fixed. The process is also very time consuming and often involves a manual passing of information from designer to designer in a “throw-it-over-the-wall” type approach.

The ASDL approach seeks to reduce cycle design time to allow existing organizations to be more effective. Several enabling technologies are required to make this transition possible.

Traditional, Point-Design Philosophy

- May be characterized as a manual, deterministic, data driven, serial or parallel, disciplinary-centric, point design process
- Design requirements, and technology assumptions are usually fixed and a design space exploration is performed around one or a handful of concepts (point solutions)
- As organizations strive to decrease costs and reduce operational overhead, the number of personnel available for given activities is decreasing
- At the same time, the demands on the organization for more in depth analysis at the conceptual and preliminary stages is increasing
- As a result, a paradigm shift is required to reduce design cycle time, allow for more iterations, and increase fidelity
- Traditional organizations can be supported and enhanced by several enabling technologies, to be presented here, that allow for this transformation to take place in a practical fashion

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Georgia Institute of Technology
Aerospace Systems Design Laboratory

To facilitate this transition, a critical element is an integrated modeling and simulation environment. The automation of the design process using a commercially available tool will allow the ability to perform physics-based design without the reliance on historical data. This environment will also allow the creation of parametric tradeoff environments, in which a dynamic design space can be created.

Using this environment, probabilistics can also be brought into the design process to quantify risk.

A key enabler for more advanced design using integrated systems is intensive computer power.

What is needed for the Paradigm Shift to occur?

- Transition from single-discipline to multi-disciplinary analysis, design and optimization
- Automation of the resultant integrated design process
- Transition from a reliance on historical data to physics-based formulations, especially true for unconventional concepts
- Means to perform requirements exploration, technology infusion trade-offs and concept down selections during the early design phases (conceptual design) using physics-based methods
- Methods which will allow us to move from deterministic, serial, single-point designs to dynamic parametric trade environments
- Incorporation of probabilistic methods to quantify, assess risk
- Transition from single-objective to multi-objective optimization
- Need to speed up computation to allow for the inclusion of variable fidelity tools so as to improve accuracy

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Georgia Institute of Technology
Aerospace Systems Design Laboratory

Furthermore, uncertainty is prevalent at every step in the design process. By examining the disciplinary uncertainty for each of the design tools, trades and "what if" scenarios can be performed to make the designer aware of this inherent uncertainty in his or her decisions.

The latest advances in integration technology allow for a collaborative design to be performed across multiple departments, and in some cases, even across multiple geographic locations.

Replacing higher-fidelity tools with surrogate models (metamodels or Response Surface Equations) allows information to be brought forward in the design process. These methods allow the integration of legacy tools, and allow the user to see what is happening inside the tools by examining trends and validating whether these trends represent the physics of the problem. This advantage is called "transparency."

Finally, multi-attribute decision making techniques can be used to account for the fact that objective functions seldom contain only one objective. Decision making can be facilitated by using collaborative tools to quantify customer requirements when possible.

Elements needed to enable this Paradigm Shift

- Advances in MDA/MDO methods and techniques to encompass the holistic nature of the problem, emphasis on ***uncertainty*** associated with the early design phases
- Creation of computational architecture frameworks to allow for easy integration and automation of sometimes organizationally dispersed tools
- Emergence of commercially available frameworks will further expedite the usefulness of the proposed approaches
- Creation of physics-based approximation models (surrogate or meta-models) to replace the higher fidelity tools which are usually described as too slow for use in the design process, cryptic in their use of inputs, interfaces and logic, and non-transparent (lack of proper documentation, legacy)
- Use of probability theory in conjunction with these meta-models will enable us to quantify, assess risk and to explore huge combinatorial spaces
- In fact it will enable us to uncover trends, solutions never before examined in a very transparent, visual, interactive manner
- Use of Multi-attribute decision making techniques, pareto optimality, genetic algorithms to account for multiple, conflicting objectives and for discrete settings

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Georgia Institute of Technology
Aerospace Systems Design Laboratory

Surrogate models are a key enabling technology for physics-based design. The first and primary benefit of these models is the acceleration of the design process. An additional benefit is that a surrogate model can be created around a proprietary preliminary design tool. This model cannot be reengineered to produce the tool or understand what is happening inside it. The model merely replaces the proprietary tool with a rapid black box that is only defined for a range of inputs for the problem that is specified. The mother organization retains the ability to use the original code and can make surrogate models for a variety of problems, controlling their access.

These models can be used to rapidly trade off requirements, technologies, and design concepts during the early design phases.

Key Enabler – Surrogate Models

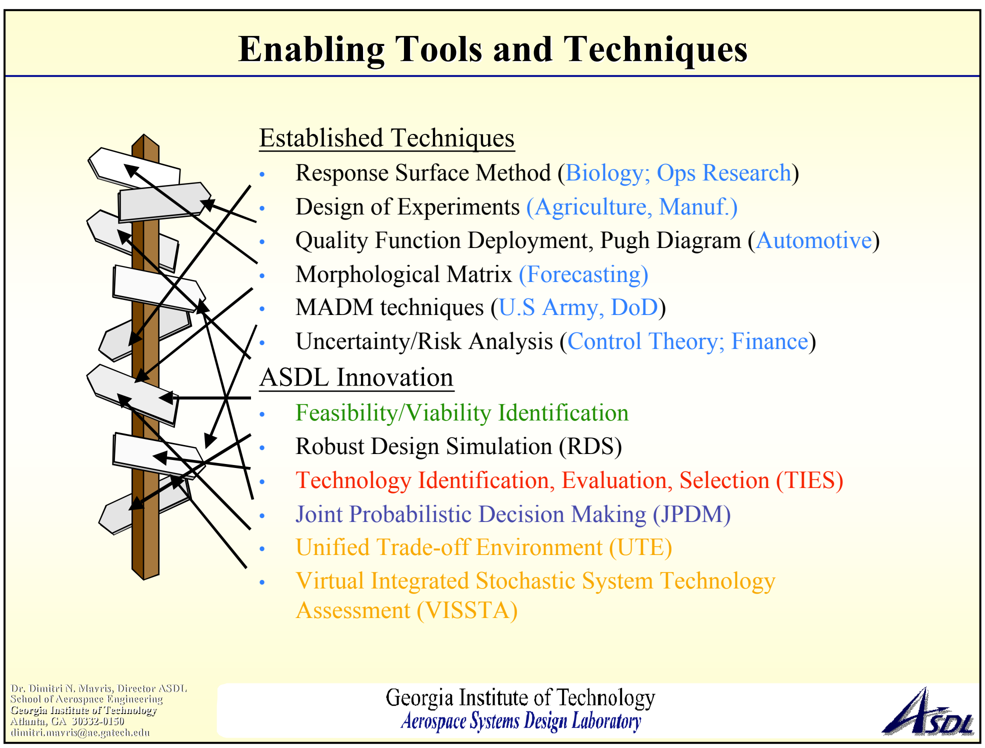
Reliance on meta-models or surrogate models as a means to :

- Speed up processes, protect proprietary nature of codes used, overcome organizational barriers (protectionism of tools and data), allow for the framework to be tool independent (no need for direct integrations of codes), this also enables our desire for variable tool fidelity formulations, further it will allow the designer to perform requirements exploration, technology infusion trade-offs and concept down selections during the early design phases (conceptual design) using physics-based methods
- These surrogate models can also be used at the integrated system level to determine responses at that level. This will allow us to move from deterministic, serial, single-point designs to dynamic parametric trade environments

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Georgia Institute of Technology
Aerospace Systems Design Laboratory

This slide highlights some of the enabling tools and techniques in use at the Aerospace Systems Design Lab. Several of the tools have been borrowed from other disciplines and modified to suit the systems design problem. ASDL students and researchers have additionally developed the methods at the bottom of the page for specific, higher-level applications. These methods generally indicate structured approaches to problem solving, technology identification, and robust design.



As our colleagues from the PIDO community have mentioned, there is a tremendous advantage to linking design codes in an automated environment. Typically, a user expects to see at least an order of magnitude reduction in design cycle time once a suite of tools is integrated.

Integrated Design: Reduction in Cycle Time Through Automation

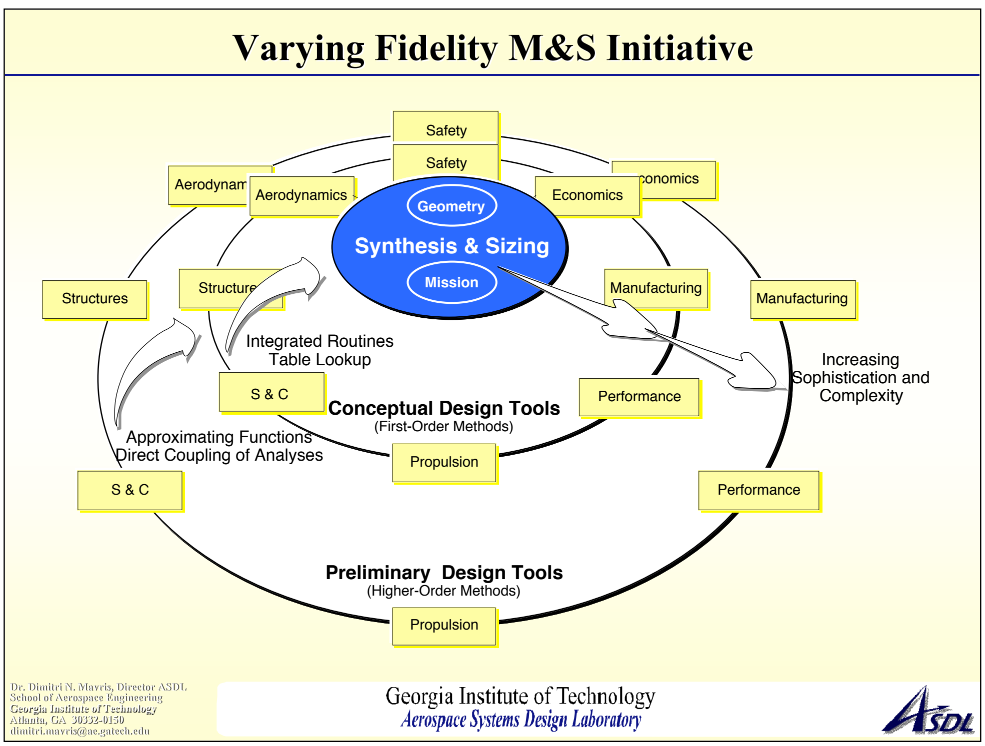
- Performing an integrated design involves linking conceptual and preliminary design tools in a computational environment that automatically passes information between design codes
- Enablers:
  - Computational environments such as ModelCenter or iSIGHT, …
  - Design codes with simple inputs/outputs without hard coding of design variables or internal optimizations that may skew results
- Integrated design provides tremendous advantages in design cycle time by eliminating the re-keying of information from output files to input files.
- For example, a missile design environment was programmed as an integrated suite of codes. It takes 35 seconds to perform a design. If the codes were not linked, it would take approximately **45 minutes** to pass the information back and forth and check for errors!

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

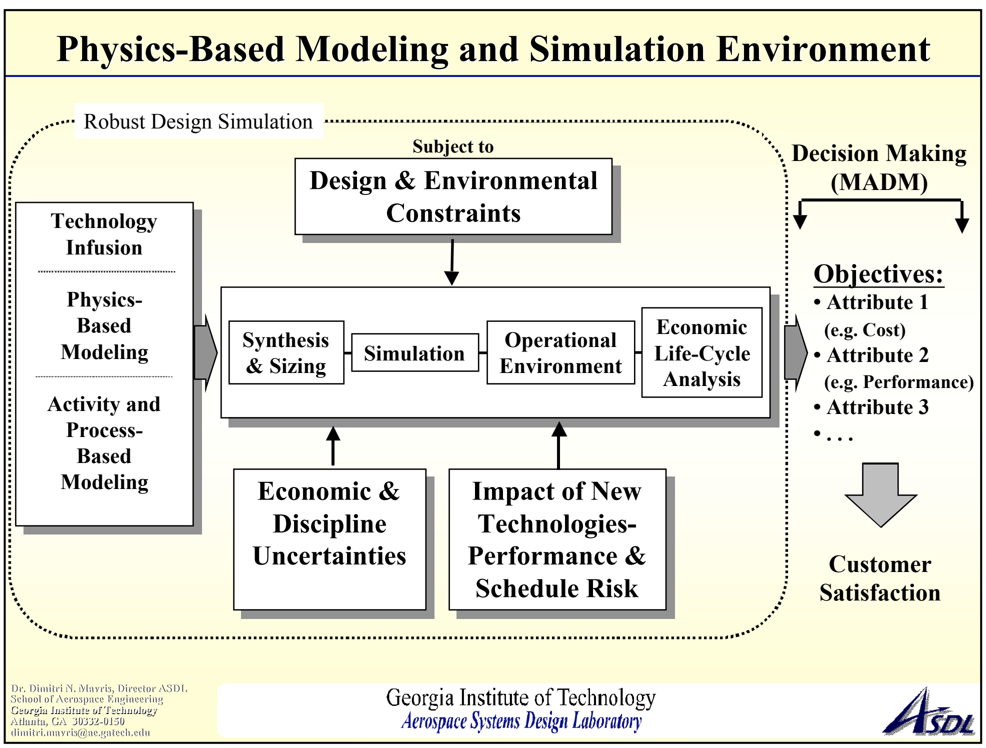
Georgia Institute of Technology
Aerospace Systems Design Laboratory

A key feature of the ASDL approach is the fact that often, codes of varying levels of fidelity are required at different stages of the design process. Shown here is a sizing and synthesis-centric approach to design whereas the geometry and mission analysis rely on the disciplines in the two outer circles. For the conceptual design phase, the inner circle is used. These methods traditionally involve table lookup routines, response surface models, and other surrogate models for rapid design space exploration.

The outer ring represents the preliminary design tools, that are traditionally more accurate and require more computing resources to run. These analysis can either be approximated with surrogate models or directly linked to the analysis. Obviously, the first choice is desired for expediency, and the second choice for accuracy. A combination of the two are utilized in a variable fidelity modeling and simulation environment.



The key to the physics-based modeling and simulation environment is the robust design simulation, which is essentially the linked process using an automation tool. This environment is subject to design constraints such as requirements, and environmental constraints that are usually very stringent. Furthermore, uncertainty can be brought in to this process, and a gap analysis can also be performed to determine which technologies are required to make a system feasible and viable.



Whereas the integrated design environment can be used to run a single point in a deterministic way, the key advantage to this environment is its ability to take in distributions of inputs to both explore the design space and quantify uncertainty.

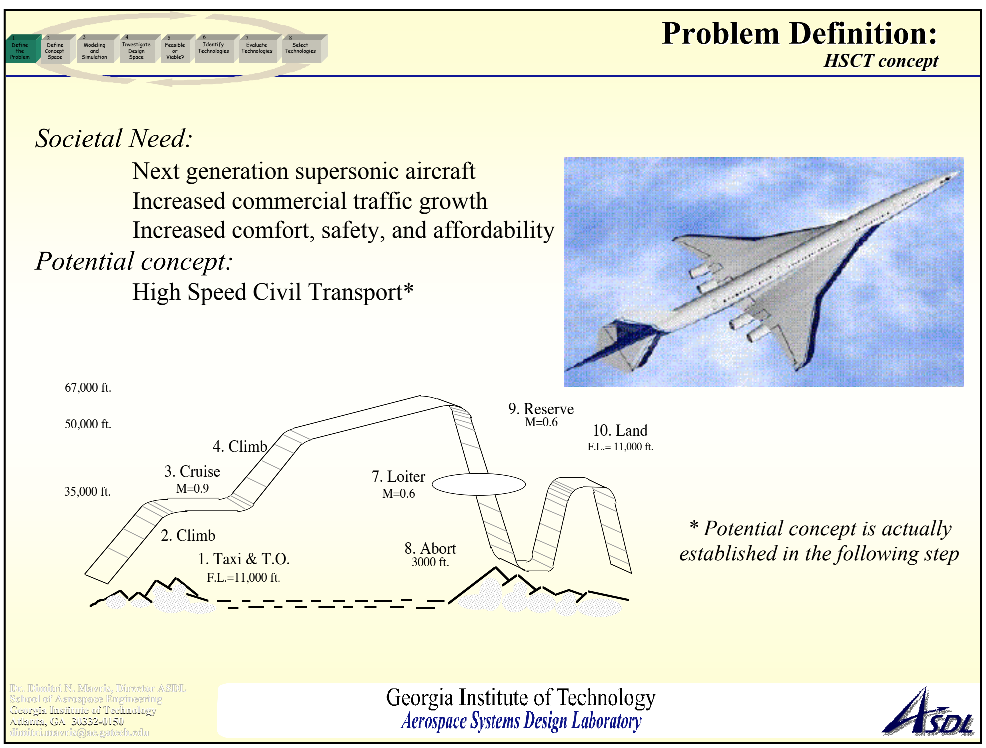
Parametric Design: Using an Integrated Design on a Large-Scale

- The integrated design environment is an enabler for a parametric design study
- Instead of passing in a series of input variables, a parametric design can take a *distribution* of inputs.
- In this manner, an entire design space can be explored, rather than small perturbations around a single point design
- Large design spaces may take too long to explore by traditional means
  - The integrated design environment above can be used to generate metamodels of the design process
  - These metamodels, custom made for a given range of inputs, can be evaluated in a spreadsheet hundreds of times per second
  - Metamodels represent another order of magnitude in reduction for design cycle time.

Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Georgia Institute of Technology
Aerospace Systems Design Laboratory

The following several charts show a variety of examples and how the necessary pieces come together. Shown here is a mission profile for a High-Speed Civil Transport (HSCT) aircraft. The requirements are set by the customer, and are typically fixed. ASDL's requirements exploration allow these requirements to become variables in the process, so that the "showstopper" requirements can be quickly identified and perhaps relaxed if they are merely "desirements."

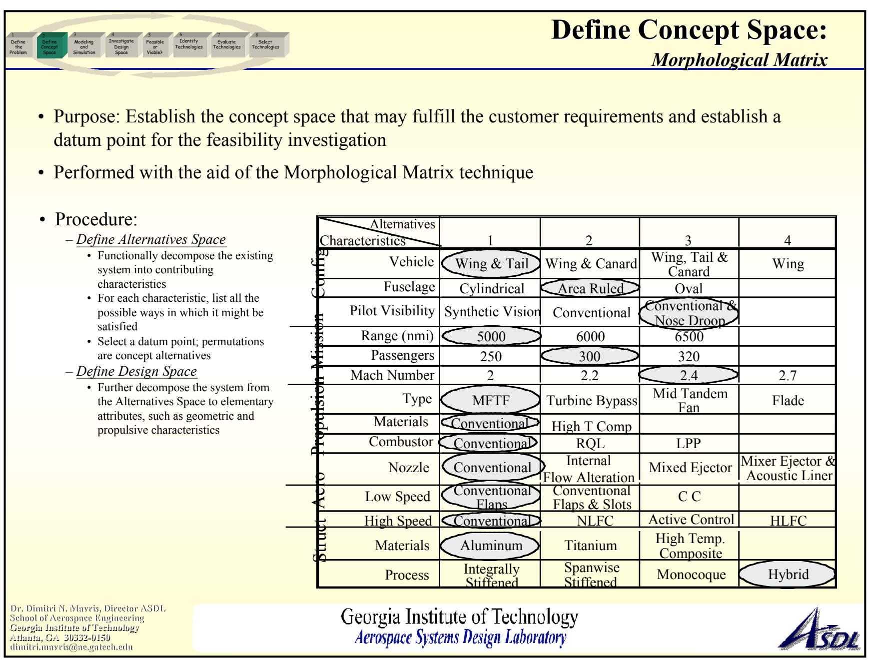


With the requirements defined, a potential class of vehicles must be defined. A structured means of doing so is with a Morphological Matrix. The morphological matrix is nothing more than a decomposition of all possible contributing elements of the system. It is a means to brainstorm and think out of the box for potential solutions to the problem.

For example, the project manager could bring together all of his experts and decompose the system. Do we want a wing and tail vehicle? Or a wing and canard? And so on. If you do this for each element of the system, then you have effectively defined the alternative concept space which may have mission parameters, technologies, and so on.

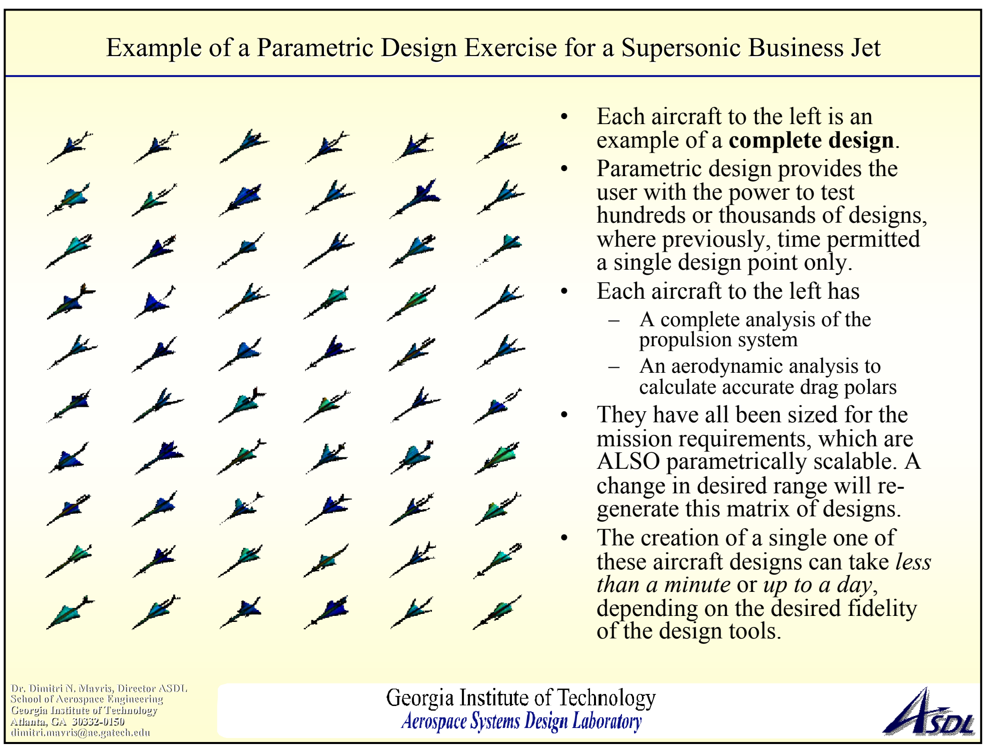
Once this matrix is sufficiently defined, one must establish a baseline to continue on with the TIES method. You do this by selecting one element from each row like the circled items, usually present day capabilities. This is your baseline that you will do all deviations on.

Next, that system is further decomposed into geometric and propulsive parameters that will define the design space to be investigated for feasibility.

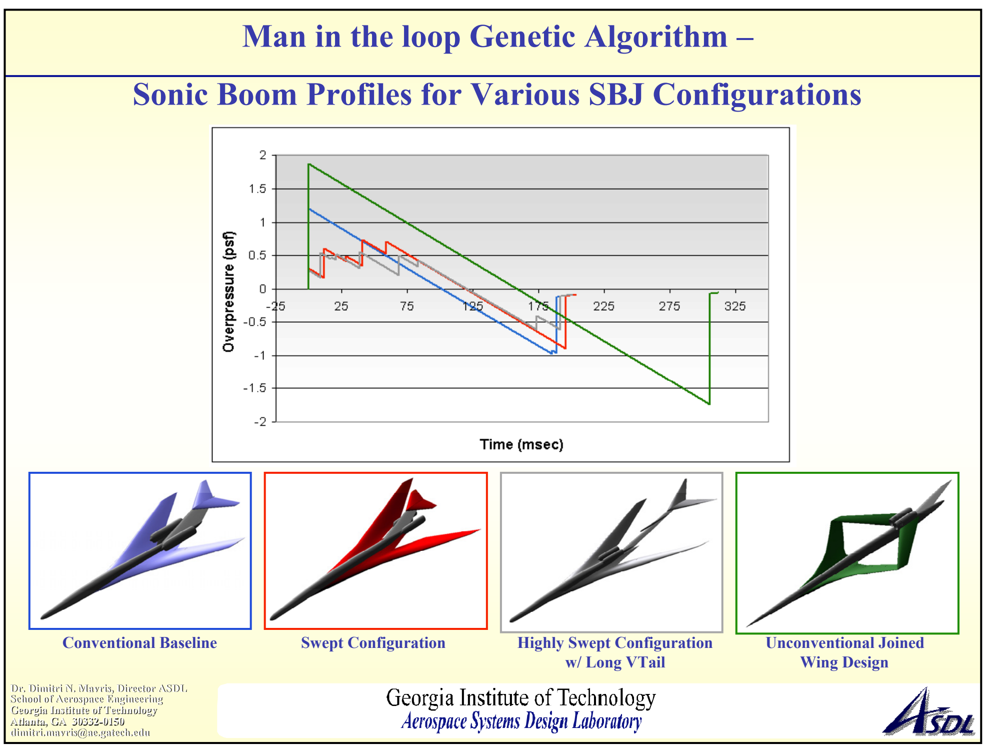


This is an example of a series of outputs generated based on a "man in the loop genetic algorithm" for a supersonic business jet design. Each of these configurations represents an aircraft that has had an aerodynamic analysis to calculate accurate drag polars and a complete propulsion cycle analysis. A parametric engine deck has been generated for each of the configurations and they are all fuel balanced for the same mission.

The creation of one of these cases can take up to a day with no surrogate models or under a minute if effective surrogate models are used. The man in the loop genetic algorithm allows the designer to view certain configurations and to highlight those which he or she thinks are infeasible based upon designer intuition. Often, characteristics like flutter and divergence are not analyzed in the conceptual design phase; however, a trained engineer can determine which configurations are undesirable from that approach. This design method combines the advantages of rapid run time with surrogate models with higher fidelity analysis AND designer intuition.



Additionally for selected configurations, the designer can request a sonic boom analysis both to narrow the field of candidates and to improve his/her expert intuition. Shown here is the blue baseline configuration. The sonic boom overpressure is decreased in the red configuration due to the increased sweep of the aircraft. The boom problem is essentially solved by the third configuration; however, issues such as takeoff rotation, flutter, and the construction of this highly swept configuration clearly pose issues to the designer. The green configuration indicates a solution proposed by the genetic algorithm, but clearly the sonic boom is larger than the baseline case. In this manner, different configurations can be examined in real-time. The computer program likes the third choice, but the experienced designer does not.

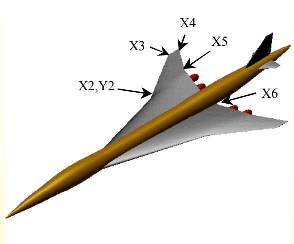


Now that you have a general concept baseline definition, you must establish the design space for which you will investigate feasibility and viability with respect to the customer requirements. In this example, both geometric and engine cycle parameters are considered, such as wing area, fan pressure ratio, and planform geometry definitions.

Define Concept Space:

Define Design Space

Note: The geometric and propulsive parameters may vary in the ranges defined with the same likelihood since at the outset, there should be no preference of values. Hence, uniform distributions are assigned to each parameter.



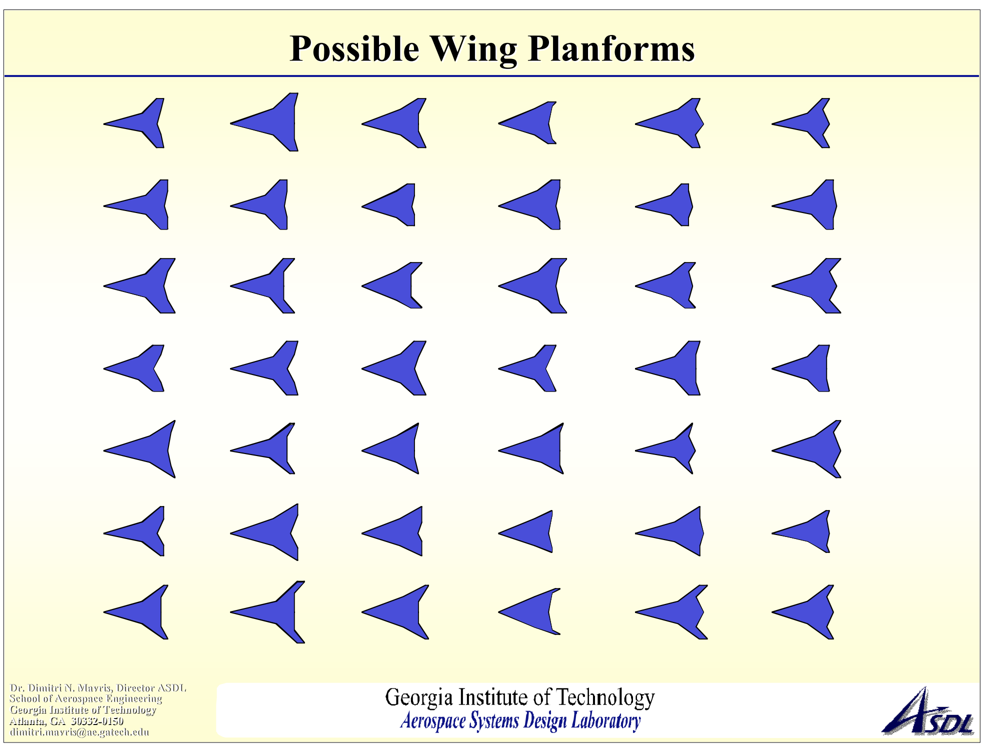
Variable	Minimum	Maximum	Units	Description
SW	7500	9000	ft^2	Wing area
TWR	0.29	0.33	~	Thrust-to-weight ratio
TIT	3000	3400	^oR	Turbine Inlet Temperature
FPR	3.5	4.5	~	Fan Pressure Ratio
OPR	18	21	~	Overall Pressure Ratio
CLdes	0.08	0.12	~	Design lift coefficient
X2	1.54	1.69	~	LE kink x-location*
X3	2.1	2.36	~	LE tip x-location*
X4	2.4	2.58	~	TE tip x-location*
X5	2.19	2.37	~	TE kink x-location*
X6	2.18	2.5	~	TE root x-location*
Y2	0.44	0.58	~	LE kink y-location*
t/c_root	3	5	%	Wing root t/c ratio
t/c_tip	2	4	%	Wing tip t/c ratio
SHref	400	700	ft^2	Horizontal Tail area
SVref	350	550	ft^2	Vertical Tail area

* Variables Nondimensionalized by wing semi-span

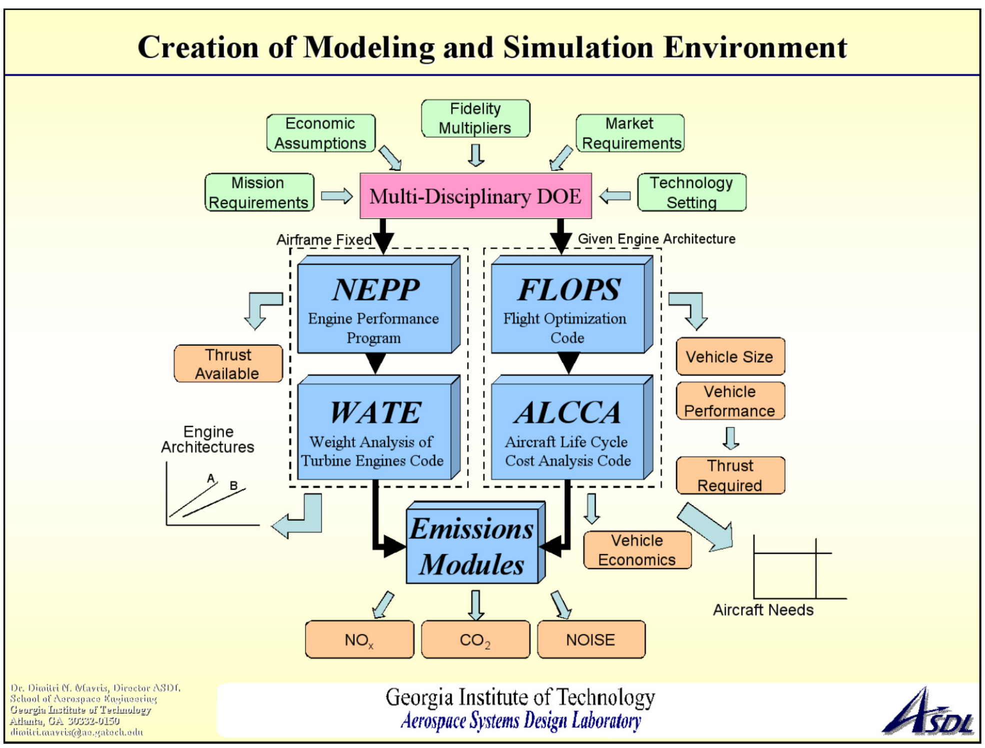
Dr. Dimitri N. Mavris, Director ASDL
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
dimitri.mavris@ae.gatech.edu

Georgia Institute of Technology
Aerospace Systems Design Laboratory

From the previous slide, here are the possible wing planforms for the HSCT. All these planforms at least appear feasible to the designer and can be carried on for further analysis.

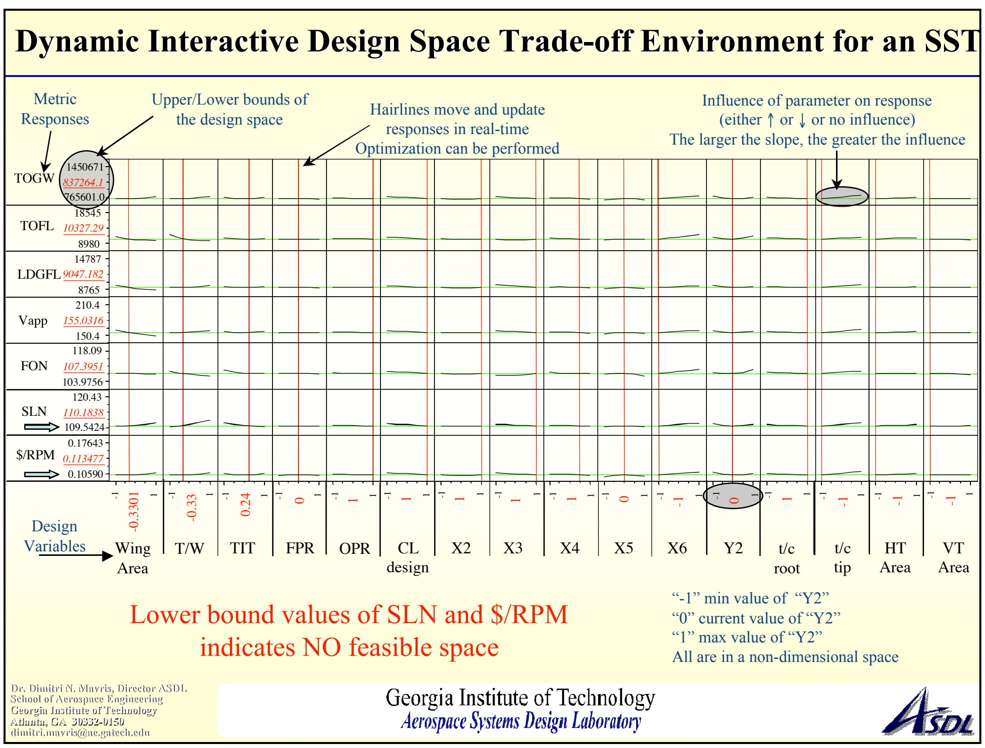


Graphically, a modeling and simulation environment looks as shown, whereas the engine performance analysis and weight estimation are coupled with the aircraft design and life cycle cost code. Emissions, economics, noise, required thrust, and vehicle performance are all analyzed in this environment.

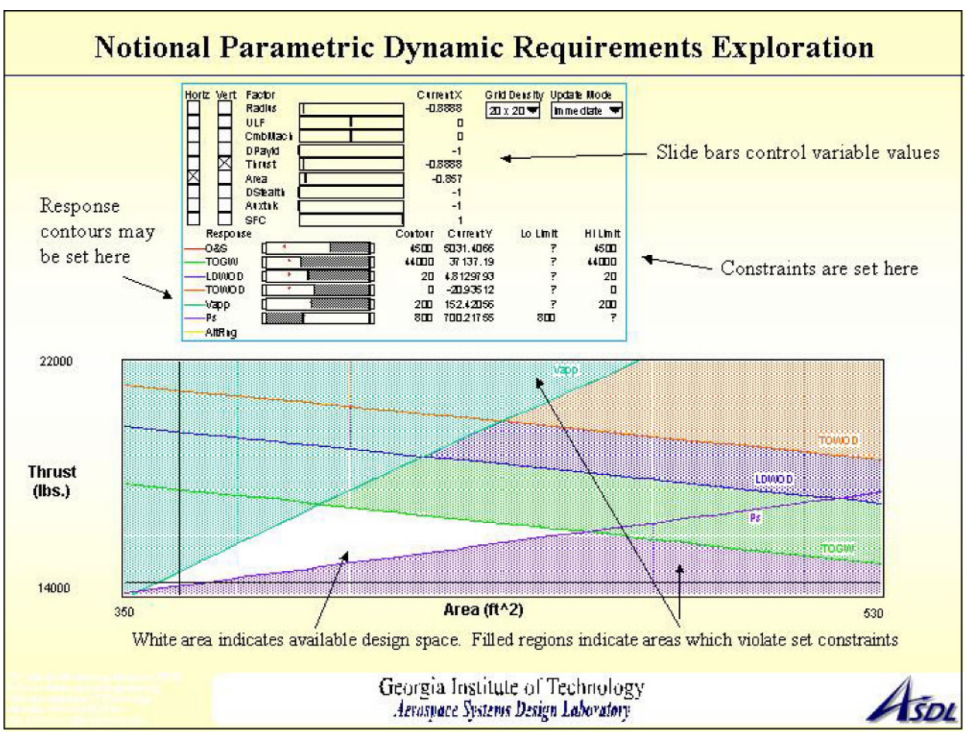


A dynamic tradeoff space for an HSCT is shown here. The various outputs are on the y-axis and the various inputs are shown on the x-axis. This environment can be operated like a calculator, where the red hairlines on the x-axis can be set to different values between the low and high range for each variable. When these values are changed, the slopes for the entire calculator update due to multivariable interactions. The slopes of the lines indicate the partial derivative with respect to each of the X's with all other variables held constant (for example, the upper left box is the partial derivative of takeoff gross weight with respect to wing area, and so forth).

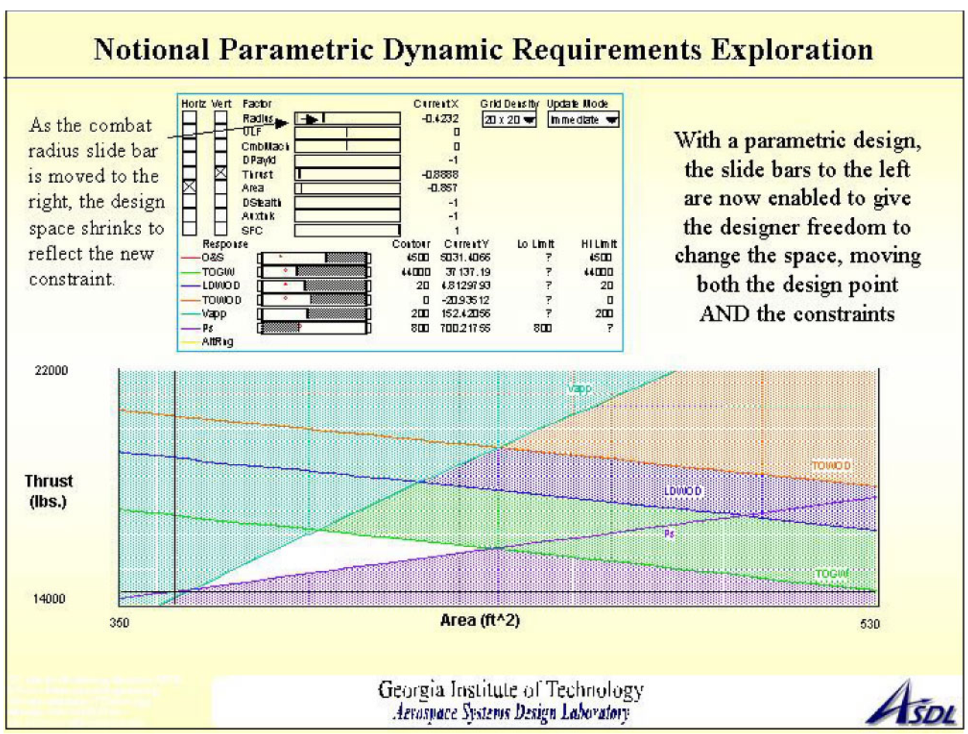
These lines are also an indicator of the required fidelity of the analysis codes. If a slope is steep for an analysis that has a low fidelity, then the penalty for missing the correct value is amplified because it has a larger impact on the candidate response.



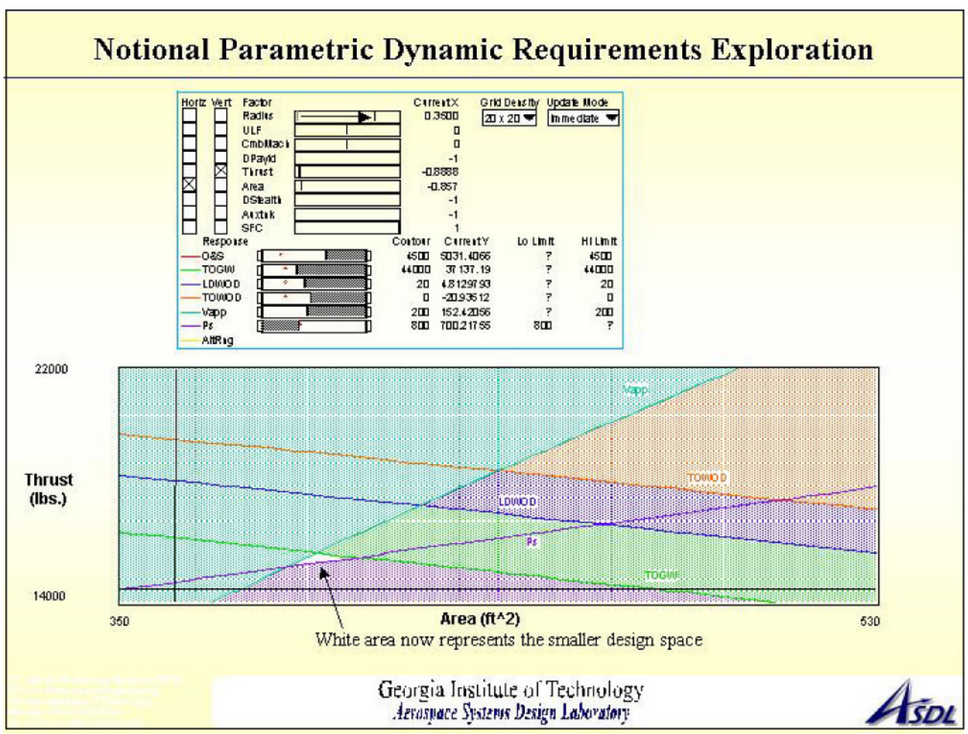
Shown here is a surrogate model integrated into a dynamic requirements exploration space. This example is for an F-18E/F fighter, where the parametric space for the F-18C/D was to be stretched to include the E/F derivative. The white area in the above plot indicates a feasible design region. The hairlines are set to the design point for the F-18C. Note: the information on this chart has been altered to preserve any sensitive data values and cannot be used to back-out any proprietary information.



When the combat radius slide bar is increased (meaning more combat radius is desired), the design space shrinks. As the hairlines indicate, the F-18C now has insufficient excess power to accomplish this mission.

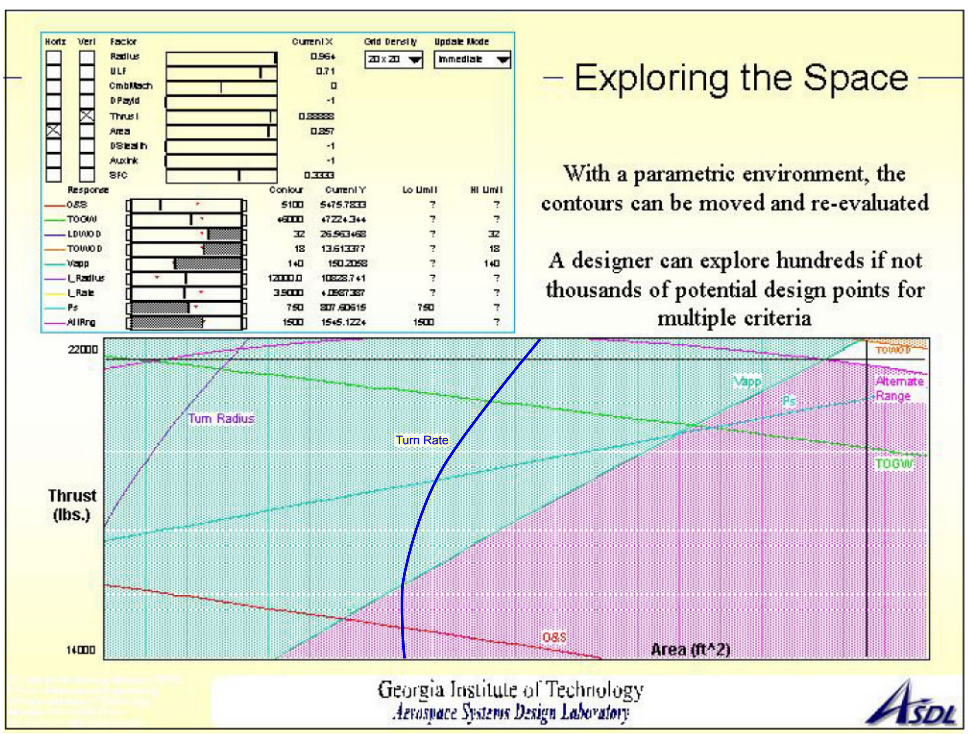


The design space continues to shrink as the combat radius is decreased.



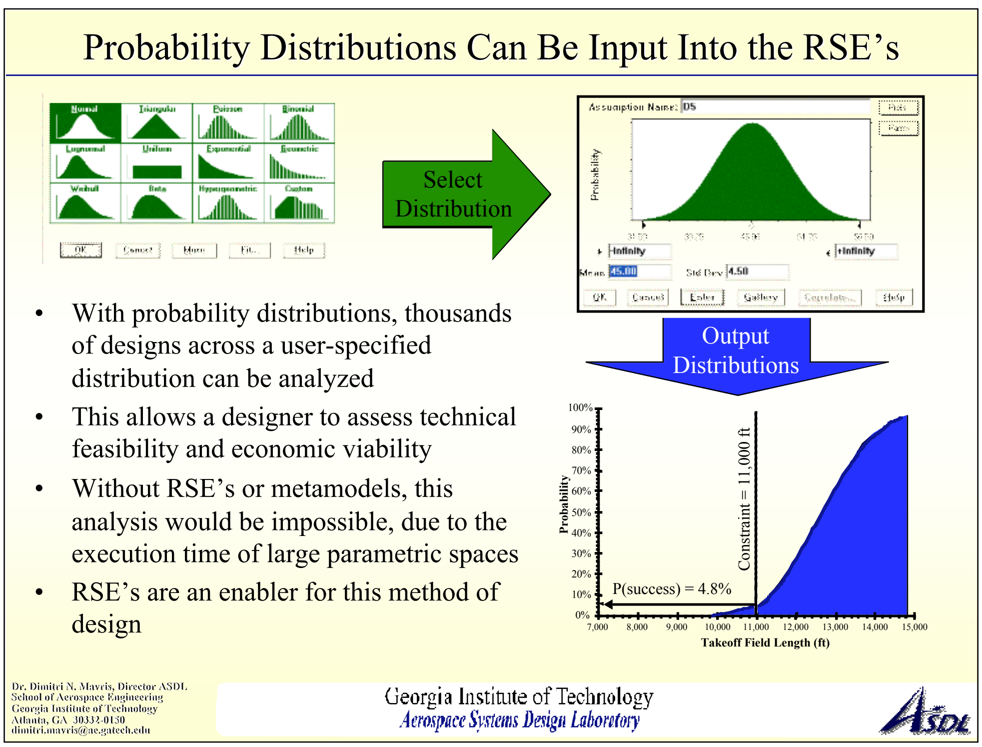
A new environment was created with different contours when it was discovered that the previous environment was not entirely accurate. The engine deck provided on the previous chart was for an F-18C that uses the F404 engine. The F414 was produced for the F-18E/F, and the F414 engine has a better SFC (specific fuel consumption) than its predecessor!

As a result, a slide bar for the SFC was placed into the environment. When this slide bar is set to the value of the SFC for the F414, a region of the design space opens up. The hairline values (sanitized to preserve proprietary information) are set to the F-18E/F, which falls in the feasible region.



The surrogate models (response surface equations) can also take inputs in the form of different distributions. These distributions are actually thousands of discrete runs that are rapidly executed in the environment. The parameters of the input distribution are defined, and the cases are run, producing a cumulative distribution function (CDF) of the output on which the probability of success of meeting various goals can be established.

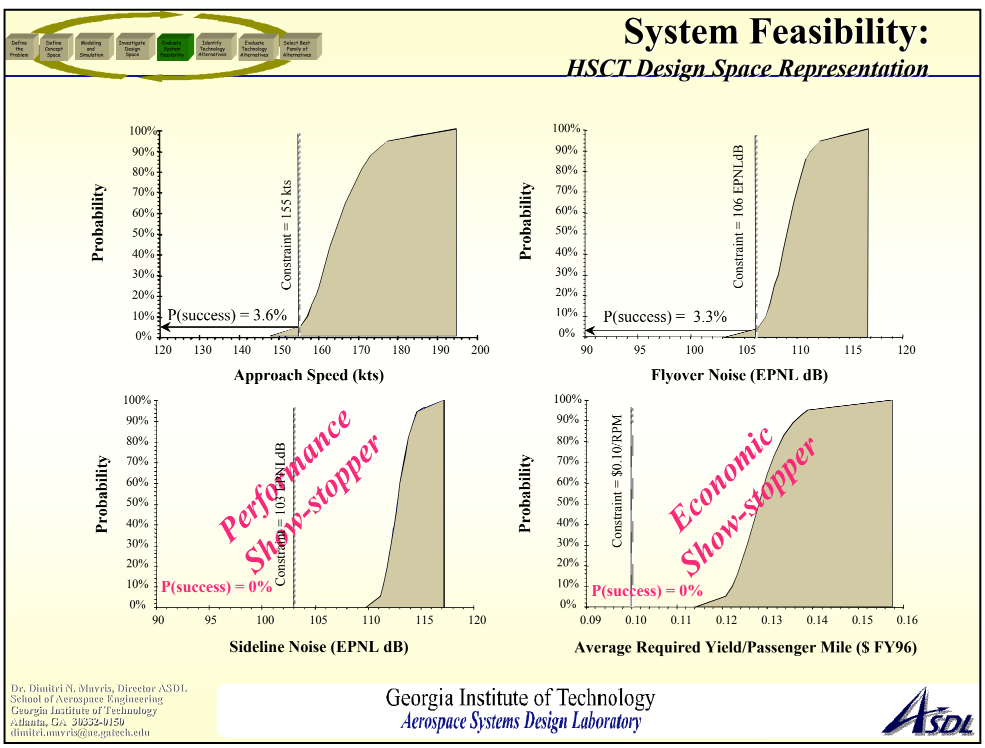
Without surrogate models, this analysis would take too long to be useful to a designer.



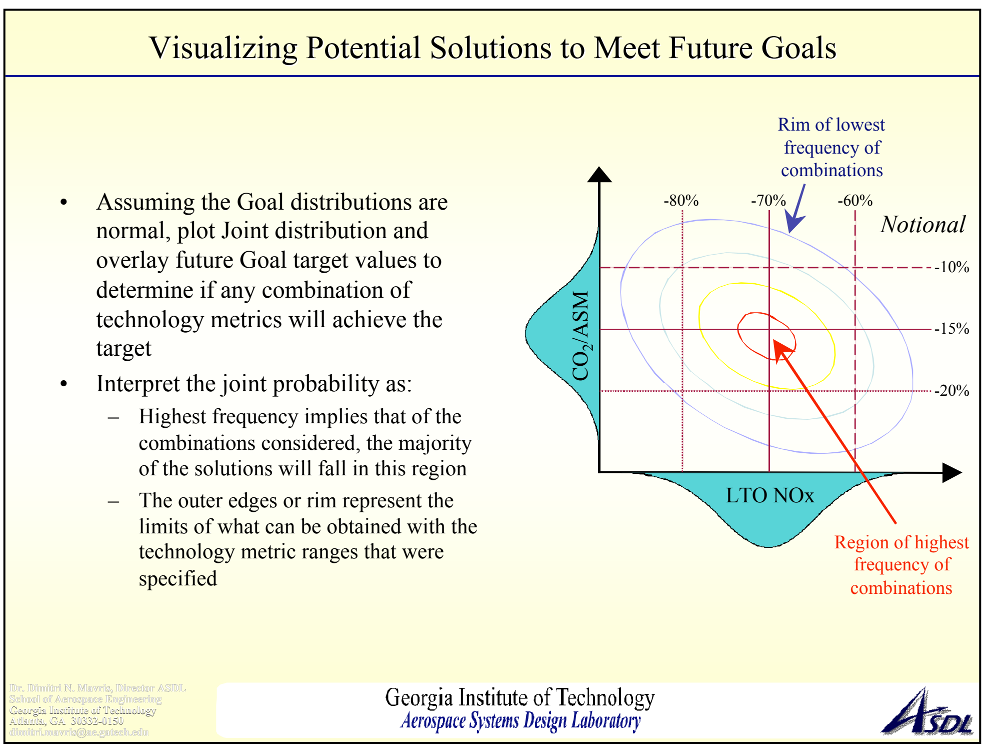
A sample of a probabilistic output for four goals is shown here. This aircraft has a low but finite amount of the design space that meets the approach speed and flyover noise constraints. Note, if the probability of success is too high, the requirements for the design are likely too loose.

However, also of note is the two showstopper cases in which none of the design space can satisfy the requirements for sideline noise and average required yield/passenger mile.

These two failures indicate that technologies must be infused to reduce noise and increase economic viability. ASDL methods allow the quantification of how much improvement is needed, and what the probability of success in the presence of uncertainty and noise will be.



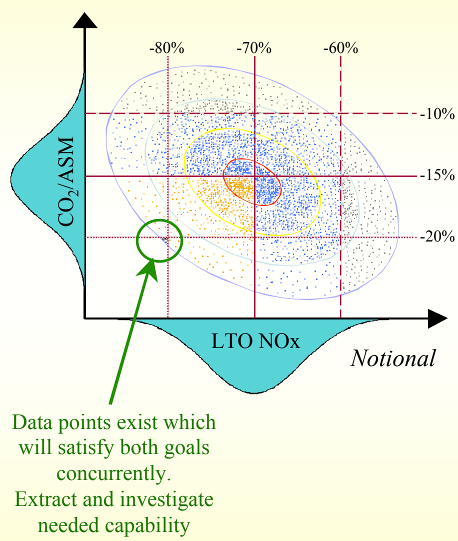
By looking at a contour plot of the Joint Probability Distribution and overlaying the future target values, the combination of technology metrics that will achieve the target can be determined. The contours represent lines of isoprobability. The skew in the distribution means that the two metrics are correlated.



The data points from the Monte Carlo Simulation can be placed onto the contour plot, and the data points that meet the goals can be extracted. When multiple combinations exist that satisfy the new goals, then the selection of the appropriate path may be determined by inspection. For example, looking at the path of least resistance, looking at a physically realizable solution, or balance with other metrics (noise, cost, vehicle performance, or development time).

Selecting Potential Solutions to Meet Future Goals

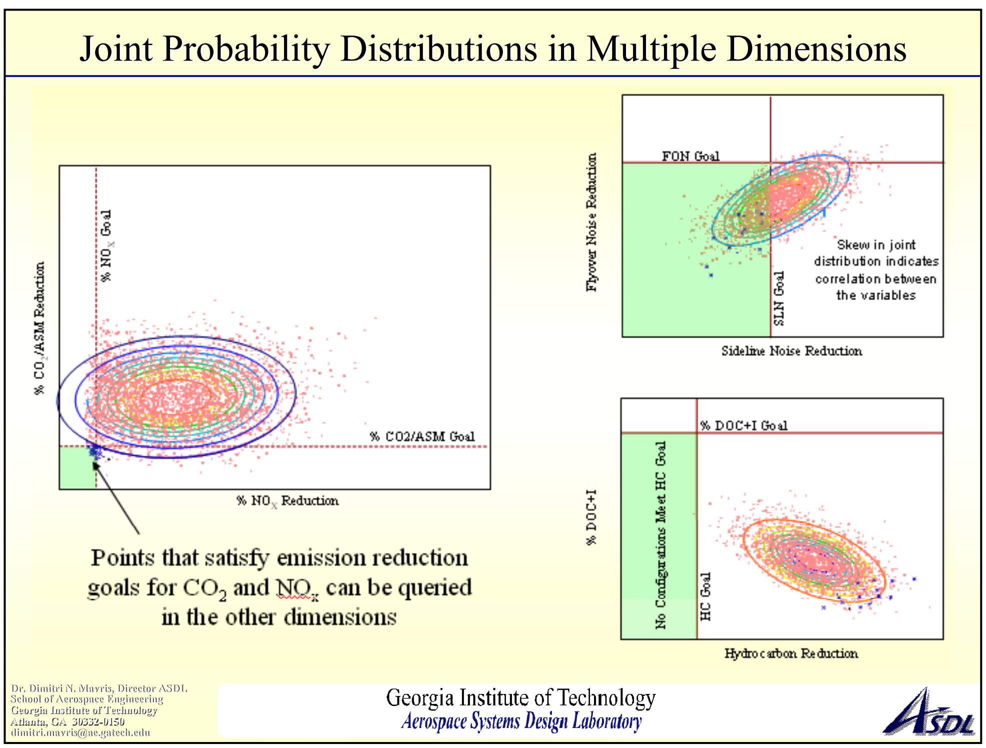
- To acquire the technology metric values that meet the new Goal values, simply overlay the Monte Carlo Simulation data
- Pick the data points that meet the goals and extract the associated technology metric values
- If multiple combinations exist that will satisfy the new goals, then selection of the appropriate path may be determined by:
  - Path of least resistance (based on the degree of difficulty)
  - Physically realizable solution
  - Balance with the impact to other metrics (noise, cost, vehicle performance)
  - Balance with the cost to achieve and the time to develop with the performance capability needed



Georgia Institute of Technology
Aerospace Systems Design Laboratory

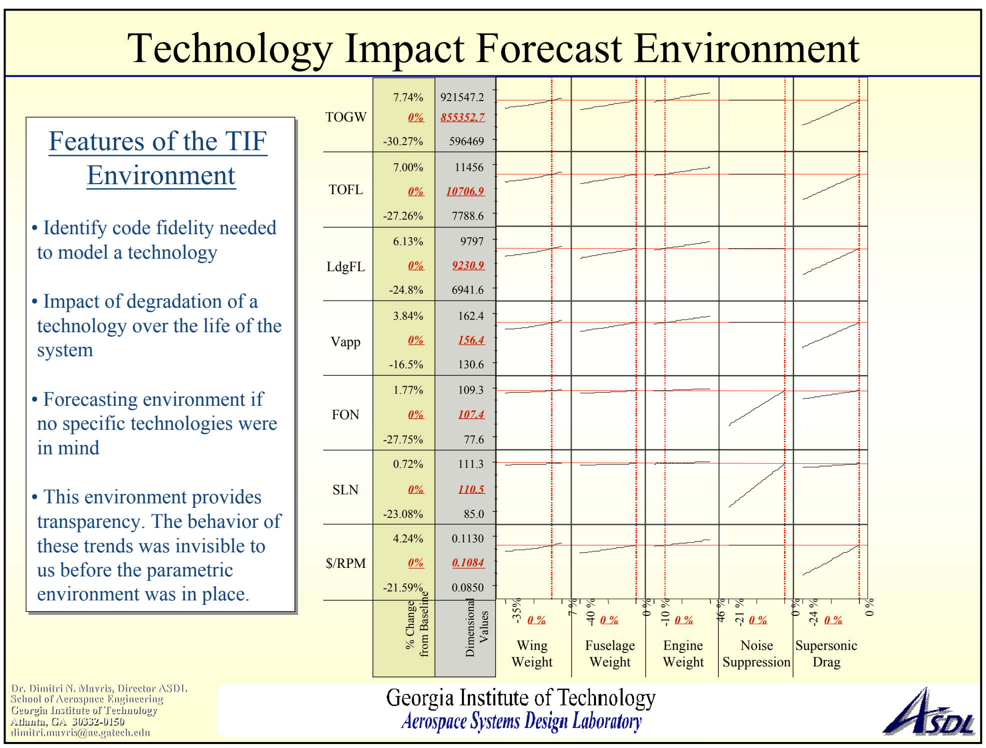
These joint probability distributions can be viewed in multiple dimensions. If the CO2 vs NOx plot on the left is used to examine whether configurations meet the emissions goals of the program, the highlighted cases in the green region can be changed to blue X's. These values then appear instantly in the other plots shown on the right (using a software tool called JMP Statistical Discovery Package). As a result, the designer can instantly see whether her or she likes the selected points, and whether those points meet the noise and economic goals of the program.

From this analysis, some of the selected points meet both noise goals. All selected points meet the economic goal (% DOC+I) but none of the highlighted points meet the unburned hydrocarbons (HC) goal. This requirement must be relaxed or technologies must be infused.

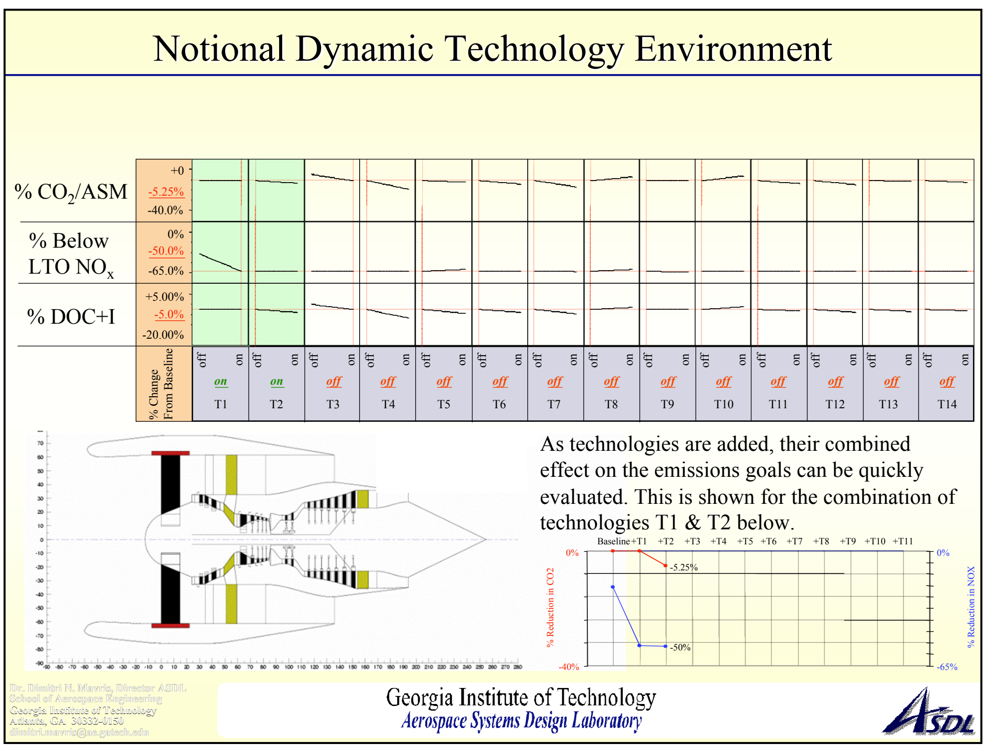


The technology forecasting environment (TIF) previously shown has another additional benefit. A “gap analysis” can be performed using this environment to see the relative improvement required in the various design parameters to meet the program goals. These settings can determine what types of technologies may be required.

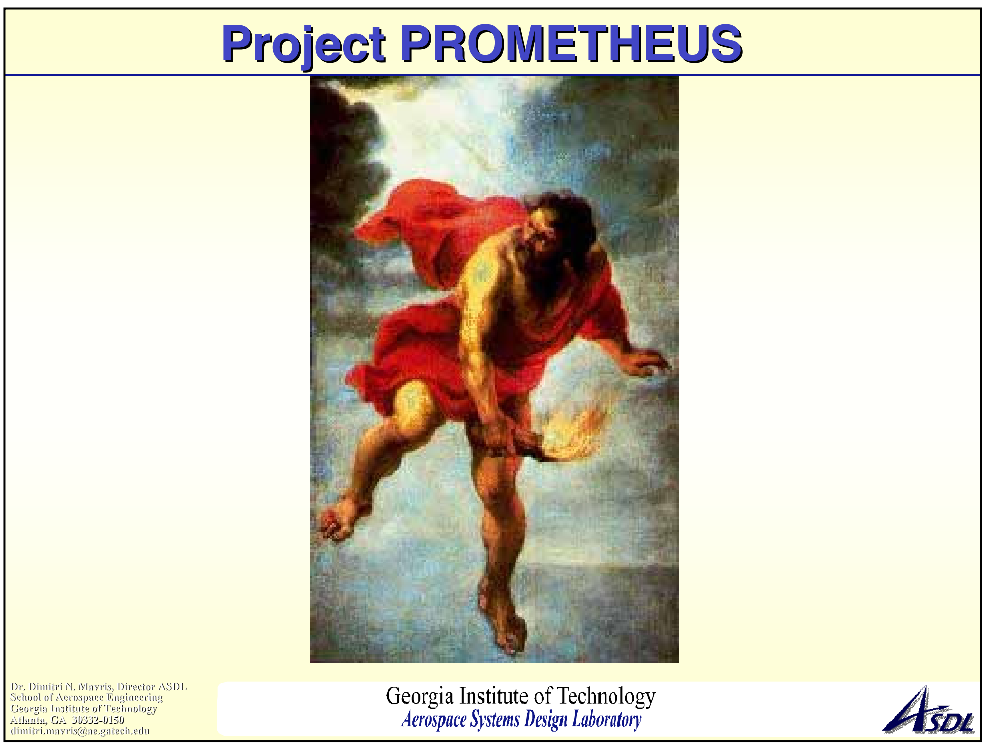
For example, if a reduction in wing weight and fuselage weight is required to meet economic goals (due to a lighter aircraft burning less fuel and hence costing less to operate), then advanced structural material technologies may be required to meet the goals of the program.



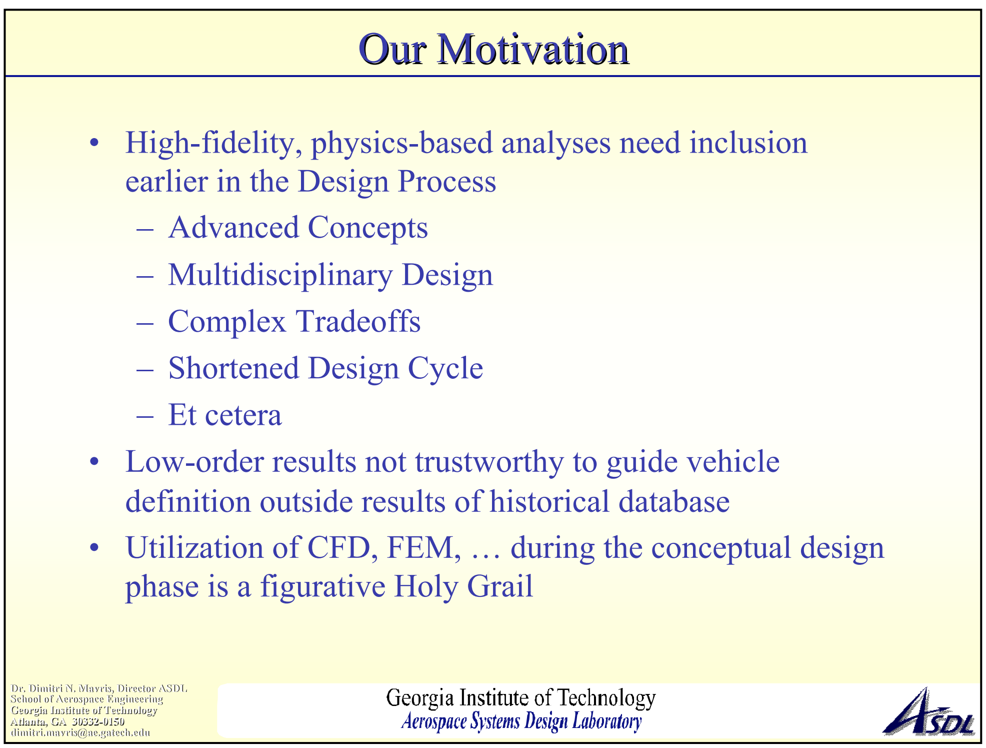
Finally, this environment can also be used with TECHNOLOGIES across the x-axis instead of design variables. In this case, the technologies have two settings, off and on. Turning a technology on as shown initiates a step-change in the output responses. In this example for a large passenger transport, both engine and airframe technologies were examined in conjunction. Adding technologies reduces or increases the responses on the left, and also re-evaluates the engine flowpath code to produce a new picture at the bottom left of the screen. This is helpful for our collaborative partners from the engine community, who can look at this flowpath and determine whether the highlighted configuration is feasible based on their engineering intution.



Project PROMETHEUS is an ASDL-inspired initiative to bring higher fidelity analysis to the hands of the decision maker and the conceptual designer through the use of advanced design methods and high power computing systems.

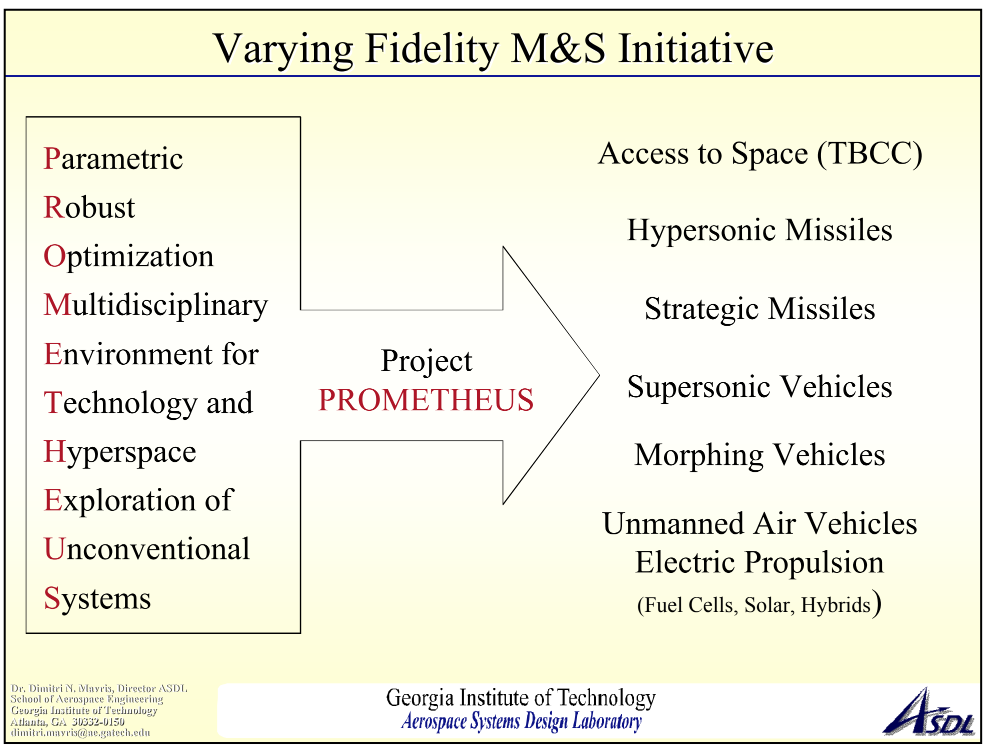


PROMETHEUS will examine using advanced design methods on unconventional problems that require collaboration and physics-based design.

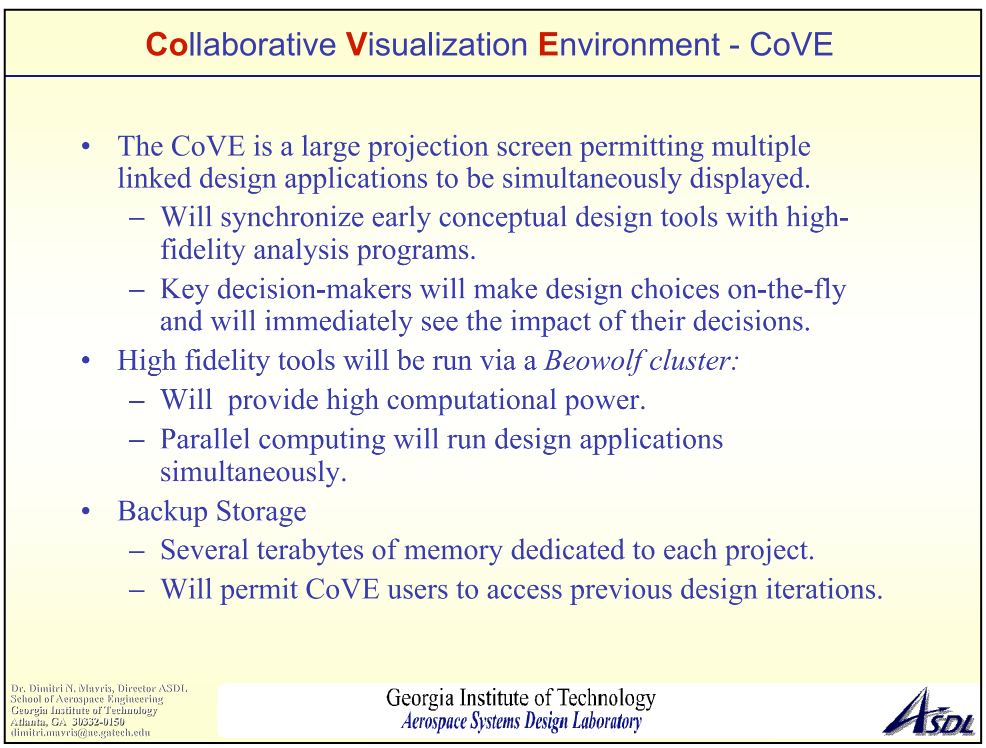


The PROMETHEUS endeavor is being applied to six graduate design competitions this year, as shown above. These six competitions span a wide range of designs.

Also, all of the designs in this year's competition feature multi-mission capability. From cruise missiles that can loiter and dash to tunable infrared signature missiles to intelligent UAV's, the PROMETHEUS project is looking at unconventional systems that also have the versatility and robustness to perform several missions.



As the result of an Office of Naval Research (ONR) Defense University Research Instrumentation Program (DURIP) grant, the ASDL has constructed a nearly ~$1M facility on the Georgia Tech campus to facilitate advanced collaborative design and decision making, as well as serve as a central processing area for distributed computing. The PROMETHEUS teams are actively using the CoVE for their design competitions this year.

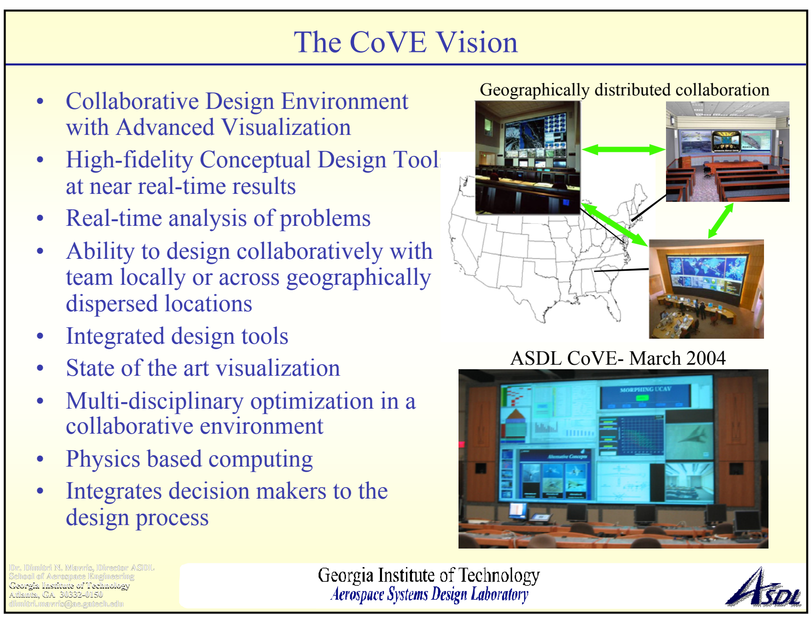


Real time analysis of problems—With the near real time computing capabilities, analysis and design can be accomplished by a team in a revolutionary time frame. The design environment at ASDL will transform how engineering design is approached in all fields of engineering. Physics based computing and real time analysis can be used in industries ranging from aircraft design to submarine design. This is the wave of the future.

Ability to design with team—In this dynamic environment with the near real time capabilities, all the key decision makers will be able to actively participate in the decision making and design process of the different functions of the CoVE. This will allow for designs to be created in significantly less time and with less hassle of correspondence.

Integrated design tools—Using system integration method software, such as "Model Center" or "Fiper", to coordinate the response of several design software tools decreases the design time by eliminating the setup procedures associated with each individual procedure.

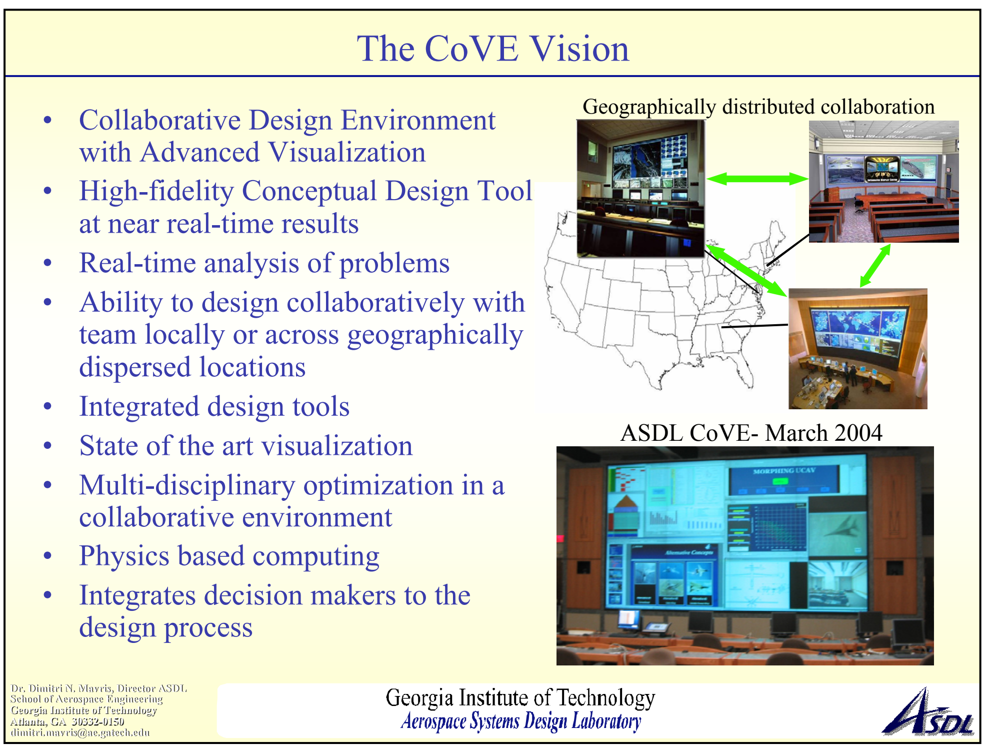
State of the art visualization—The state of the art display screens enable decision makers to view the results from analysis in plain view. The hassle of using multiple computers and multiple viewing windows is eliminated. With the simulation and design results in one viewing area, the design team can discuss the results devoid of clumsiness associated with using multiple standard computer monitors. This state of the art visualization will also enable the designers to add enjoyment to their tasks by offering a "sci-fi", or movie like environment to work with. This added excitement will ensure that the designers and engineers using this environment will become more productive and efficient.



Multi-disciplinary optimization in a collaborative environment—Any design is created by a design team. In several cases, design teams consist of individuals with conflicting schedules or physical barriers. Until now, design time has spanned months or years according to varying complexities because of three reasons; long analysis using many programs, time availability and long distance distribution of key decision makers. The CoVE environment will drastically decrease the amount of time associated with a single design because of its multi-disciplinary optimization and collaborative environment. With this state of the art design environment, physics based computing and simulations can be run and displayed in near real time allowing for key decision makers to see results and make decisions in one conference. Decision makers from afar can participate with the built in video conferencing capabilities. The data is encrypted and sent to the user on the other end of the video conference and that individual can voice their opinions about the issues at hand.

Physics based computing—Many modern designs are created with physics based computing methods or they desire the ability to analyze data with this capability. The CoVE and associated hardware will enable this high-fidelity computing to be accomplished at ground-breaking speeds.

Integrates decision makers to the design process



Finally, this is a photograph of the CoVE in action during a notional review of a morphing UCAV.

The 18 foot screen uses 12 x 64 inch plasma screens in a seamless manner to convey information in a high-resolution manner. This is useful because the massive amounts of information generated in these collaborative designs are difficult to visualize and the advanced visualization capabilities of the ASDL are looking for new ways to present the information so that all relevant information can be seen at once. Shown in this notional example are the following:

1) The ARIS flowchart and data management tool. ARIS allows the storage and retrieval of all program files. These files can be attached to the steps of the process, keeping the team organized and allowing digital reviews to take place.
2) A morphological matrix which shows all the possible combinations of the design. When a higher-fidelity capability is added to the CoVe, it will be possible to truly analyze ALL the combinations in a morphological matrix (with first-order analysis) so that trade studies can be performed on the fly. Previously, this discrete design choice only allowed a single design to be analyzed.
3) The house of quality tool for the establishment of customer importance and multi-parameter interactions.

4) A TOPSIS decision making tool with slide-bars that allow the decision makers to see the impact of varying the customer importance parameters. Before the CoVE, these values were static and needed to be generated before the presentation. With the power of the CoVE, this information can now be varied on the fly.A Powerpoint Presentation. Due to the crisp resolution of the 12 screens, it is not necessary to display the charts in full-screen mode.
5) A pareto frontier that represents the locus of optimal points in multiple dimensions. Slide bars allow the selection of a concept.
6) Television and video clips that can be pulled from a repository. In this instance, a video showing a UCAV attacking a convoy of trucks is pulled in from the Discovery Wings ™ cable channel.
7) Teleconferencing. The CoVE is equipped with the latest equipment and digital CODECS to allow teleconferencing at any site. The CoVE can connect to up to three other sites using its internal hardware, or up to 100 other remote locations using the Georgia Tech network bridge. This capability can be used to reduce travel costs and allow multi-site collaboration in a cost-effective manner.

For more information, please contact:

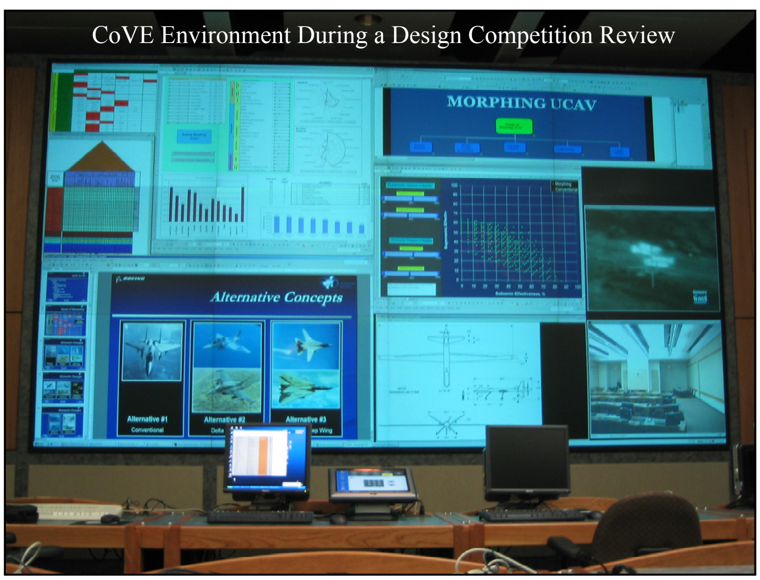
Dimitri Mavris

Boeing Associate Professor for Advanced Aerospace Systems Analysis

Georgia Tech School of Aerospace Engineering

Director, Georgia Tech Aerospace Systems Design Laboratory

Dimitri.mavris@asdl.gatech.edu



CoVE Environment During a Design Competition Review

Perspectives on Space Transportation System Innovative Design

James Blair, Robert Ryan, Luke Shutzenhofer
ASRI / NASA Marshall Space Center
Huntsville, AL

This presentation provides perspectives on innovative design of Space Transportation Systems. The authors are retired NASA engineers/managers, who are employed by AI Signal Research, Inc. in support of NASA/MSFC Employee and Organizational Development Division, providing knowledge transfer to less experienced personnel. A primary focus has been the engineering design process, its characterization, teaching, and improvement.

The presentation addresses the current design process for Space Transportation Systems (STS), its characterization and shortcomings, and discusses approaches to improve the process. The emphasis is on those innovative improvements that can be achieved in the near future.

AGENDA

Current Design Process
- Characterization
- Shortcomings

Innovative Improvements (Achievable in near future)
- Functional Relationships – Next Major Step
- Integrated Performance Model
- Sensitivities and Margins
- Risk Prediction and Probabilistics
- Communication and Information Systems
- Other Areas

Concluding Remarks

To begin with, space transportation systems are very complex systems, with many diverse parts and associated interfaces. They have extreme performance requirements and high power densities. This means that they are very interactive, and are sensitive to small variations. Consequently, design of such systems is itself a complex process. It involves dividing (compartmentalizing) the design activity into parts, then reintegrating the parts into the complete system. It is in the reintegration and the interfaces where most problems have occurred.

Furthermore, the process is sequential and iterative, involving many steps. Much communication among the many entities is required throughout the process. Because of the complexity of the design process, the resulting product has shortcomings which need to be overcome.

We have developed a symbolic model of the current STS design process in order to improve understanding and to serve as a basis for improvements. It has been taught to groups of engineers and managers; is the basis for a prototype learning module at the ODU Advanced Engineering Environments Center; and has been applied in conceptual design .

CURRENT DESIGN PROCESS
FOR SPACE TRANSPORTATION SYSTEMS

Space Transportation Systems (STS) are very complex
- Complex vehicles, operations systems, payload accommodations

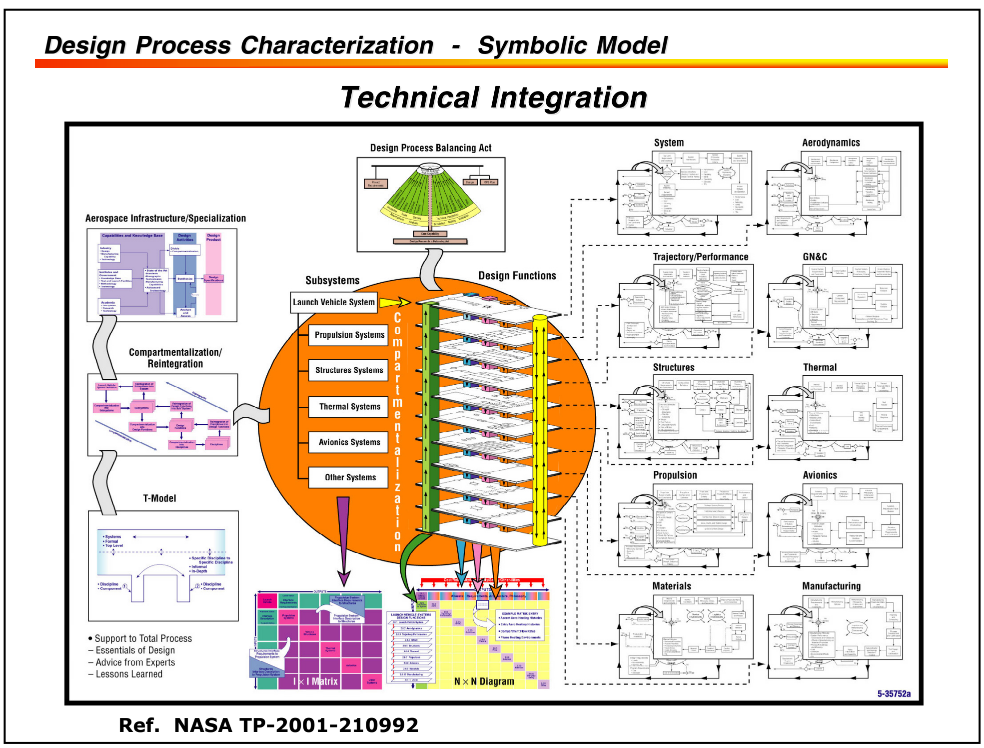
Current STS design process is complicated, involving
- Compartmentalization
- Reintegration
- Sequential iteration
- Pervasive communications

Resulting system has consequent shortcomings

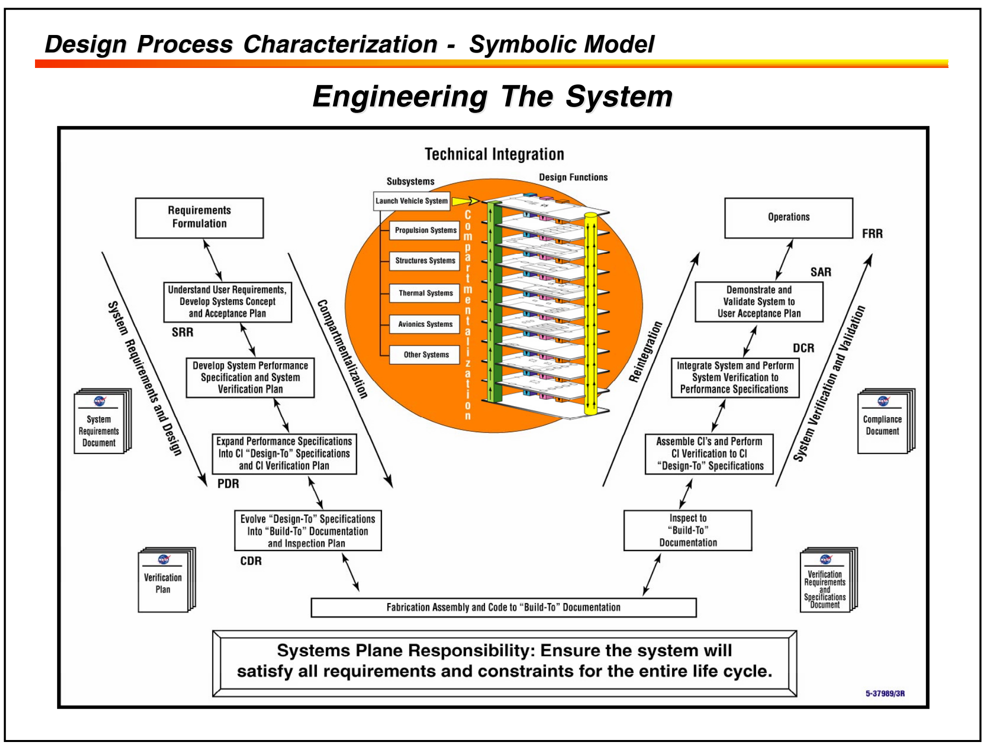
Symbolic model of current design process
- Developed to improve understanding of process
- Has been taught to groups of engineers and managers
- In prototype AEE Learning Module

This figure gathers key elements of the design process model onto one chart. The left center diagram indicates compartmentalization of the system into subsystems, design functions, and discipline functions, and its subsequent reintegration. Compartmentalization has its basis in the divisions of industry, government, and academia (top left). The "T-model" (lower left) indicates the philosophy of integration. In the center, the compartmentalization/reintegration process implementation is illustrated by a subsystem tree and a stack of design function planes. The design function planes contain the discipline functions. They are expanded on the right, along with decision gate diagrams. Vertical information flow conduits on the stack connect the design functions. Information flow matrices are shown below the stack; the left being an "IxI" matrix for subsystem interfaces, and the right being an "NxN" matrix for information flow among design functions and discipline functions. The top diagram represents how the design is iterated through trade studies to achieve the best design for the integrated system.

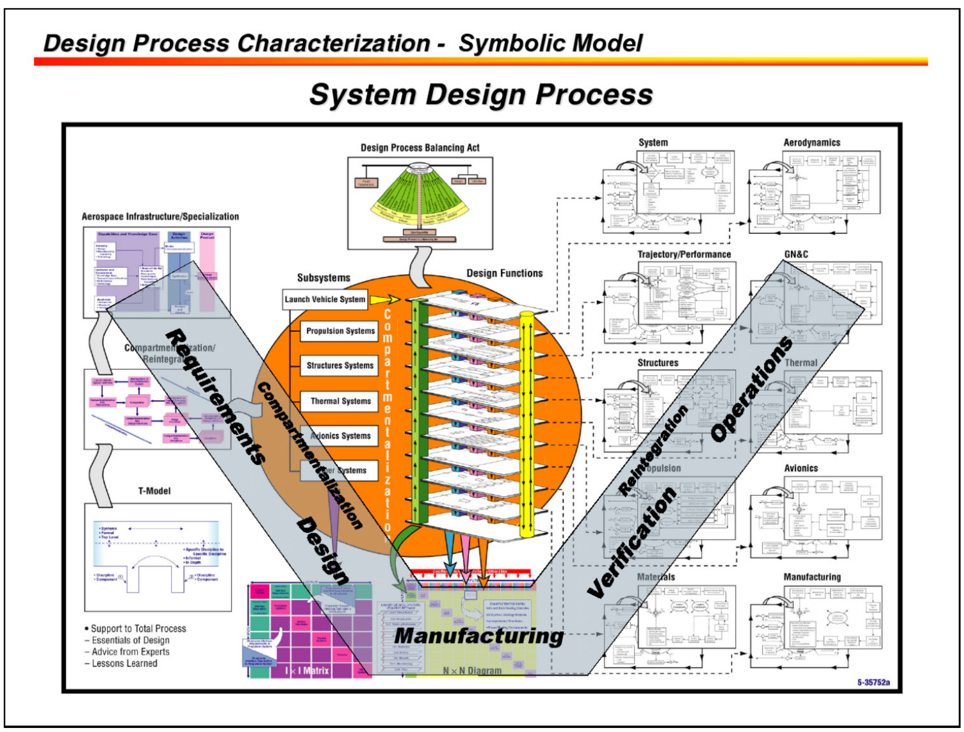
We have called this process "Technical Integration." which is a significant feature of the symbolic model that characterizes the design process as described in NASA-TP-2001-210992.



Planning, control and documentation of the process are provided by classical Systems Engineering (CSE), represented here by the Systems Engineering “V”. The “V” indicates the product life cycle from requirements through design and manufacture, then verification of the subsystems and the system, and finally, systems operation. CSE also enforces project process commonality among projects in a program, while providing discipline associated with design products and processes during technical integration execution.



Overlaying the classical Systems Engineering "V" on the Technical Integration process then represents the total System Design Process.



The symbolic model has aided understanding of the process, has helped participants understand where they fit in the process, and has potentially reduced problems in the design through lessons learned. The lessons hopefully help avoid some of the problems of the past. Some experienced practitioners have affirmed the model's applicability [usefulness], saying, "Where was this model 20 or 30 years ago when I needed it?"

However, there are major inherent shortcomings in the current process, including lack of fidelity in the conceptual design phase, fragmentation of the process leading to potential interface problems, difficulty in designing for cost and the "-ilities" (reliability, operability, etc.), difficulty in predicting risk, and inability to optimize the total system. These shortcomings result in product consequences that include performance shortfalls, unforeseen interactions and sensitivities, unanticipated failures, and high operating costs.

Overcoming these problems will require innovative approaches.

CURRENT STATUS AND FUTURE NEED

Symbolic model of current design process has been useful in

+ Aiding understanding and clarifying roles
+ Reducing problems associated with the design

However, significant shortcomings remain:

PROCESS SHORTCOMINGS

- Lack of fidelity in conceptual design stage
- Difficulty designing for cost and -ilities
- Difficulty predicting risk
- Inability to optimize the total system

PRODUCT CONSEQUENCES

- Performance shortfalls
- Unforeseen interactions and sensitivities
- Unanticipated failures
- High operating costs

Overcoming these problems will require innovative approaches

Here are some illustrations of the lack of fidelity in the conceptual design phase—concept vs. reality. The picture on the left shows Shuttle orbiter maintenance as envisioned during its conceptual design. The picture on the right shows it as it is today.

In the area of performance the Shuttle was intended to carry 65 Klbs. payload to low earth orbit. The first flight could achieve only 20 Klbs. Subsequent upgrades have increased the delivery capability, but it has never achieved the originally-intended 65K.

The Saturn V design originally had four engines on its first stage, which analysis showed to be sufficient to meet the vehicle's performance requirements. Some far-sighted persons added a fifth engine for margin, which enabled the as-built Saturn to perform its missions, including the Skylab mission.

More recently, the Access to Space project (which was never produced) predicted a dry weight of 160 Klbs. at conceptual design. An activity which put more detail into the vehicle description resulted in a more realistic dry weight prediction that was greater than twice the original value.

Cost growth is notorious. Two examples are illustrated here. STS costs are a strong function of the flight rate.

CONCEPTUAL-TO-ACTUAL SNAPSHOT

Performance

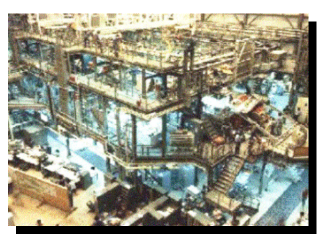
Saturn V		Space Shuttle		Access to Space - 25k Payload	
- S1C Initial 4 F1 engines		- Payload Req.	65K	-Initial Dry Weight (conceptual designer)	160k
- Payload Req.	85K	- Flight 1	20K	-Refined Dry Weight (detail designer)	354k
- Added another F1 engine		- Flight 8	35K		
- Payload capability	100K+	- Flight 100	47K		

Cost

Saturn V Total Program Cost		Space Shuttle Cost Per Flight	
- W. Von Braun	5B	- 1972	29M (1985$)
- B. Holmes	10->13B	- 1985	273M
- J. Webb	20B	- 2000	373M (8 Flts/yr)
- Actual	20->40B	- 2004	600M

Operations

Conceptual



Actual

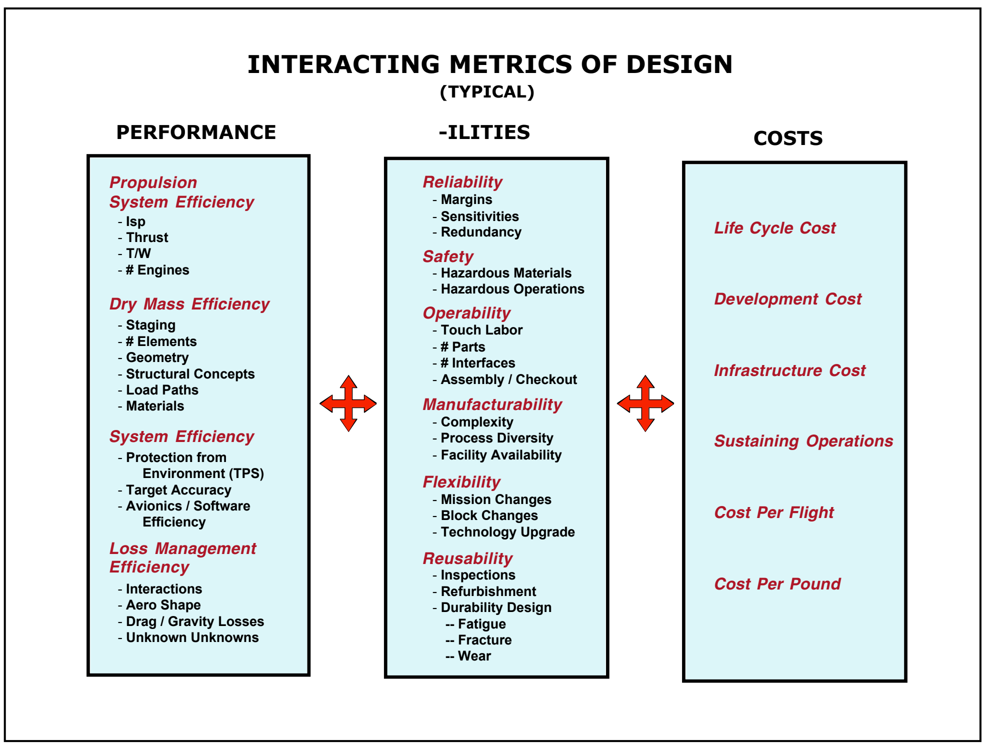
The system attributes for which we design can be represented by sets of interacting metrics. They can be collected in to three groups:

1. *Performance*, which is the physical behavior of the vehicle—its payload to orbit, its accuracy of delivery, etc. Typical performance categories and metrics are shown in the left box.

2. *The "-ilities"*, which include reliability, operability, safety, etc. Some typical "-ilities" metrics are shown in the center box.

3. *Cost*, which includes various cost metrics, typical of which are shown in the right box.

These metrics are interactive both within and among their categories. Changing one of them in the design will affect others.

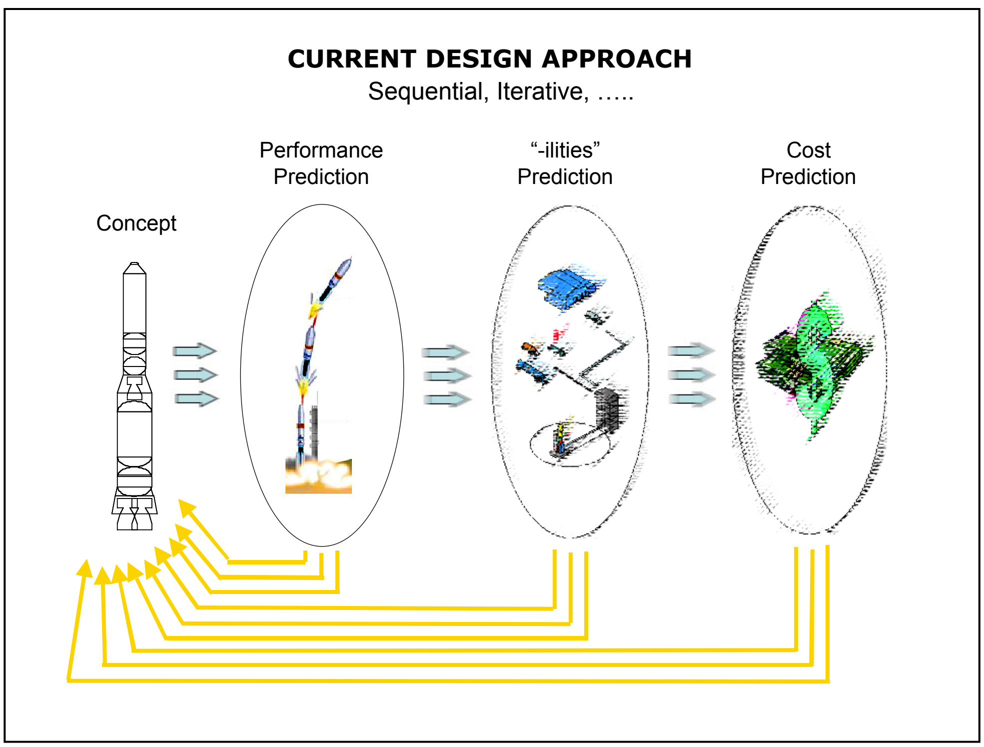


In order to design for these interacting metrics, the current design process involves a sequential, iterative approach. It begins with requirements, hypothesizes a concept (an architecture), and predicts the attributes of the concept.

First, the physical performance is predicted. The predicted performance probably does not meet requirements, so iterations on the concept design parameters are made until reasonable convergence is achieved, or else the concept is discarded. Typically, the "-ilities" are predicted after the performance. Again, iterations on the concept are made, along with updated performance predictions. Likewise sequentially with cost predictions.

Performance predictions are somewhat uncertain, but "-ilities" predictions are much more uncertain. By the time we get to cost prediction, the view is very unclear.

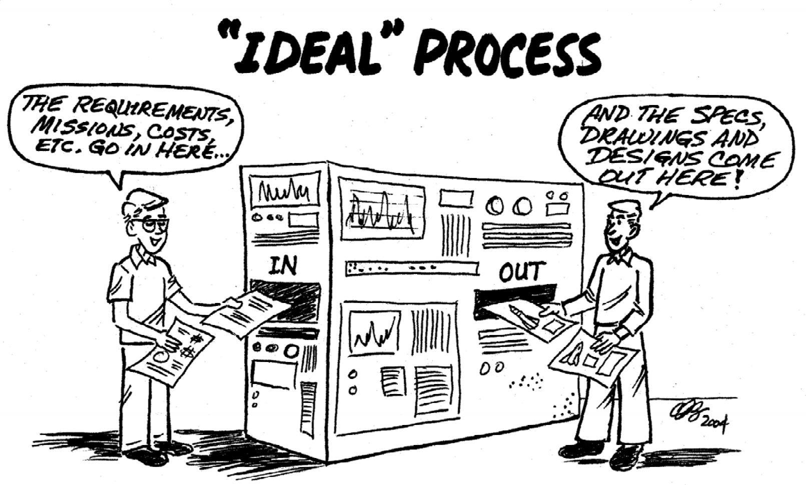
This sequential iterative uncertain process is inefficient and time consuming and produces designs that have major shortcomings. The process must be improved.



What would be an ideal design process? We might imagine something like the cartoon, where the requirements go in, and the design specifications come out.

Even if we wanted this "ideal" process (and there may be reasons to not want it), it would be very far in the future.

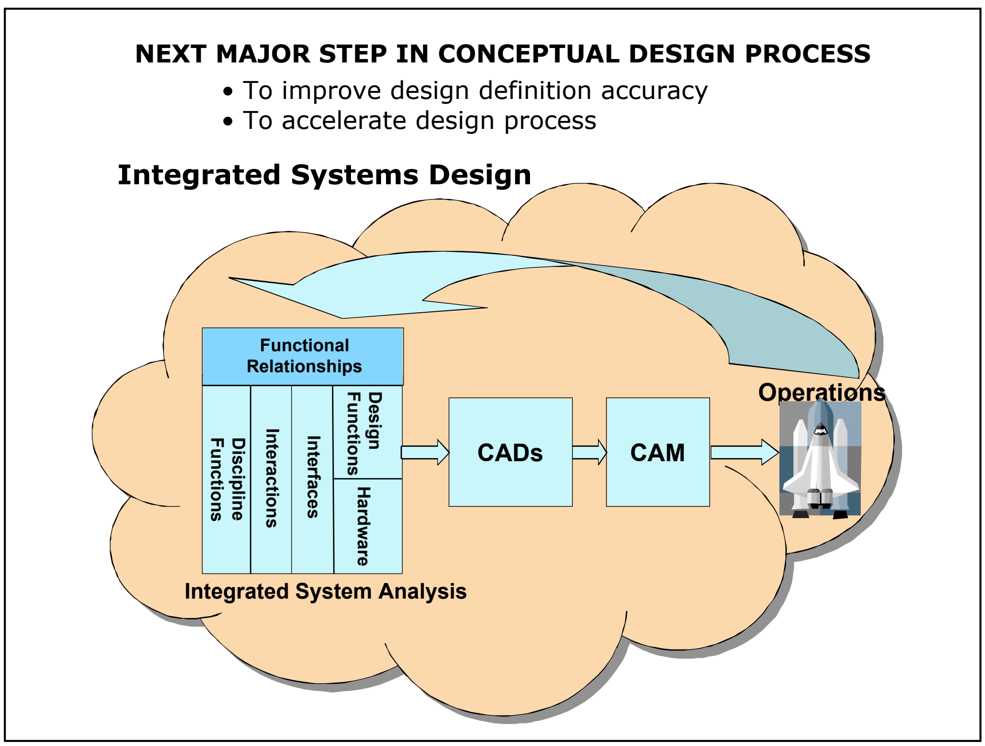
We will focus on innovative improvements that are achievable in the nearer-term.



While this ideal design process is far in the future, we will discuss major improvements that can be made in the nearer term.

The next major step that should be achievable involves integrating the system's design through functional relationships that connect the attributes of the operational system to its integrated systems analysis model.

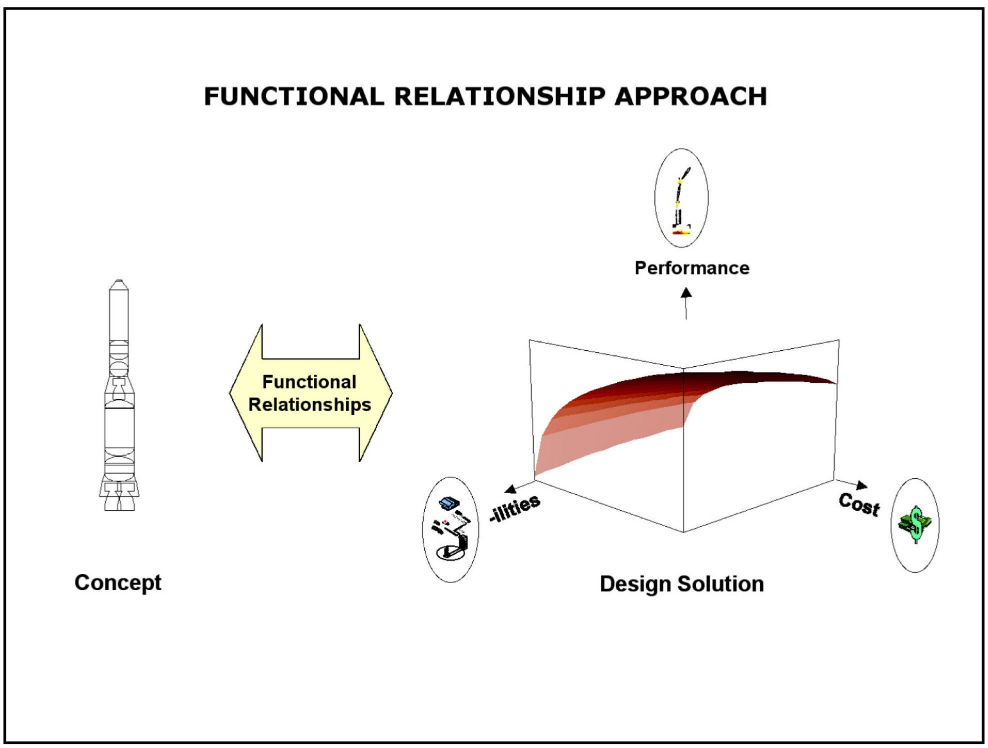
Another important feature is the integrated analysis model which combines hardware descriptions, design functions, discipline functions, and inherently accounts for their interactivity through a combined formulation. The model predicts the operational attributes. It connects through the CAD and CAM systems to the realized design product.



The functional relationship idea is illustrated by a two-way mapping between the Concept (architecture) and the Design Solution space. The space is n-dimensional but we illustrate it in three dimensions that represent the performance variables, the "-ilities" variables, and the cost variables.

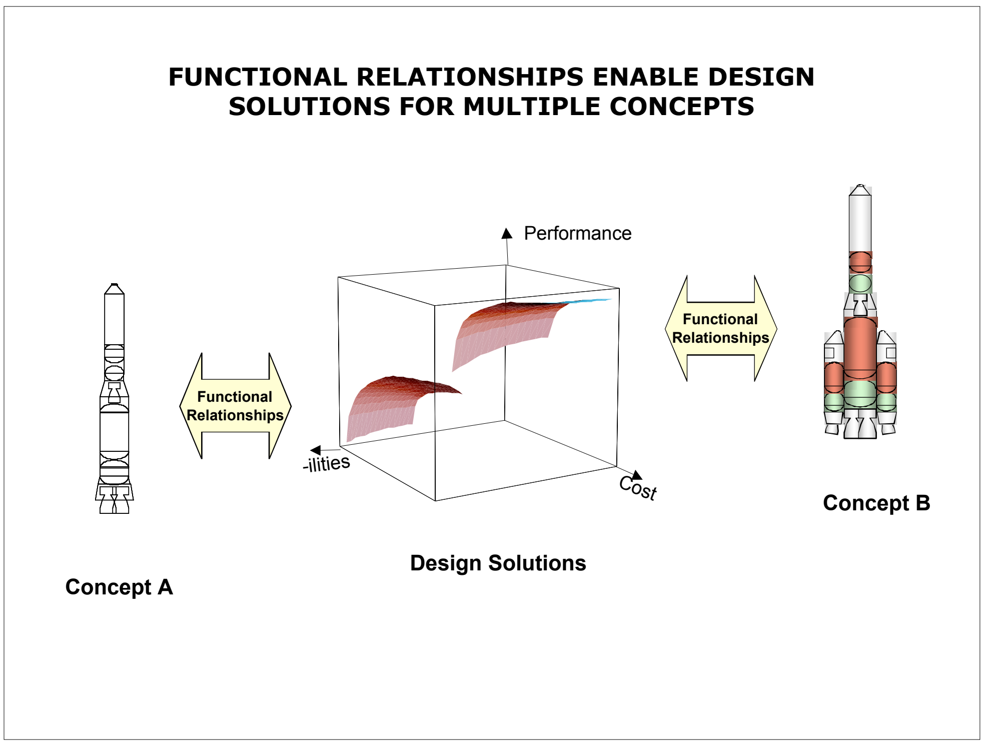
The forward functional relationship arrow represents prediction of the concept attributes. The more powerful direction is the backward arrow representing the inverse functional relationships, which map the measures of performance, -ilities and cost onto the design variables of the concept.

These functional relationships are not necessarily easy to obtain, but we need to work toward having functional relationships that bring measures of performance, "-ilities" and cost onto the designer's table.



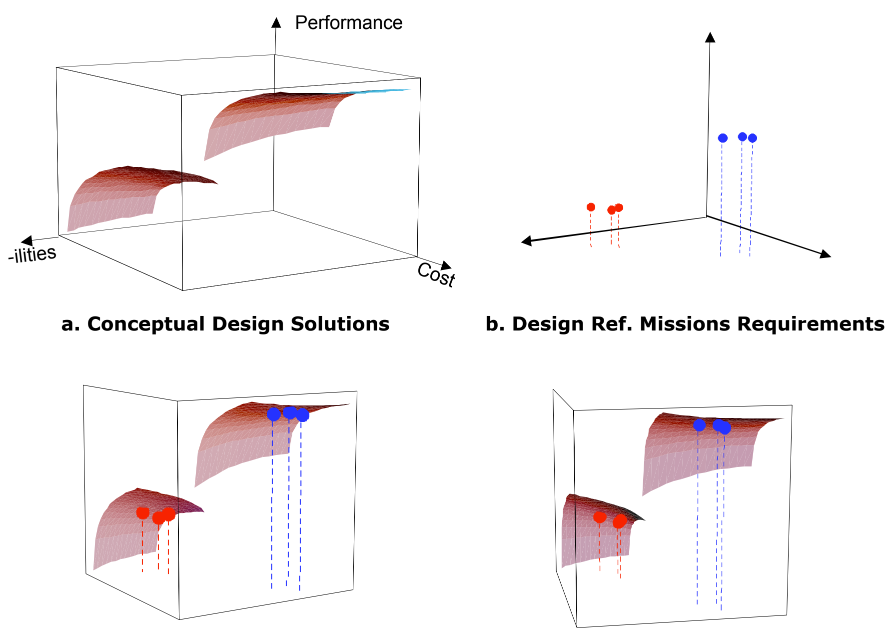
Concepts (architectures) that differ significantly map onto different surfaces in the solution space. A surface represents the effects of varying the design variables (such as skin thickness, engine thrust, etc.) for each concept. The region of validity of each concept is represented by its surface.

The difficulty associated with the design process is further complicated since we usually design new launch vehicles to conflicting needs (requirements) among the military, private sector, and NASA. This usually leads to multiple architectures. Now combining this complexity with the functional relationships leads inherently to a map of multiple concepts (architectures).



Requirements would map into this space; for example, consider various design reference missions (military, private sector, or NASA), where each might group into a set. We illustrate two sets in the figure, represented by the red and blue dots. The first vehicle would capture the red set but not the blue set. It would take another vehicle to capture those missions.

MAPPING OF SOLUTIONS TO REQUIREMENTS



c. Mapping of Conceptual Solutions onto DRM Requirements

An integrated performance model is another important component of improving STS design. A group at MSFC called the Vehicle Integrated Performance Analysis (VIPA) Team has accomplished significant progress in increasing design fidelity and reducing turn-around time.

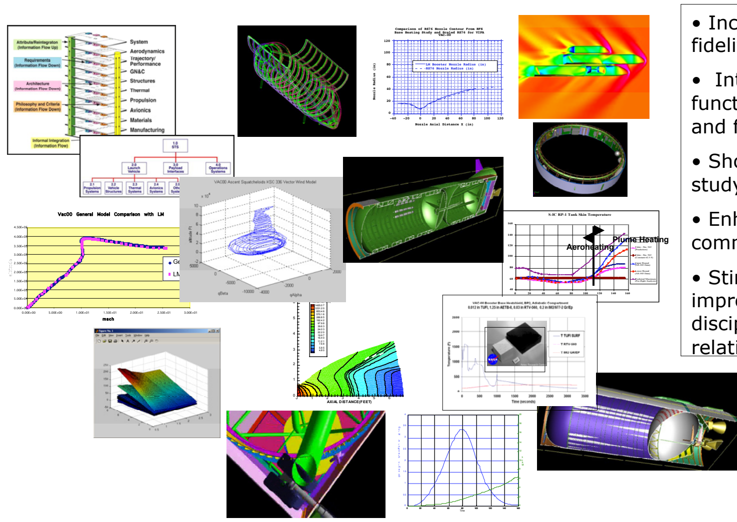
Based on the symbolic model, it employed a backbone analysis that integrated subsystems, design functions and flight sciences such as aerodynamics and performance/trajectories. The backbone model provided a connector for discipline-specific models. It is based on a parametric CAD model — level of modeling fidelity.

It has been applied to several projects where it brought the level of fidelity forward in conceptual design and identified issues not otherwise found.

Much progress was effected by the team's relationships and its adapting to the integrated environment.

INTEGRATED PERFORMANCE MODEL
AND INCREASED FIDELITY IN CONCEPTUAL DESIGN

Initial Step: **Vehicle Integrated Performance Analysis (VIPA)**

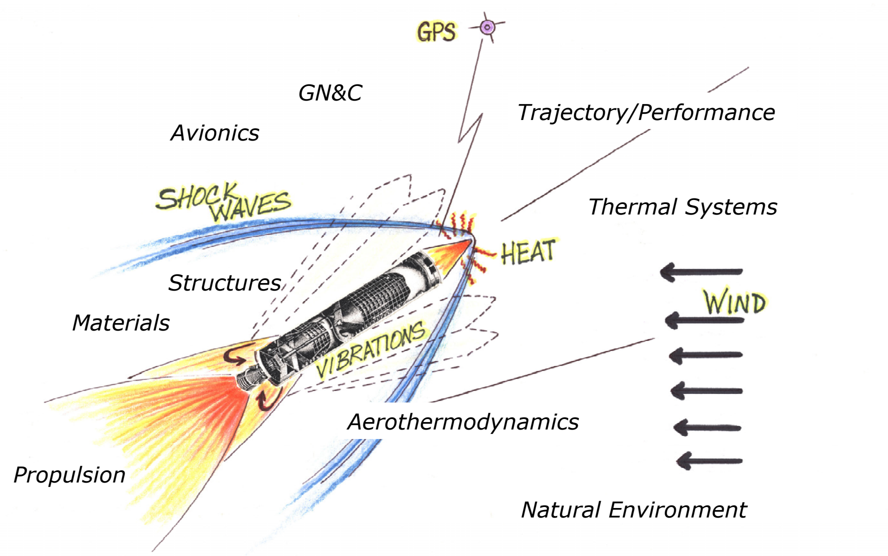


- Increased design fidelity
- Integrated design functions, subsystems, and flight sciences
- Shortened trade study times
- Enhanced communications
- Stimulated improvements in discipline functional relationships

Enabled by symbolic process model, integrated computer modeling, and team cultural adaptation

VIPA has taken initial steps, but the goal is a fully integrated high fidelity performance model that would integrate the multiple areas and avoid the problems of hand-off, interfaces, and iterations. This model would depart from the those used in the recent past where point forces, mass properties derived from mass estimating relationships, and load/thermal indicators were used. The advanced model would include structural CAD models, distributed coupled aerotherodynamics including plume effects, rigid-body/elastic-body structural response, wind profiles, dynamic characterization of GN&C systems, flight performance optimization, and so on.

INTEGRATED PERFORMANCE MODEL



Beyond the initial step achieved by VIPA, the need is to fully integrate the design functions and disciplines into a high fidelity, concurrent, interactive performance model

Another area generally lacking is determining design sensitivities, uncertainties, and providing adequate margins. It is crucial to know the sensitivity to the system being designed, and to provide adequate margins in light of uncertainties.

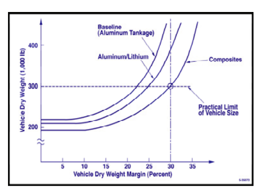
Innovation in this area can be achieved through the application of functional relationships and associated modeling error functions in conjunction with the statistical characteristics (means and variances) of all the input and coupling variables. The functional relationships plus modeling error functions would provide information relating the outputs of subsystems with coupling variables, subsystem specific design variables, and subsystem sharing variables. Calculation of subsystems output mean values and variances could be accomplished automatically. The mean values of the subsystems output variables could be approximately determined algebraically by applying the functional relationships plus modeling error functions in conjunction with the mean values of all the input and coupling variables; the second partial derivatives of functional relationships and modeling functions; and the variances of the input variables, coupling variables, and modeling error variables. The variances of subsystems output variables could also be determined algebraically in terms of the sensitivities of the functional relationships and modeling error functions with respect to all input and coupling variables in conjunction with the variances of input variables, coupling variables, and modeling errors. After the subsystems means and variances are determined, engineering judgments would be made regarding their application (experience based: one sigma, two sigma, or three sigma) in conjunction with a safety factor to assess reasonable margins with respect to the statistical determined allowable limit (experience based: one sigma, two sigma, or three sigma) of the capability of the various subsystems.

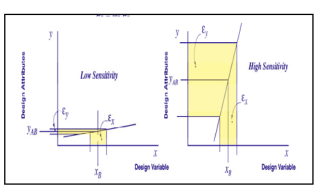
SENSITIVITIES AND MARGINS

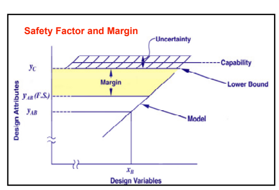
Determining design sensitivities and providing adequate margins are critical to successful design

Innovative design features:

- Automatic calculation of sensitivities by models
- Expert system to guide margin provisions
- Historical databases of key parameters







An essential adjunct to deterministic analysis and design is probabilistic description and risk prediction. Since predictions, natural environments, and hardware performance are all inherently uncertain, probabilistic approaches are appropriate for modeling and prediction.

Areas for innovation include the application of the functional relationships and modeling error functions in conjunction with the probability density distributions of all the input and coupling variables. Automated Monte Carlo or numerical methods would be used to obtain subsystems attribute distributions. In addition, the probability density distributions of the subsystems capability would be known. Then risk prediction would be made quantitatively wherever possible. Advanced approaches can assist the designer's judgment in areas known only qualitatively.

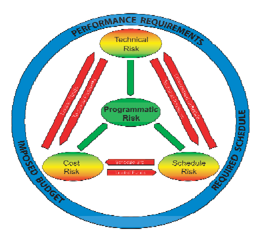
Introduction of new technologies is a crucial issue in design, and innovations are needed to assist in technology risk assessment and its mitigation.

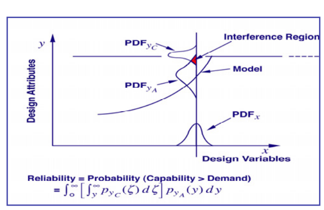
RISK PREDICTION AND PROBABILISTICS

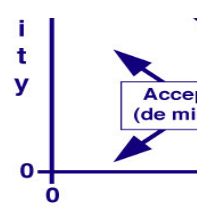
Prediction of risks and probabilistic characterization are essential adjuncts to deterministic design.

Innovative design features:

- Automated Monte Carlo of design parameters and variables to obtain attribute distributions
- Risk prediction for performance, cost, schedule
  - Quantitative where possible
  - Judgment-assisting for qualitative areas
- Technology risk assessment / mitigation

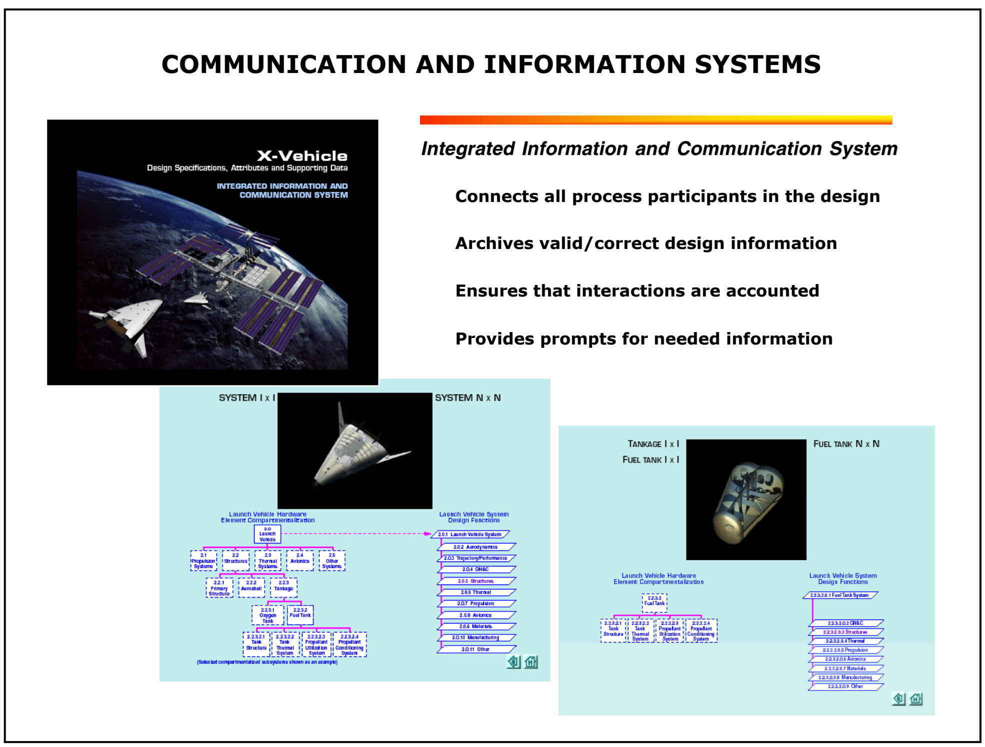






There are a number of advanced interactive information and communication systems being envisioned.

We proposed a readily achievable system based on the compartmentalization areas of the current design process, called the Integrated Information and Communication System (I^2CS). It would connect all process participants, provide common and correct design information, insure that interactions are accounted for, and particularly important, would provide prompts for needed information.



There are other areas for innovatively improving the design process, some of which are noted here.

These include:

1. Collaborative engineering tools, which has received much attention. Also included would be multivariate decision-making tools.

2. Concept generation (synthesis) tools, where in ideal terms it would be desirable to apply inverse engineering to convert requirements into design concepts. In the near term we could look to innovative approaches to stimulate the creativity of individuals in generating concept ideas.

3. Expert systems to aid the designer based on extracting information from historical databases, asking probing questions, performing reality checks, and providing lessons learned to avoid the problems of the past.

OTHER INNOVATION AREAS
include

COLLABORATIVE ENGINEERING TOOLS

- Visualization aids
- Integrated models and databases
- Virtual presence with concurrent access to graphics and data
- CAD/CAM with electronic inspections
- Multivariate decision-making tools

CONCEPT GENERATION (SYNTHESIS)

- Inverse engineering to convert requirements to design concepts (Far-term ideal process)
- Innovative approaches to stimulate creativity of individuals to generate concept ideas (Nearer-term)

EXPERT SYSTEMS

- Pertinent data collection and information extraction
- Interactions, probing questions, reality checks
- Lessons learned

There have been benefits of applying the symbolic description of the current design process; however, there is a need to innovate and significantly improve the design process.

Major improvements in fidelity and efficiency should be enabled through computer capability.

The improvements identified are reasonable to achieve in the near-term.

However, there are hurdles to be overcome in achieving the next major step in design process and tools. These include

- Defining Functional Relationships
- Integrating all the elements of the design process
- Obtaining input information for probabilistic design
- Cultural change to embrace the next major step

CONCLUDING REMARKS

- Symbolic process description has enabled understanding and improvements
- Computer capability exists to improve fidelity and accelerate design process
- Near-term improvements are achievable
- Main hurdles in achieving next major step in design process and tools:
    - Defining Functional Relationships
    - Integrating all the elements of the design process
    - Obtaining input information for probabilistic design
    - Cultural change to embrace the next major step

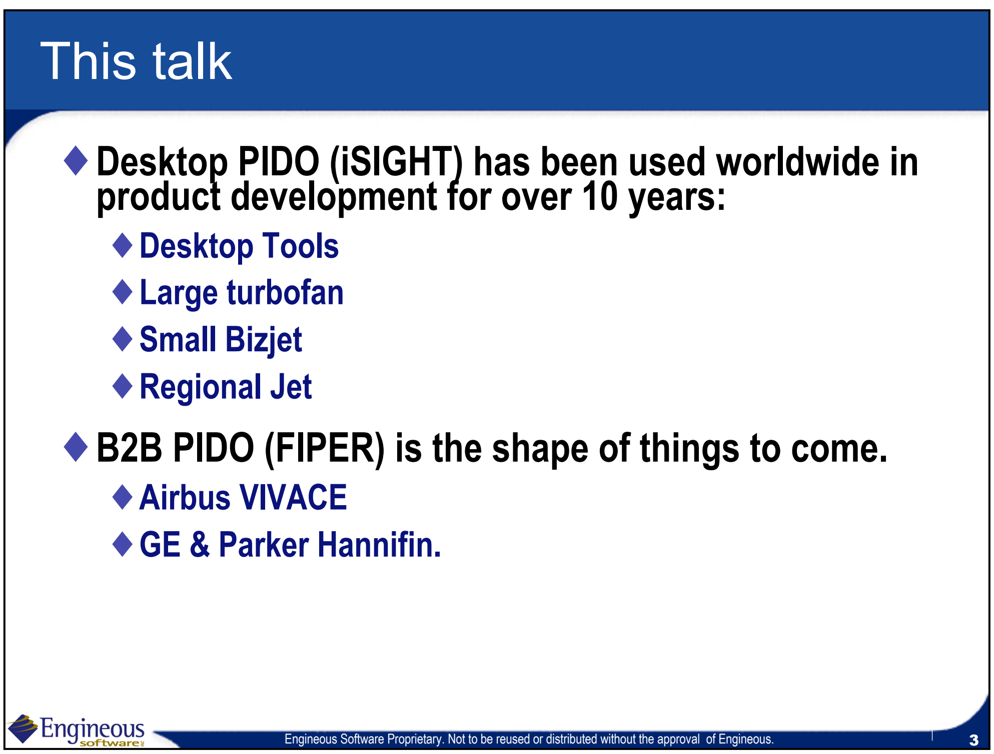
Form Follows Function and Physics: Simulation Based Optimization Drives the Shape of Tomorrow's Aerospace Products

Alex Van der Velden
Engineous Software
Atlanta, GA

In this talk we will discuss the application of commercial process integration and design optimization tools in aircraft design from small bizjets to large commercial airliners.

These tools allow us to generate aircraft designs directly based on economic and performance objectives as computed by high fidelity physics models.

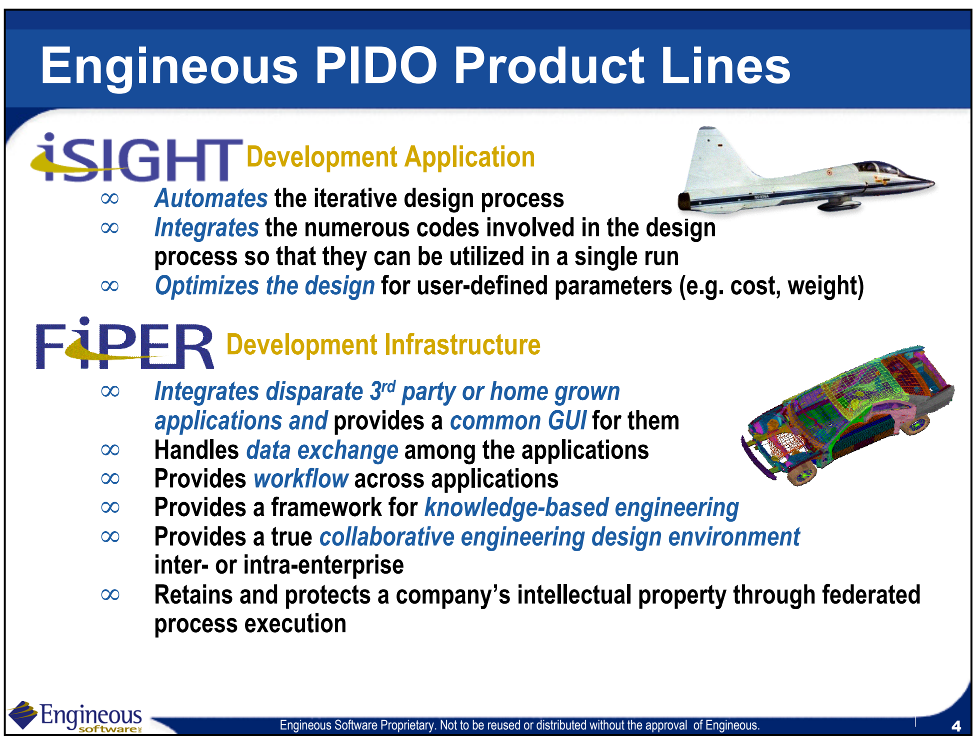
We will also take a look at the future, were integrated processes will be deployed across geographic and enterprise borders using the FIPER software.



Engineous Software has two commercial PIDO (Process Integration and Design Optimization) products:

iSIGHT executes simulation-based design processes, including commercial CAD/CAE software, internally developed programs, and Excel spreadsheets on the engineer's desktop & local network. It provides leading edge design exploration and optimization technology to ensure that an optimal design is discovered that meets or exceeds all customer requirements.

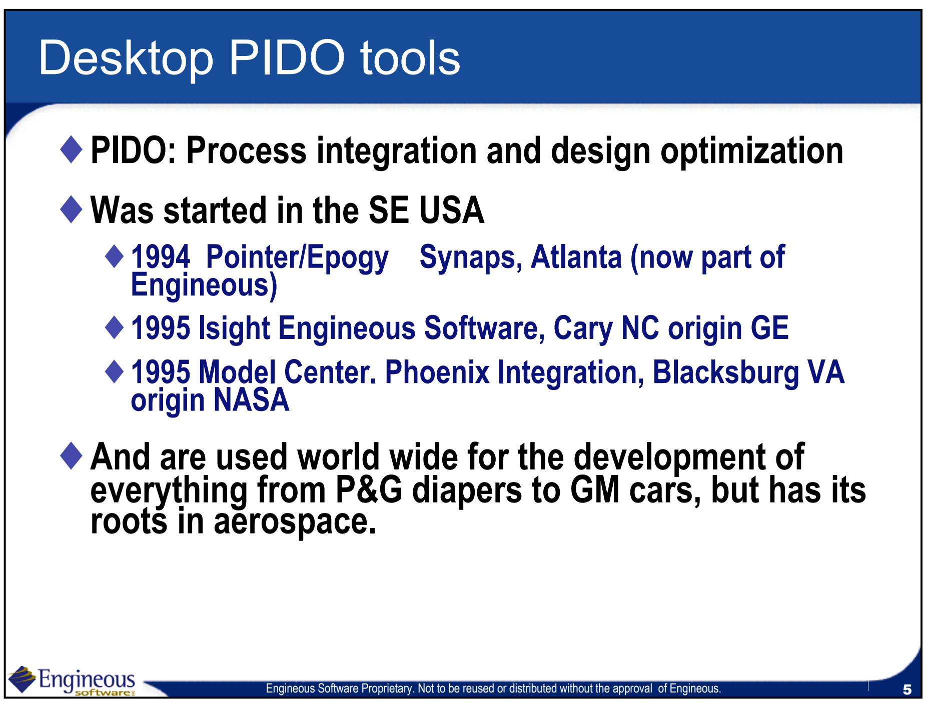
FIPER stands for "Federated Intelligent Product Environment". This allows the ability to share models between organizations, so partners can execute each others design processes in a geographically dispersed, secure mode, without exposing proprietary company data.



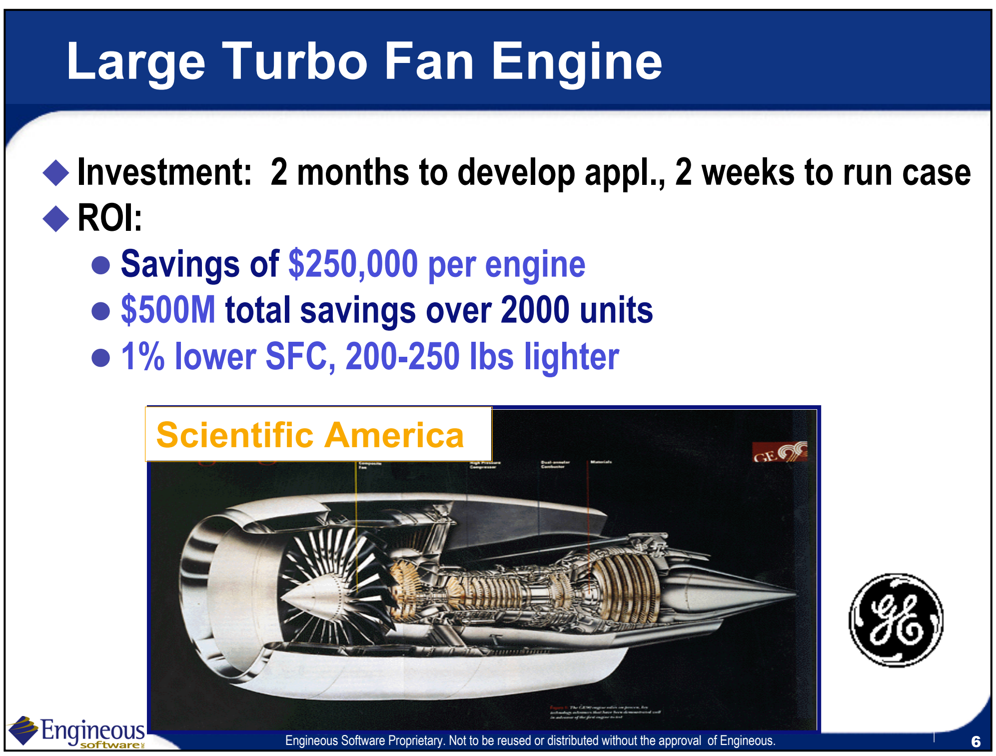
The PIDO software category was started by three company's in the South East United States in 1995. My own company Synaps, Inc. was started in Atlanta and originated out of the Airbus in Europe. Its product were Pointer and Epogy. Synaps was sold to Engineous software in January 2004 and currently Epogy and the Isight product are merged into one package. The examples that I will show in this presentation will be a mix or projects done by Synaps and Engineous Software. Engineous was founded in 1995 by Siu Tong and originated out of software developed at General Electric.

Phoenix Integration's Model Center software was founded by Brett Malone in Blacksburg VA and is mainly used at NASA and other government agencies.

Engineous Software is currently the market leader with over 50% market share, but currently there are a dozen software companies competing for this emerging market.



One of the first applications of Engineous Software (before it was commercialized) was on a large turbofan engine in 1991. Within two weeks the optimization of the turbine disks allowed one stage out of seven to be removed. Without the software this would not have been possible. This saved a quarter a million dollars per engine, reduced the sfc and made the engine 250 lbs lighter.

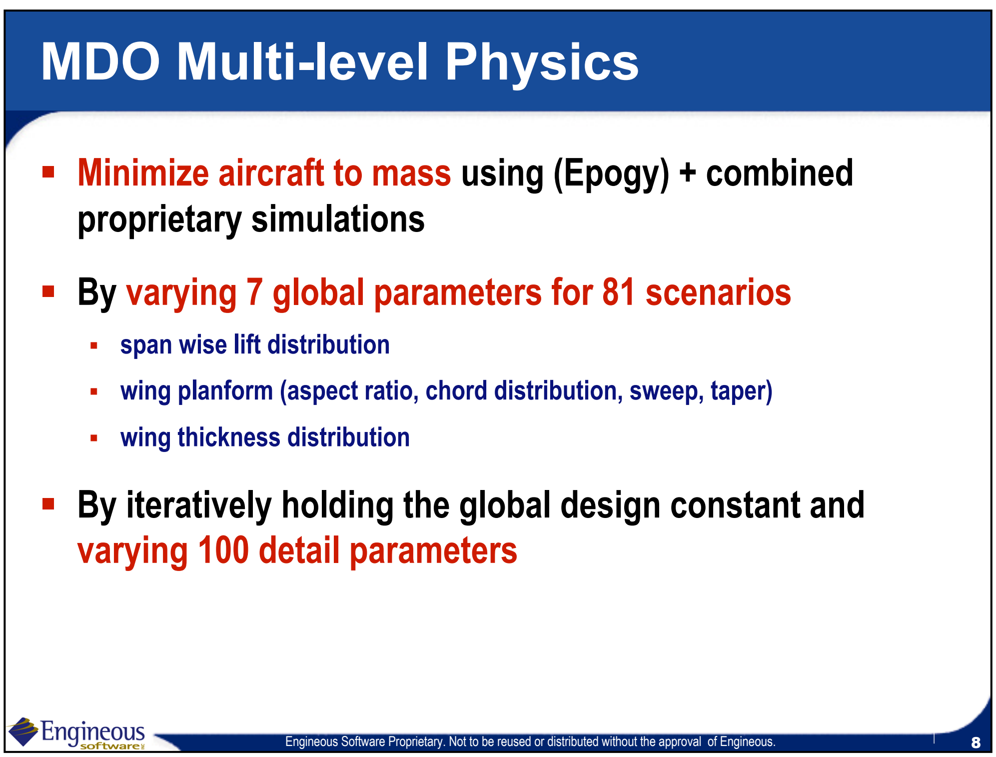


One the other side of the Atlantic Airbus used our software to support its very large transport aircraft development. (Aviation Week Feb 22, 1999) The software was developed & used over a 5 year period and created significant insight in how to reduce the weight of such a massive aircraft.

In this case the physics was modeled as carefully as possible using computational fluid dynamics and structural codes. The problem was to find the right exterior and interior shape in order for the wing structure + fuel to be minimal for the design range and payload.

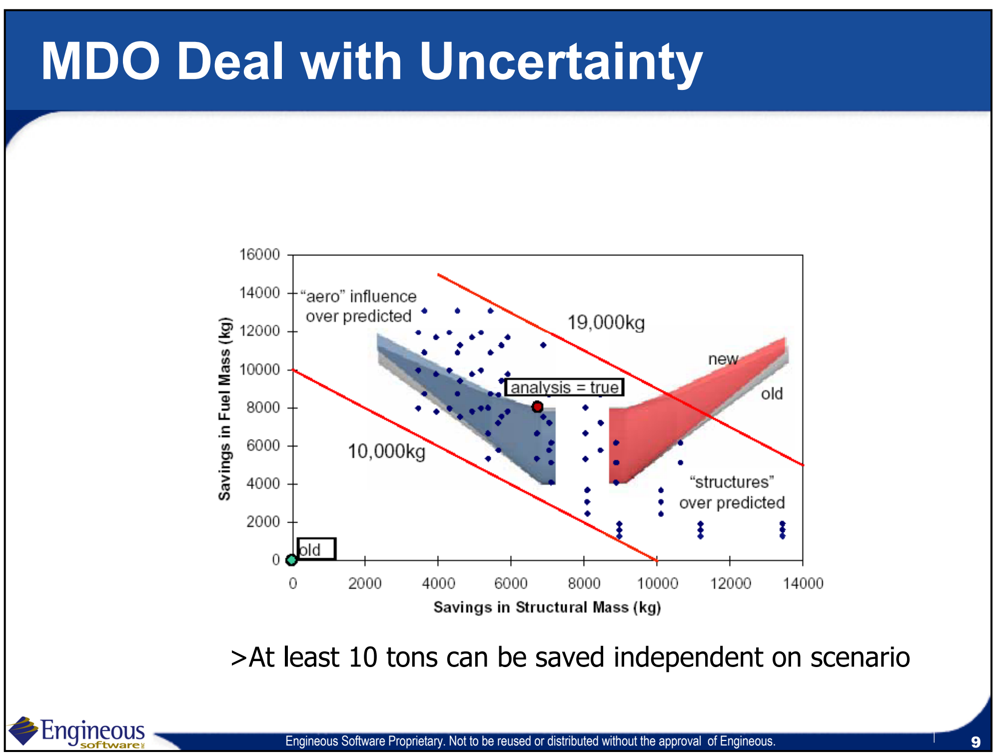
The design team faced a lot of uncertainties. For instance we did not know exactly what level of bias/error to expect from the computational codes. These expected biases were captured in 81 scenarios. Each scenario was considered equally likely. To goal was to find a solution that was good whatever the right scenario was.

7 top level design variables were selected to represent the wing planform, thickness and spanwise lift distribution. The spanwise lift distribution determined the structural optimization and we were therefore more or less able to decouple the structural and the aerodynamic optimization of the problem.

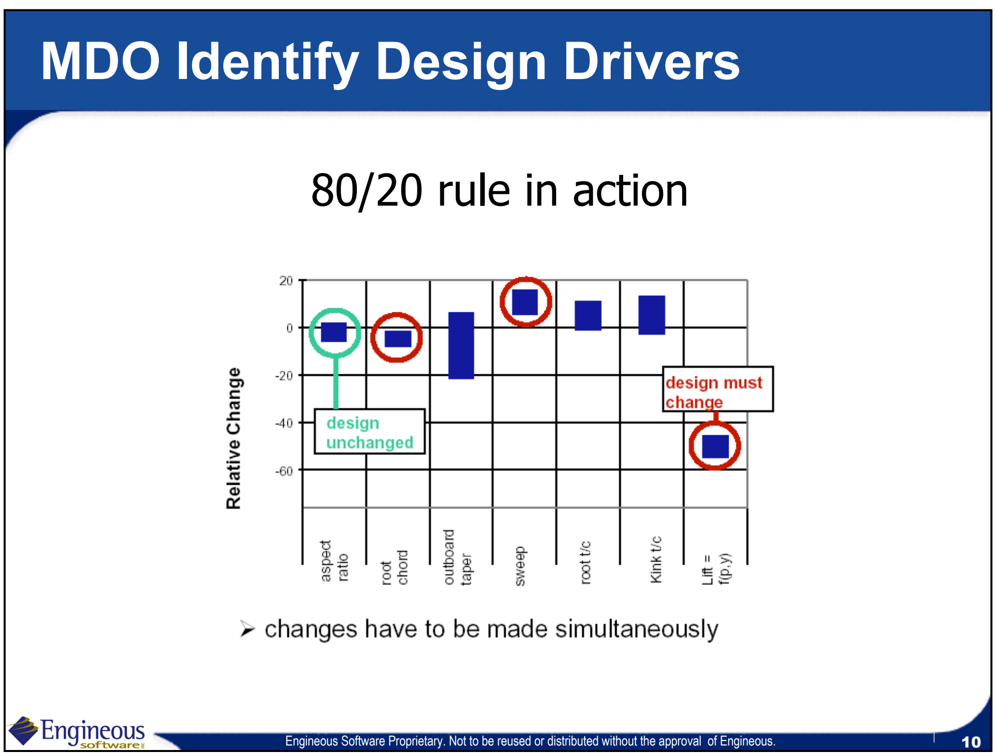


For each of the 81 scenarios the the multi-level optimization loop including detailed structures and aerodynamics was completed.

It was interesting that all of the solutions showed basically the same aspect ratio wing and that whatever we assumed it should be possible to save at least 10,000 kg.



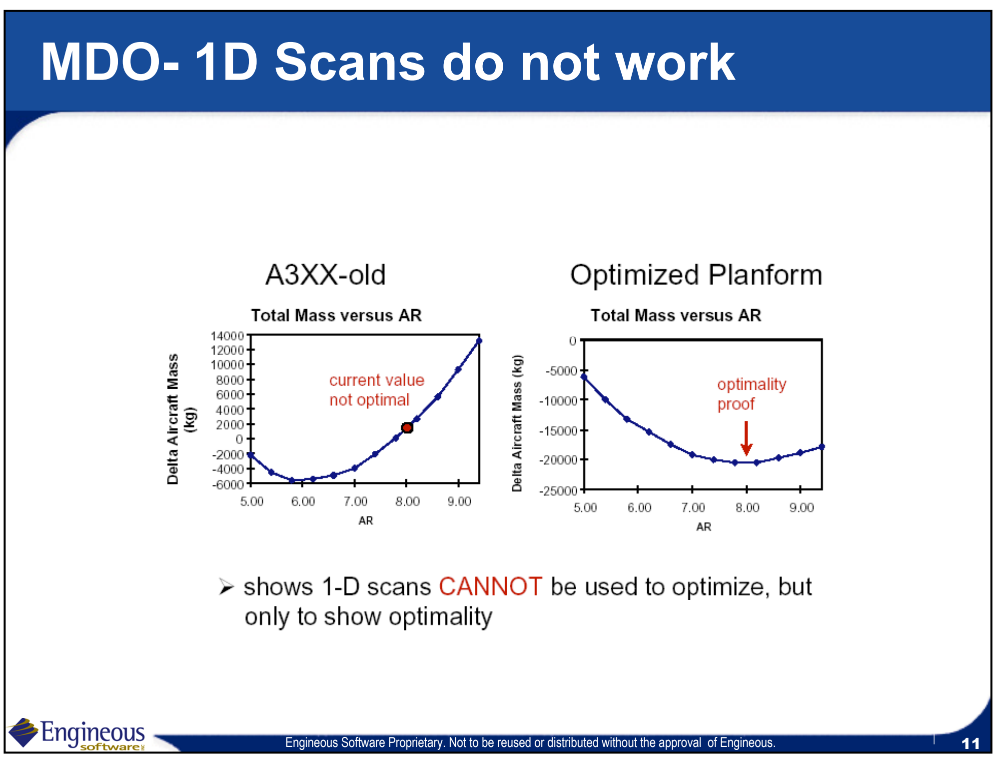
We were interested how the optimum of the top design variables was affected by the different scenarios and found that the aspect ratio of 8 was definitely the right answer. However, we also found that it was probably better to increase the sweep a few degrees and get a totally different non-elliptical wing loading.



This result was non-intuitive and cannot be obtained by sequential 1D scans of the design space.

For instance, starting from the baseline wing with aspect ratio 8 reducing the aspect ratio to 6.5 actually improves the max takeoff weight of the aircraft. The reason is that the baseline wing was rather thin and the structural benefits outweigh the increase in drag. If from that point I would do a scan varying thickness I would simply confirm that the current thickness was optimal…

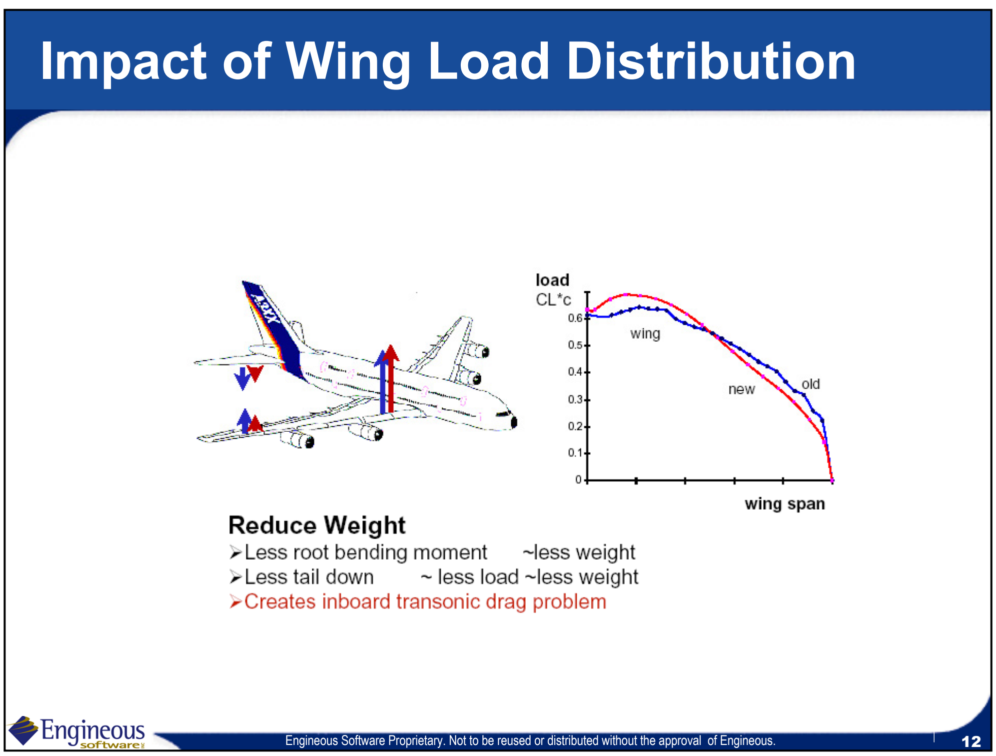
If I vary the aspect ratio of the optimized wing I can indeed show that it is in a local minimum. Showing local minima is a good application for 1D scans.



Years earlier Airbus had considered this as a possibility. The benefits of unloading the tips were numerous.

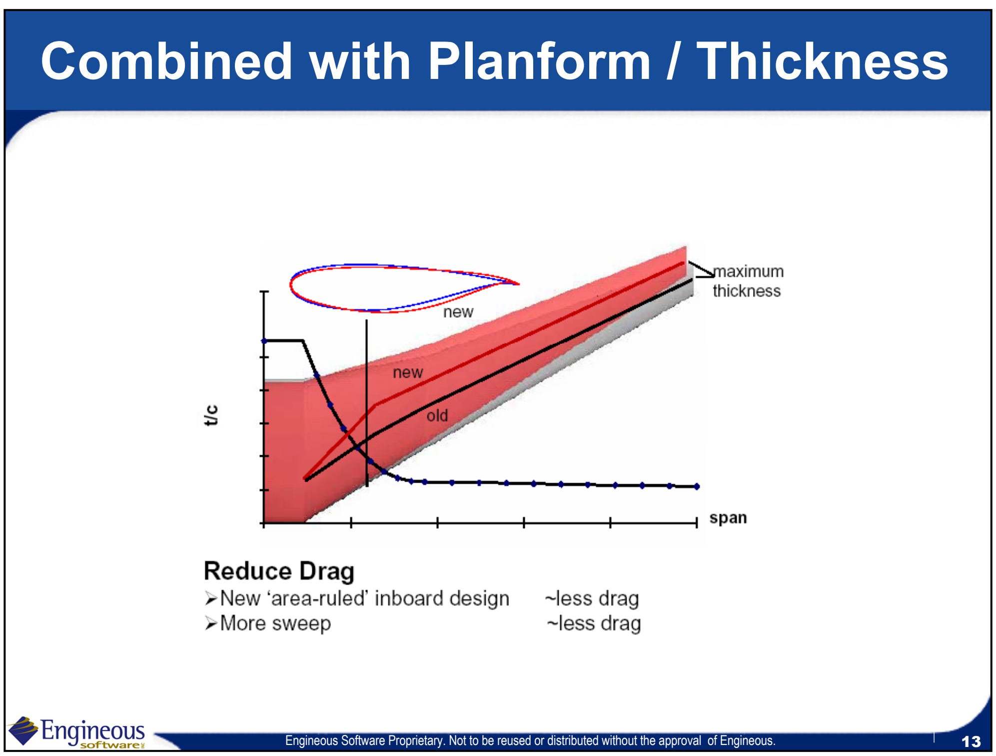
Less root bending moment created less wing structural weight and an nose up pitching moment that reduced the need for more tail down load (typical for statically stable aircraft). Less tail down of course requires less lift on the main wing for the same upwards force and thus we save not only drag, but also wing weight.

The real problem was the fact that in previous studies the increased inboard loads caused the transonic drag to rise to unacceptable levels.

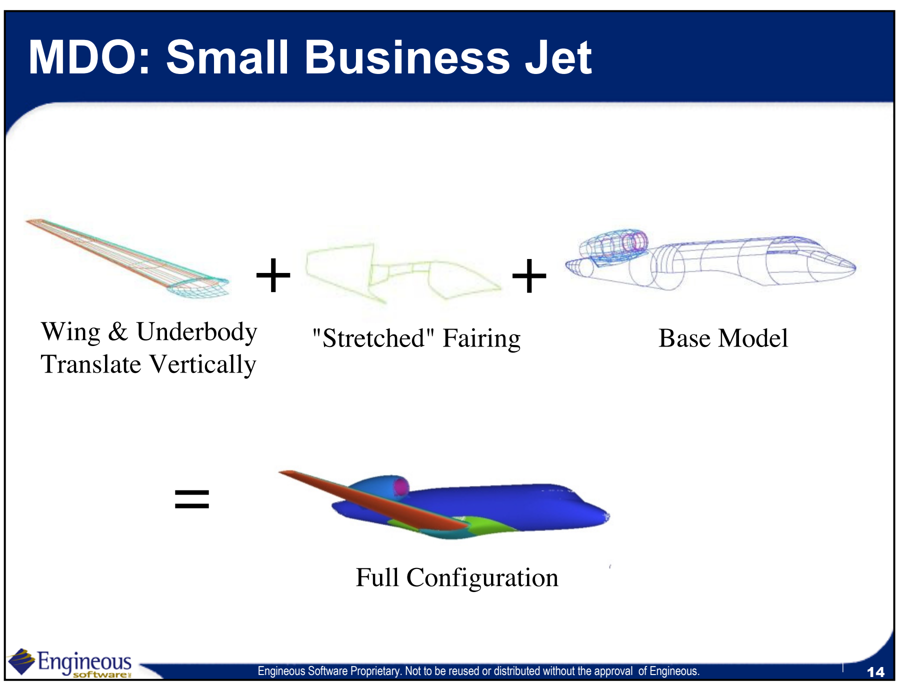


Not so here. This study showed that it was possible to increase the inboard loads without increasing the transonic drag.

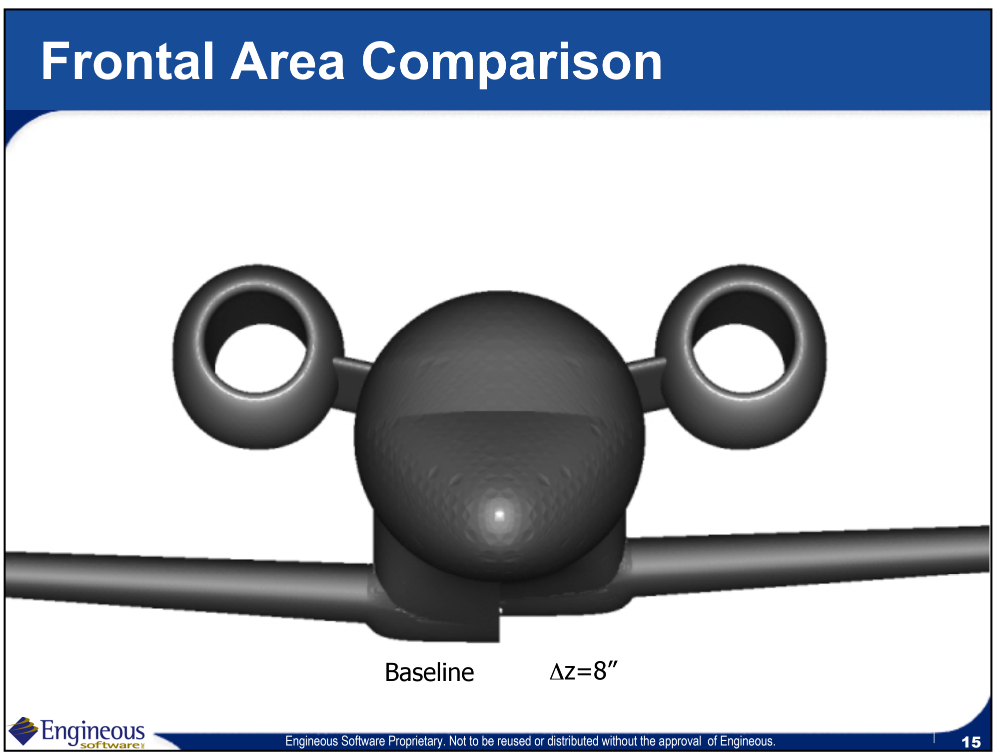
The detailed aerodynamic shape optimization had shifted the location of maximum thickness-to-chord further aft. In effect the maximum thickness iso-line was now more swept and the wave drag was reduced. Wing optimization put area-ruling in the wing whereas on the B747 it is done by putting the hump on the fuselage.



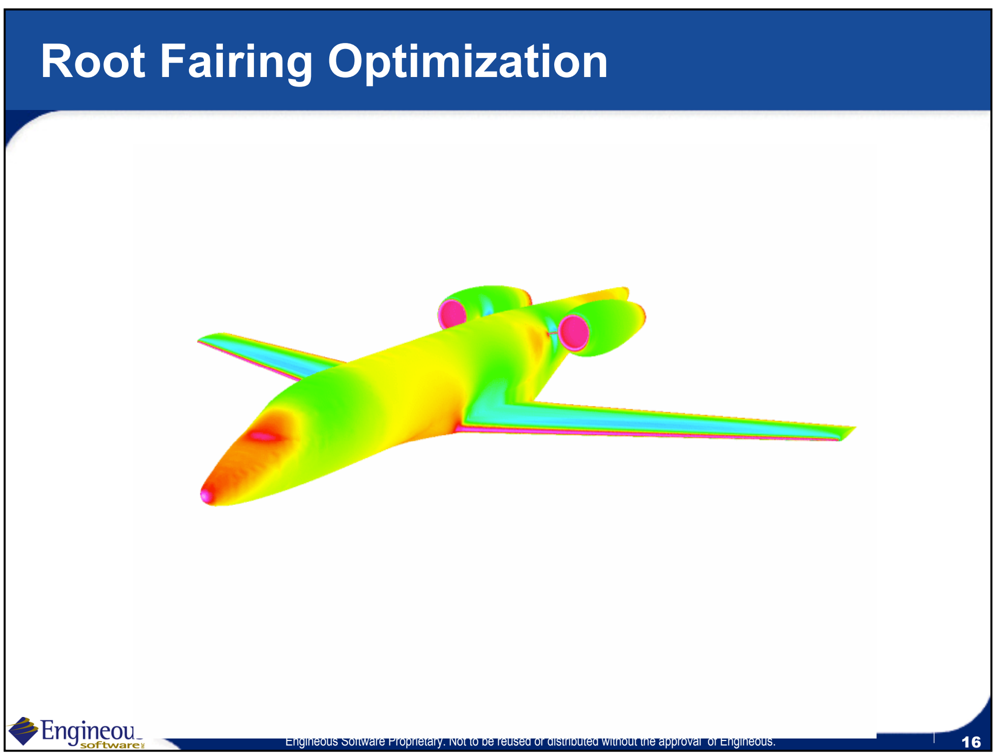
In recent years most aircraft builders have started to use PIDO software. As computer power is going up and CFD calculations are faster it is now possible to shape optimize CAD geometries directly with coupled commercial CAE tools.



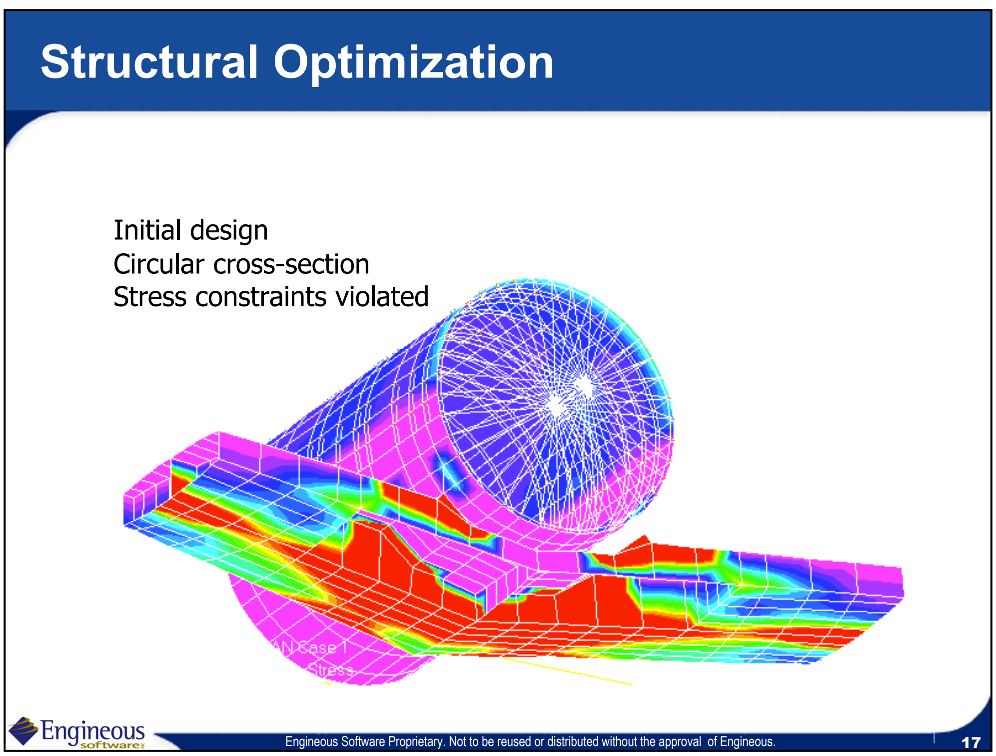
In one such application a well know business jet manufacturer was interested in the ‘best’ wing fuselage intersection design. For a given amount of aisle height we can attach a thick low weight wing center section with a large fairing or a thin wing center section with a small fairing. The fairing has both weight and drag. The picture above shows two fairings with extreme values of the fairing height.



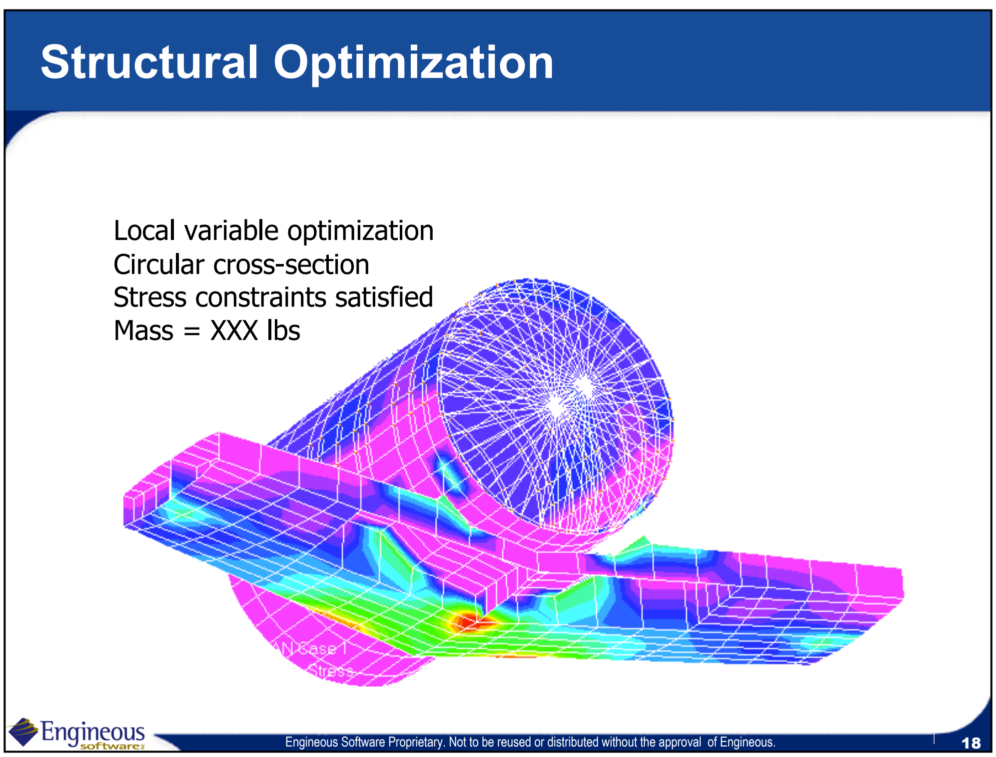
In this application the aerodynamic and structural problem were decoupled using the fairing height. For a given fairing height an optimal fairing was designed which produced a computed drag and which had a known weight.



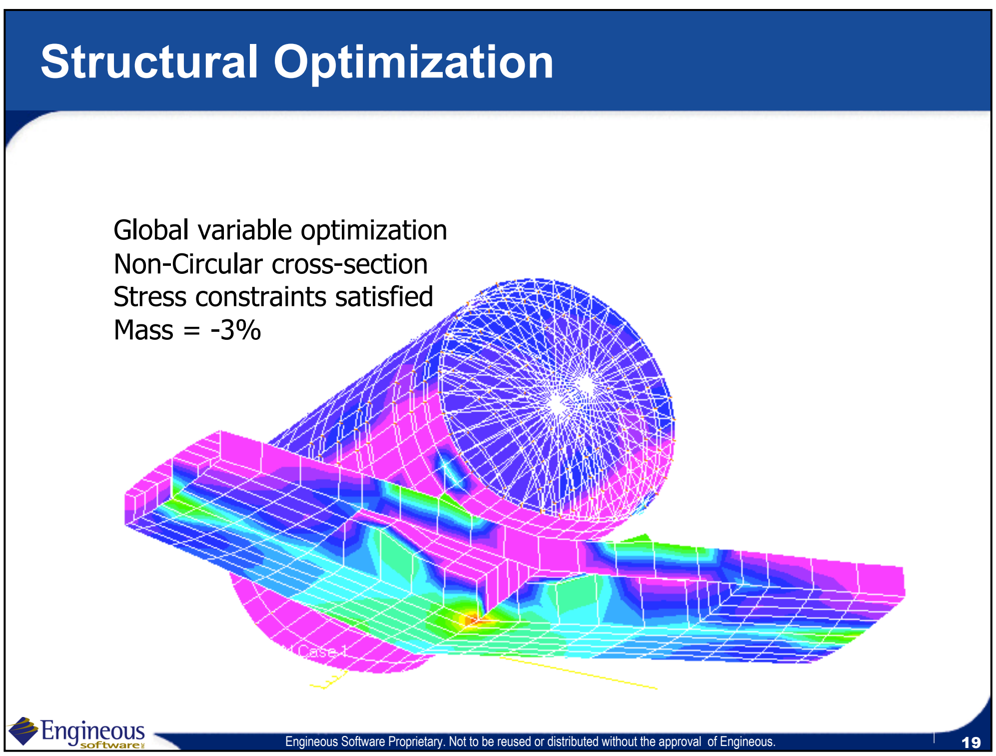
For a given fairing exterior height we still had the option of having a low center section beam and a circular fuselage center section and a tall center section beam and a non-circular center section. In one case the fuselage was light and the center section wing was heavy and in the other case it was the other way around.



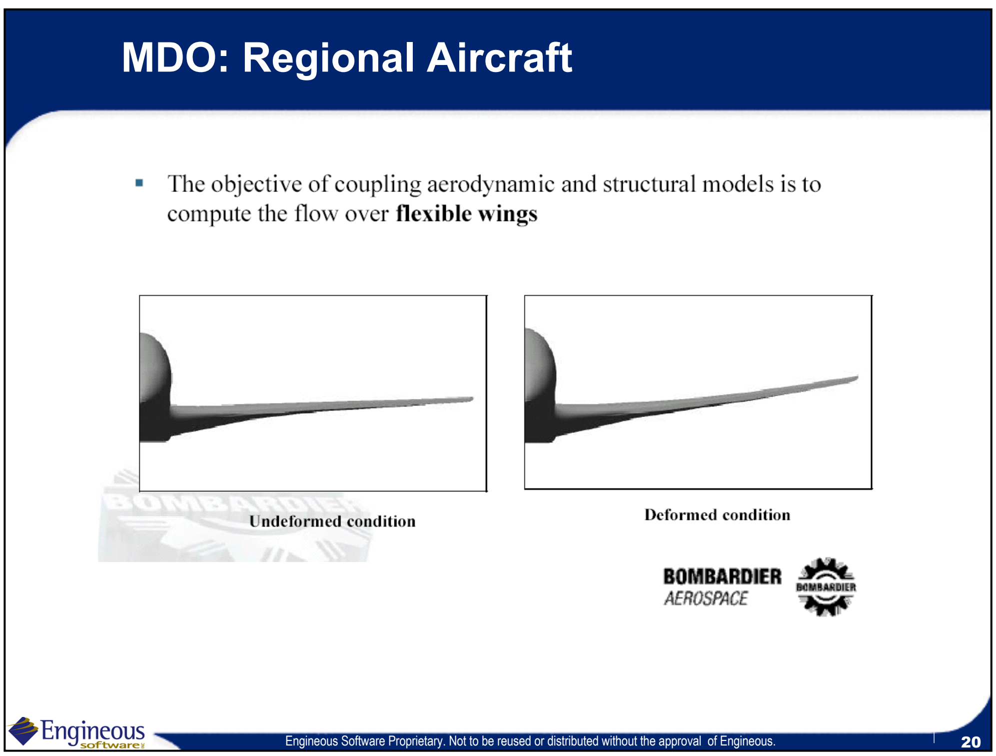
The structural optimization had two steps. The optimum fuselage non-circularity and beam height were computed for an optimal structure. The optimal structure was calculated by optimizing the thickness of the structural elements for minimum weight for dozens of fatigue load cases.



In the end the optimum overall shape was somewhere in the middle and it was some 3% lighter than the baseline configuration.

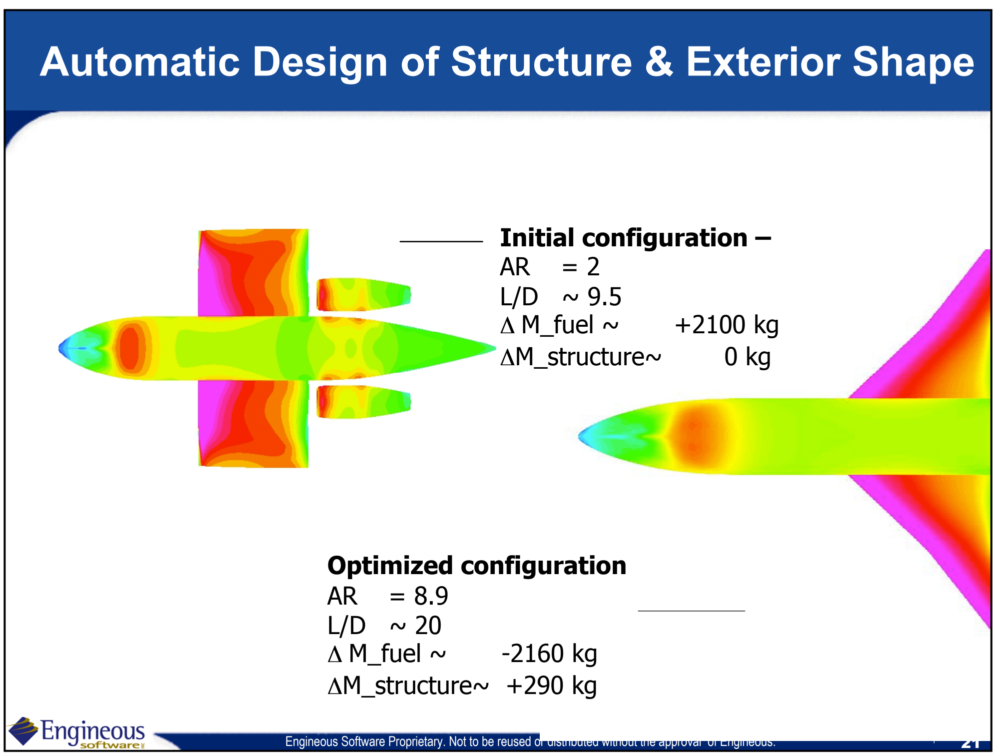


The Bombardier company of Canada has pushed the envelope even further with our help. They directly optimize internal structures, aeroelastics, wing profile and planform shape for optimal aircraft performance and economy. (Daratech Aero 2003)



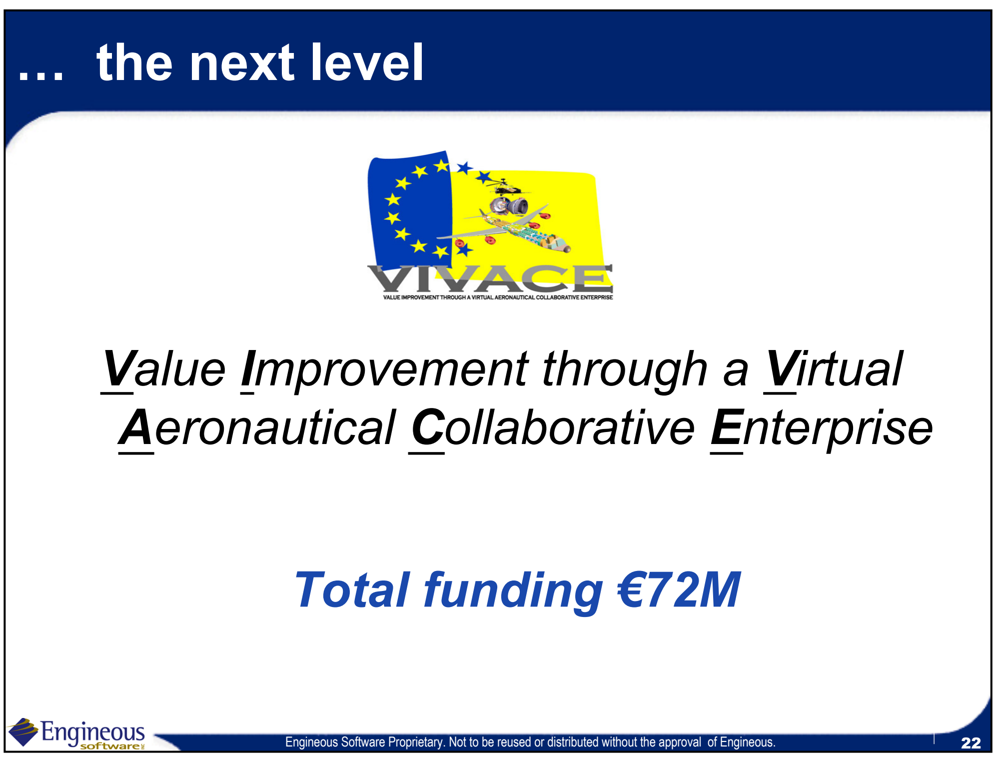
This shows that it was possible to start with a rectangular wing of aspect ratio 2 and optimize it to a very high performance wing with sweep. It must be noted that all of this required a new NEC supercomputer and thousands of iterations.

This study showed that higher wing sweeps than employed conventionally may be better for regional aircraft.



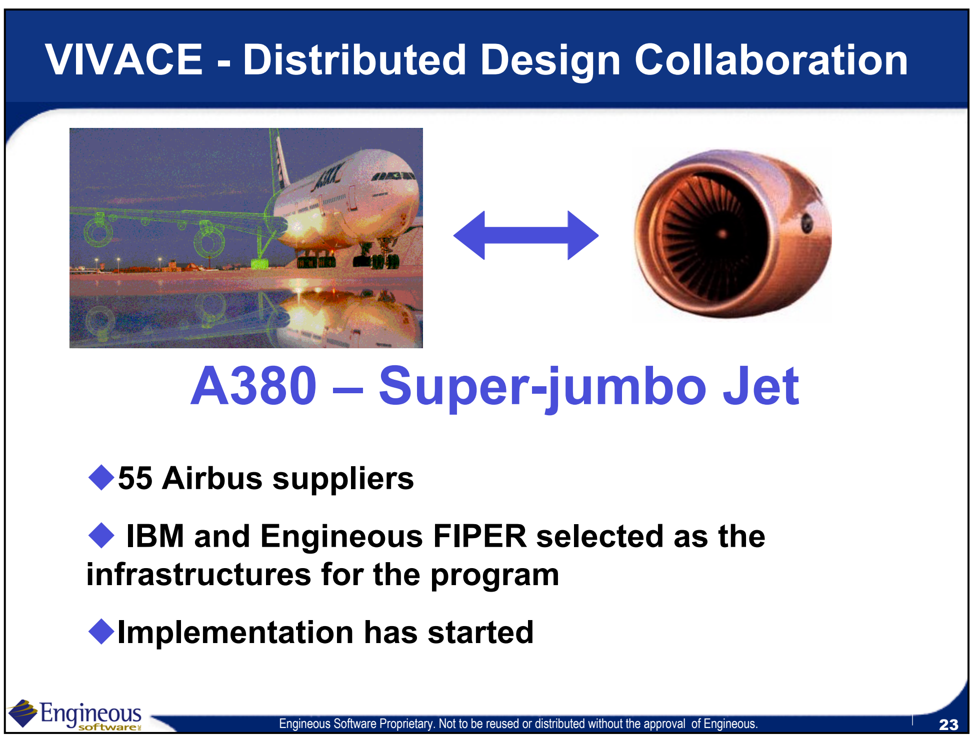
Today the question is no longer “will it work for our application”, but more “will it work for our enterprise.”

The scalability of PIDO software solutions is at the core of Airbus’ VIVACE program.

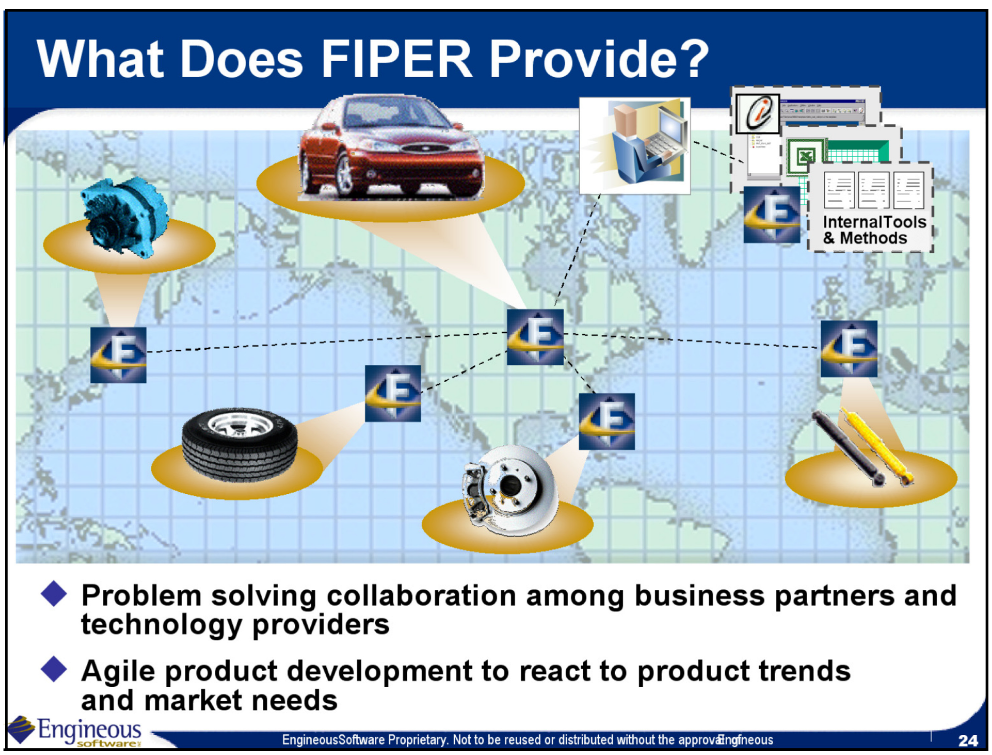


The VIVACE program ties together Airbus with its suppliers. One of them is GE. The same engine core that is used on the GE-90 is planned to fly on the A380.

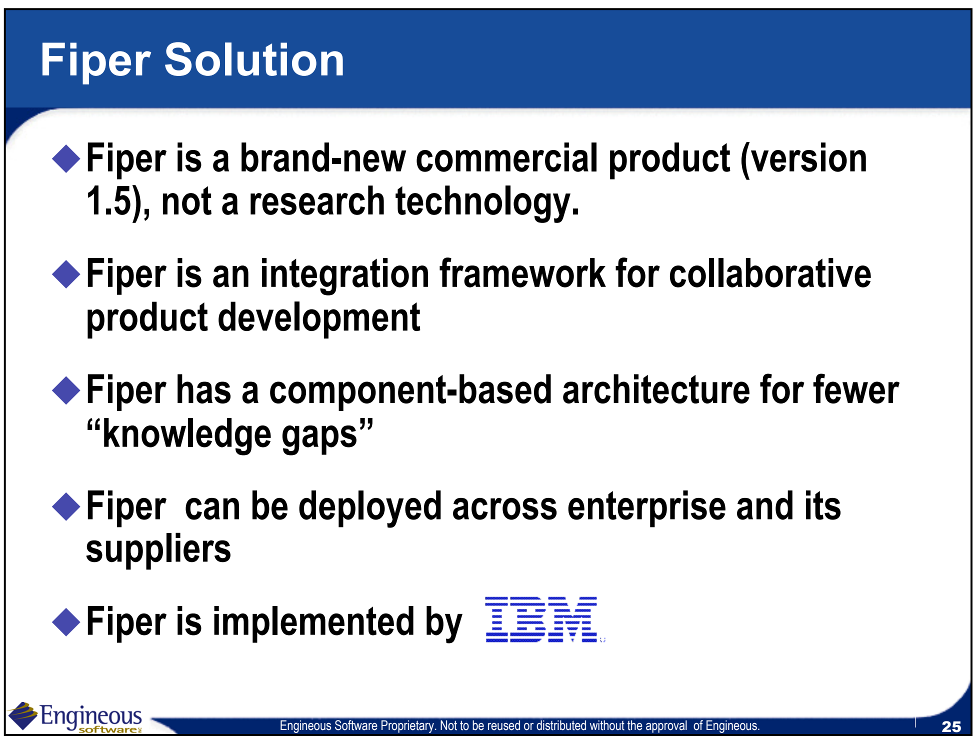
IBM and Engineous were selected as infrastructures partners for this program. The reason for Airbus to select Engineous is its new FIPER software.



FIPER allows you to deploy integrated processes across geographic and enterprise borders. This allows partners to share models securely without exposing each others proprietary company data.



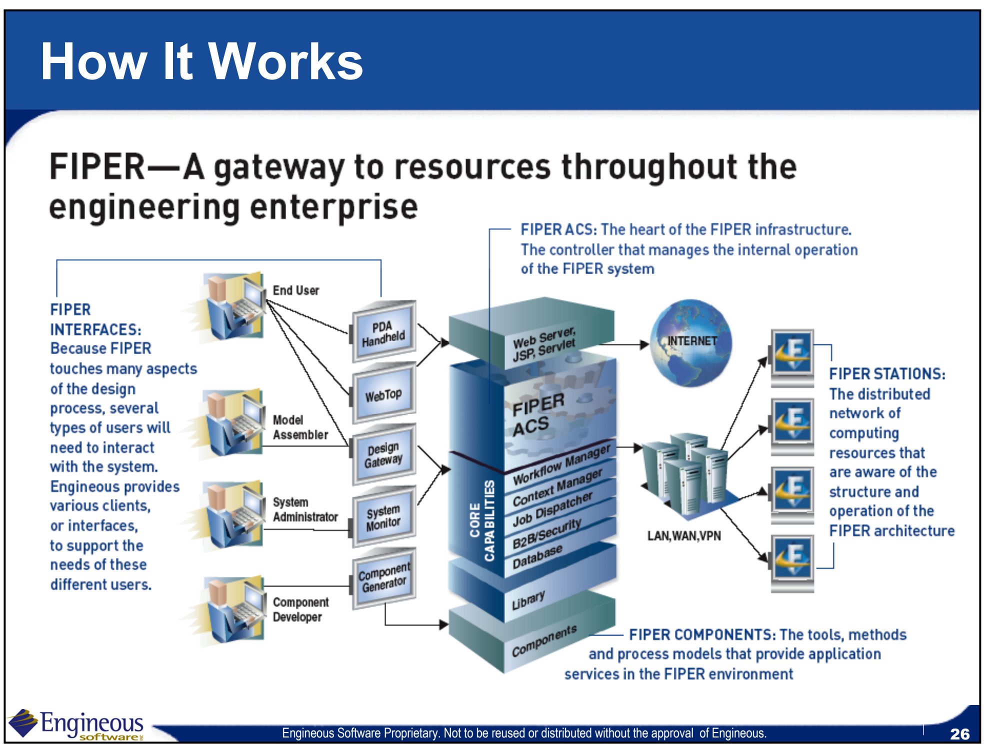
FIPER is process integration at an enterprise level and intra-enterprise level. The component based java architecture reduces the number of “knowledge gaps” which allow the components to be reusable by people other than the original author. This software also requires middleware (such as web sphere) and is not intended for the engineers’ desktop. Engineous has teamed up with IBM in order to implement FIPER solutions.



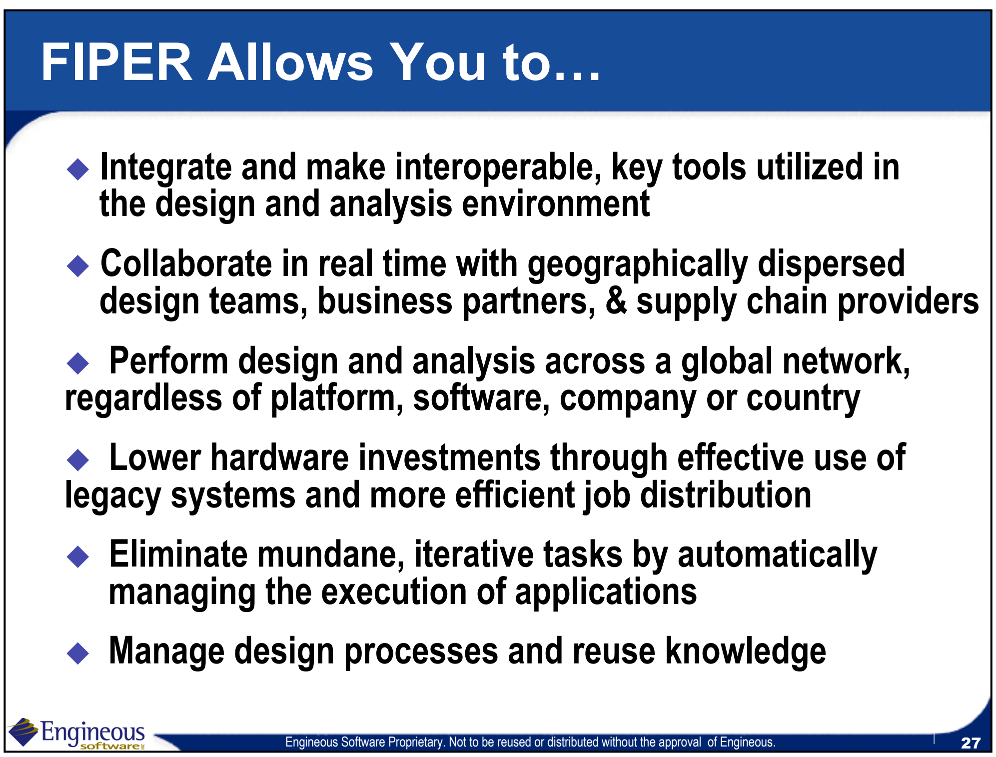
Because FIPER touches many aspects of the design process, several types of users need to interact with the system using various clients. Users include systems administrators using the system monitor , component developers using the component generator and the model assembler using the design gateway. The end user will interface through a web top or the design gateway.

The FIPER ACS is the heart of the FIPER infrastructure. It is the controller that manages the internal operations of the system.

Finally FIPER stations are the distributed network of computing resources that are aware of the structure and operation of the FIPER architecture.

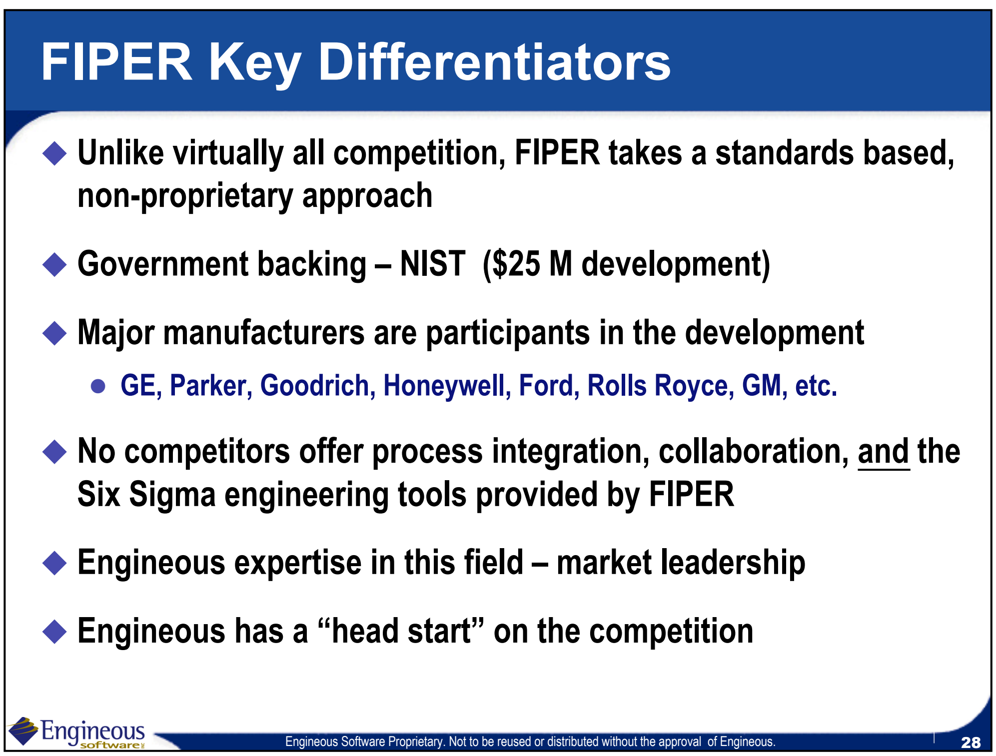


FIPER allows you to integrated and make interoperable the tools that are utilized in the design and analysis environment. It allows you to collaborate with geographically dispersed team members, business partners and supply chain providers. It allows you to perform design and analysis across a global network regardless of platform, software, company or country.



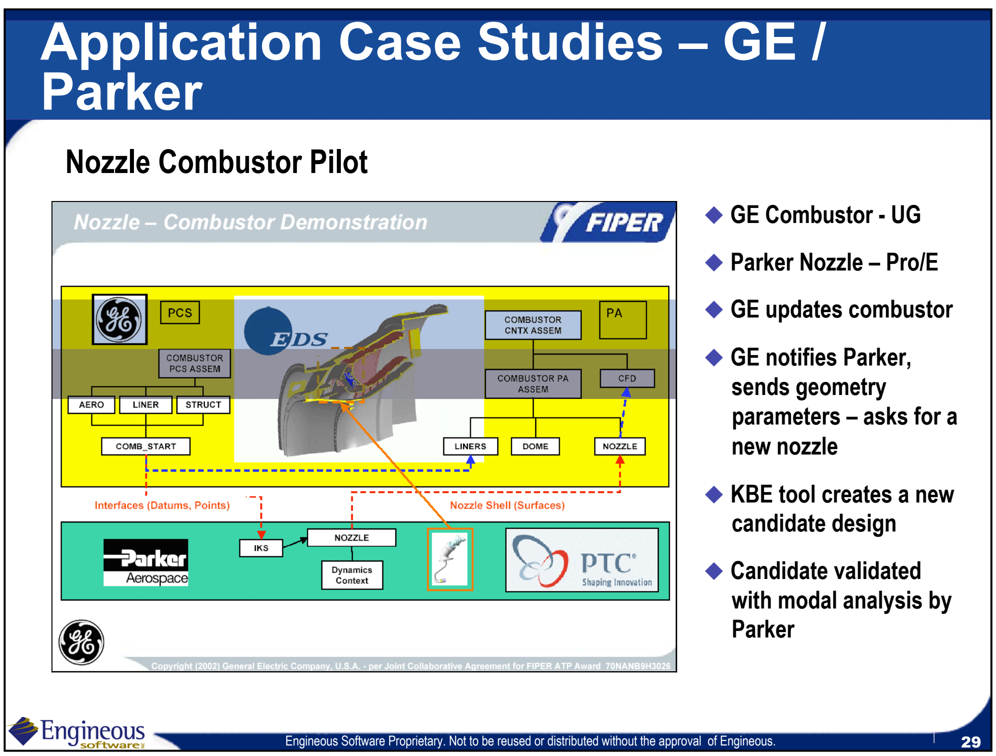
FIPER takes a standards based no-proprietary approach. It was developed by government backing from the National Institute of Standards during a $25,000,000 development program. Major manufacturers such as GE and Honeywell participated in the development.

FIPER is a next generation tool for the next generation of aerospace products.



About a dozen pilot programs are already completed with the FIPER architecture. In this example GE has modeled the combustor of a jet engine with Unigraphics CAD software. Parker models its nozzle using the ProE CAD software.

When GE modifies its combustor, the FIPER system automatically asks Parker for a modified nozzle. Based on the changed requirements, Parker generates a new nozzle design using a knowledge based engineering tool. A modal analysis of the nozzle is then performed to validate the design.



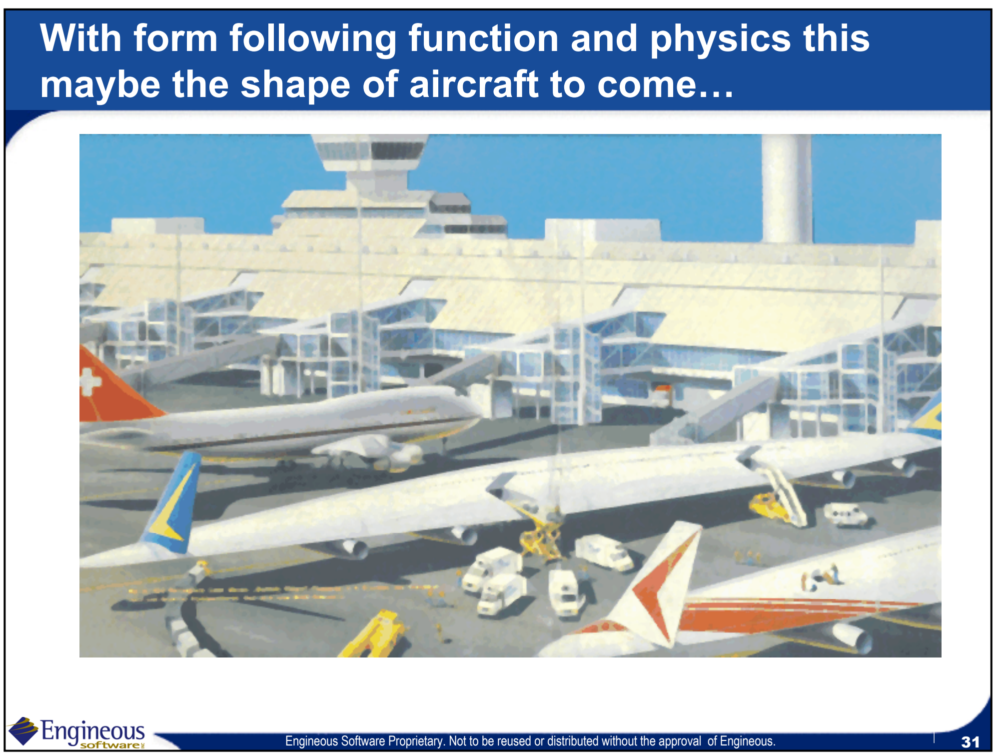
Summary

- Process Improvement is the "Final Frontier" in cost reduction, profit improvement
- Many companies have taken initial steps in this direction, but have not gone the distance
- iSIGHT, with more than 200 companies using it, has a proven track record in this area
- FIPER is far ahead of the competition in addressing this urgent business requirement

Today High fidelity analysis integrated with PIDO tools, such as iSIGHT allows the assessment of radically new aircraft shapes.

FIPER makes it possible for aircraft manufactures to share the aircraft design processes (and its associated risk) with many partners.

These developments of reduction of risk through better analysis and spreading of risk through partnerships may allow us to develop a next-generation of higher-performing non-conventional aircraft such as the oblique flying wing.



Formalizing Conceptual Design

William Wood
Department of Mechanical Engineering
University of Maryland
Baltimore, MD

Formalizing Conceptual Design

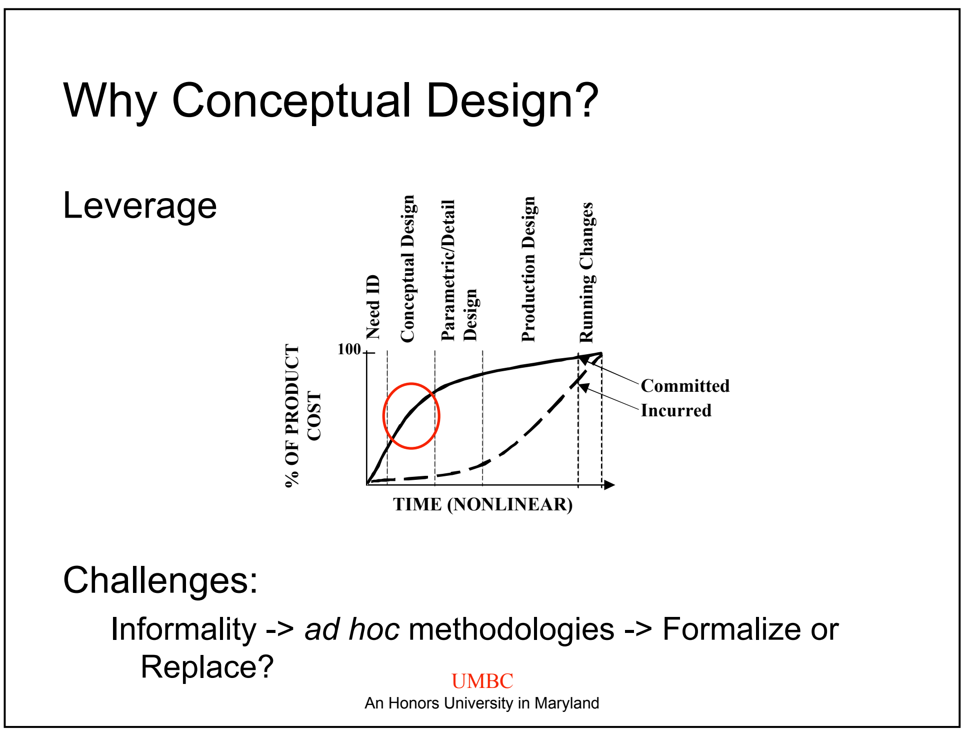
Because of its influence on all downstream processes, conceptual design is a critical part of the design process. The informal nature of information in conceptual design provides distinct challenges for formalization. This presentation introduces a view of conceptual design based in both descriptive research (what designers *actually* do) and prescriptive research (what, in a rational world, designers *should* do). This leads to a framework for design built around recognizing uncertainty in the requirements for the design and selectively reducing this uncertainty as design alternatives are initiated, developed and selected.

The techniques presented include methods for modeling the design/requirement 'space'; developments of normative decision theory both for formalizing the selection of design alternatives and the refinement of design requirements to support this selection; and the adaptation of methods form communication theory to provide rich measures of the 'size' of a design space. Together, these techniques provide a framework for formalizing conceptual design that embraces the uncertainty and informality inherent to the process.

Why Conceptual Design?

Conceptual design takes place in the earliest stages of the design process, but commitments made here extend far down the product development path. At the same time, conceptual design is not a particularly costly exercise. For example, changing concepts to improve manufacturability may save more in the production design/implementation stage than the entire cost of conceptual design. Anecdotally, conceptual design is largely responsible for the success or failure of a project.

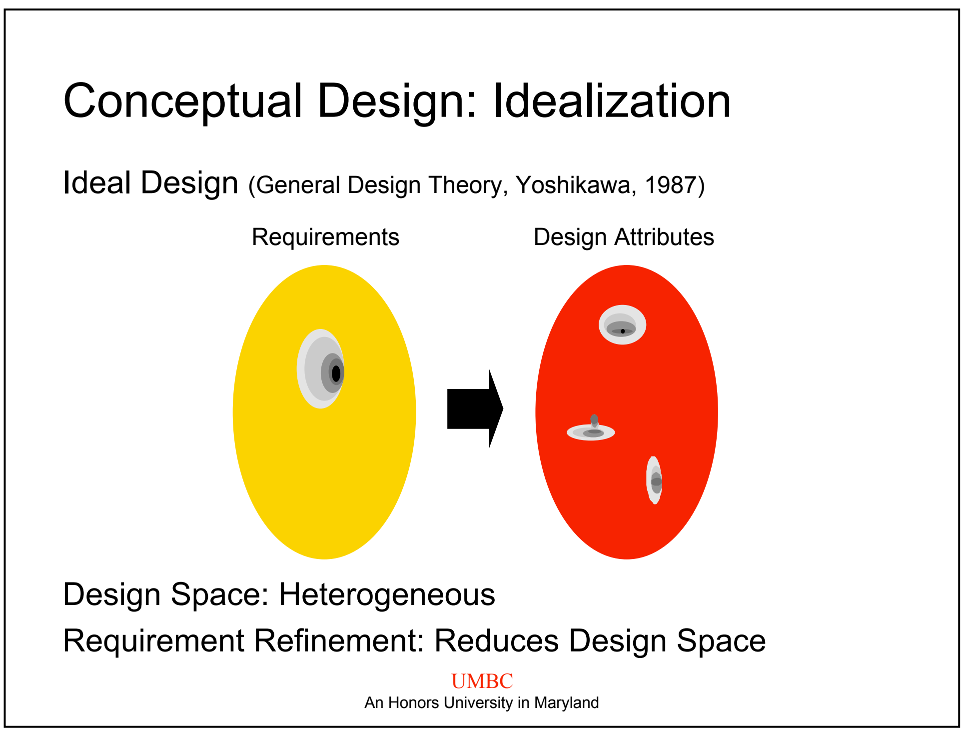
But although conceptual design has the greatest leverage in the design process, its informality tends to thwart our efforts at using this leverage. Most conceptual design methodologies are *ad hoc*, developed based on tradition or experience. The question for design researchers is whether the best of the *ad hoc* methods should be formalized, or whether the lot of them should be replaced by more normative methods.



Conceptual Design: Idealization

From a global process viewpoint, design is the process of finding an arrangement of components to satisfy a set of requirements. In evaluating theories for design, Yoshikawa suggests an ideal design process: all 'design' is done on the requirements side; a design 'oracle' automatically maps these requirements into possible designs implied by a given set of requirements. 'Loose' requirements imply many design solutions. Designers might choose one of these, or they might restrict the requirements further toward generating better design performance. As the requirements are refined, the design oracle automatically shrinks the size of the design space. This continues until the requirements imply a single design solution – further requirement refinement would produce no solution.

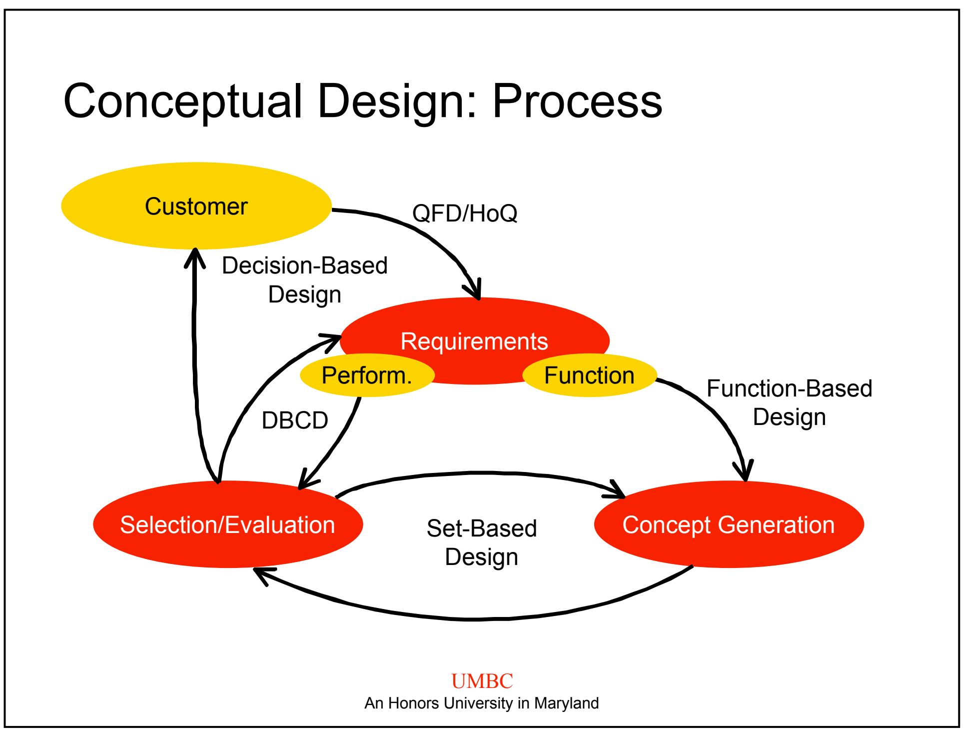
Of note in this process is that the design space implied by a requirement is heterogeneous – multiple types of design can often meet the same requirements. As the requirements are refined, the design space becomes less heterogeneous – only one type of design will end up being chosen. If refinement does not produce a single design, the designer has 'left some money on the table' in terms of design optimality.



Conceptual Design: Process

The process of conceptual design begins with the customer. Methods such as QFD and the House of Quality are typically used to translate customer needs into engineering requirements. Requirements themselves come in two main forms: functional requirements that specify what a design must do and performance requirements that measure how well it accomplishes this function. Functional requirements provide the impetus for concept generation; formal 'German-school' function-based design proceeds from a formal decomposition of the system. Evaluation of the generated designs is done according to performance specifications. The results of both processes are fed back into the requirement process: if no clear decision can be made among alternatives there are two basic paths – reduce uncertainty in the requirements or reduce ambiguity of the designs. The former requires refining performance requirements, the latter functional requirements.

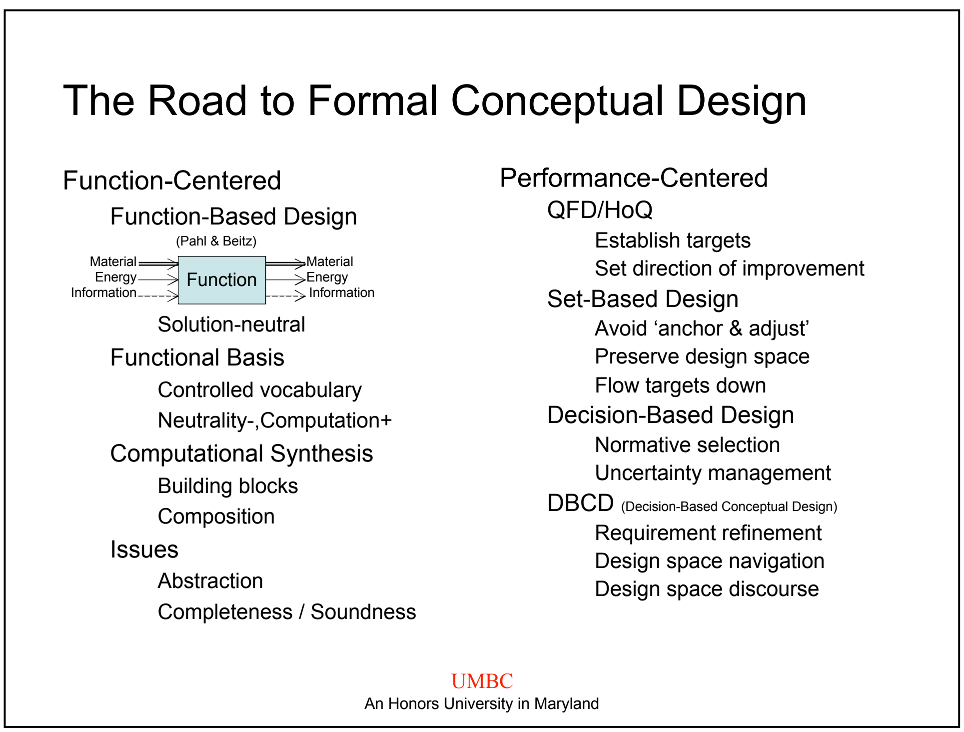
Of note in this process are a couple of normative methods for design. Set-Based design describes the Toyota design process in which requirement refinement is purposely withheld from the designers, forcing them to maintain a greater number of possible designs. Decision-based design has focused on the application of normative methods from decision theory, primarily in the performance requirement/design selection loop. Decision-Based Conceptual Design merges these two methods, promoting initial requirement ambiguity while providing decision-based means for determining paths toward refining requirements in the context of design selection.



The Road to Formal Conceptual Design

Formalization of the process of conceptual design can operate on either of the two paths stemming from requirements. On the function side, some formalization has already been suggested in the systematic design process of Pahl and Beitz. This provides a framework for treating function as the transformation of material, energy, and/or information. Others have developed basis languages for use in this framework toward making it more computable. Some have extended this work further toward automated design generation based on case experience derived from reverse engineering existing products. The main issues in this final step revolve around the abstraction level at which function is treated as well as the completeness and soundness of the synthesized designs.

From performance requirements, QFD provides a basic input to the process in the form of design metrics, directions for improvement for each metric, and a set of targets for the collection of attributes. Set-based design operates over uncertain targets, flowing them down into subsystem design with increased uncertainty to ensure full design space exploration. Rather than using uncertain targets, decision-based design generates a value function that can be used to evaluate uncertain design outcomes. Decision-based conceptual design (DBCD) works in both modes, evaluating the effect of refining requirements in the context of deciding among design alternatives at various levels of abstraction.



Complex Systems

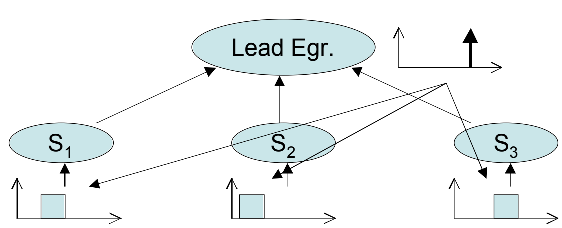
Coupling is what makes systems complex: requirements are coupled to each other within the design space and subsystems are coupled to each other through functional interactions. Descriptive of Toyota's design processes, set-based design provides a means for managing complex design processes by propagating uncertain requirements into the subsystem level and using the design space generated by subsystem designers to get a realistic picture of complex interactions. The options generated at the subsystem level are then evaluated by a lead engineer who decides where and by how much the uncertainty in the requirements is reduced.

Complex Systems

Coupling:

- Requirements
  - Overall requirements passed down to subsystem level
- Function
  - Subsystems interact with each other

Set-Based Design (Toyota - descriptive/Ward et al. – prescriptive)



UMBC
An Honors University in Maryland

Set-Based Design

In set-based design, subsystem designers are required to develop design solutions that cover a range of potential requirements. Uncertainty about performance targets prompts designers to study the many possible tradeoffs among competing design objectives. Set based design is controlled by a powerful lead engineer who moves the process forward by selectively reducing requirement uncertainty. Where uncertainty greatly influences cost (or lead time or quality, etc.), it is reduced; decisions within subsystems whose performance is less sensitive to requirement uncertainty are delayed.

Ward et al. have developed prescriptive methods for set-based design, focusing on the propagation of uncertainty from requirement to design space. While these methodologies provide a theoretical basis for set-based design, their implementation through interval calculus methods fails to capture the richness of uncertainty propagation. Too often, the design space implodes based on small changes in requirements. We propose an implementation based on probabilistic modeling to propagate uncertainty more accurately from requirement to design space.

Set-Based Design

Subsystem Input
- Uncertain Targets
- Functional Requirements

Subsystem Output
- Set of designs

Control
- Successive refinement of targets
  - Include ‘stretch’ as part of initial uncertainty
  - Refinement = Selection
- Manage design space size

Methodology
- Combine design/requirement modeling space
- Formalize selection/refinement process
- Measure ‘size’ of design space

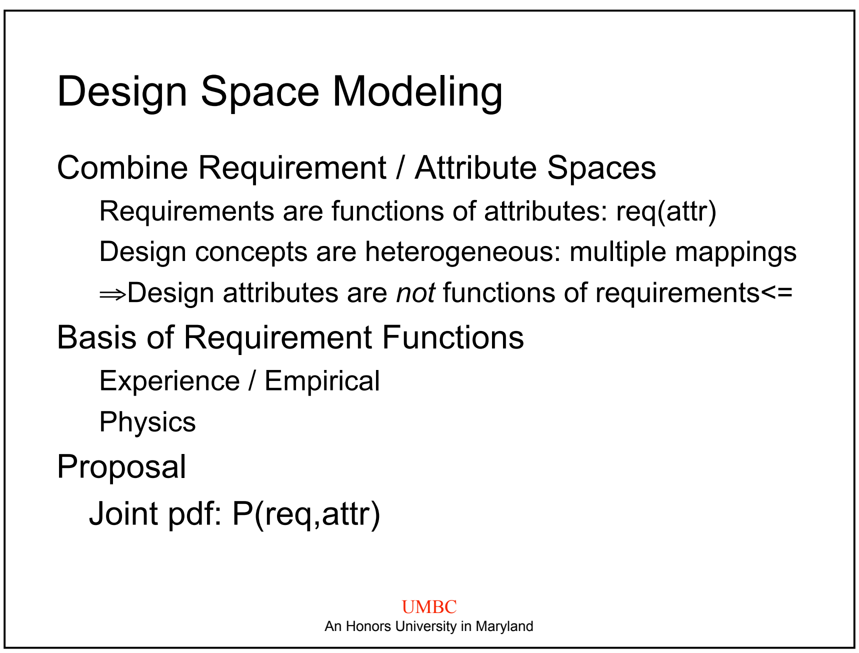
UMBC
An Honors University in Maryland

Design Space Modeling

Building on Yoshikawa's ideal design model and the methodology of set-based design, representing the design space is at the heart of decision-based conceptual design. In typical design situations, requirements are evaluated using function of design attributes. But as demonstrated earlier, the design space contains distinct concepts, heterogeneous both in their detailed description and in the function used to generate design evaluations. The intuitively obvious result is that we cannot merely invert the design-> requirement mapping to generate new designs because the inverse mappings are *not* functions.

In addition, the functions that map from design to requirement may be derived from physical first principles, in which case the functions are generally well-defined, or those functions might be derived from experience, in which case the function represent approximations of mappings. Design space models must respond to both modeling sources.

To combine analytical and experiential, and to provide inverse mappings from requirement to design attribute, DBCD uses a single joint probability density function to model both requirement and design attribute spaces.



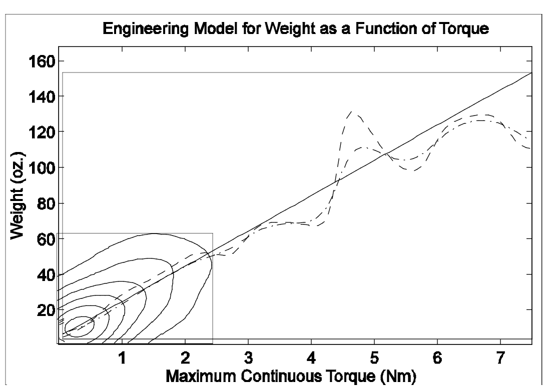
Example: Motors

The equation below assembles a joint pdf from multidimensional samples of the design space. A Normal density function is drawn around each design space sample; the sum of these individual pdfs generates the overall probability density function. The figure below shows the joint pdf of motor weight and output torque for a set of dc electric motors drawn from a catalog. Compared to the single regression line typical of other modeling methods, DBCD operates over the joint pdf, capturing the underlying uncertainty of the heterogeneous data points. The contours show that most mostors form the catalog are relatively low mass/low torque motors. They also indicate a wide spread in the possible underlying relationship between the two. Dashed lines show the expected value of weight conditioned on torque. Both show a trend consistent with the regression in areas where there is a lot of data, although no predefined functional relationship is required to bias the result. Where data is more sparse, the method based on a less-smooth generalization of the motor data shows greater variation in the model.

Example: Motors

$$P(\mathbf{x}) = \frac{1}{(2\pi)^{d/2}\sigma^{d}} \frac{1}{n} \sum_{i=1}^{n} e^{\frac{(\mathbf{x}_i - \mathbf{x})(\mathbf{x}_i - \mathbf{x})^T}{2\sigma^2}}$$

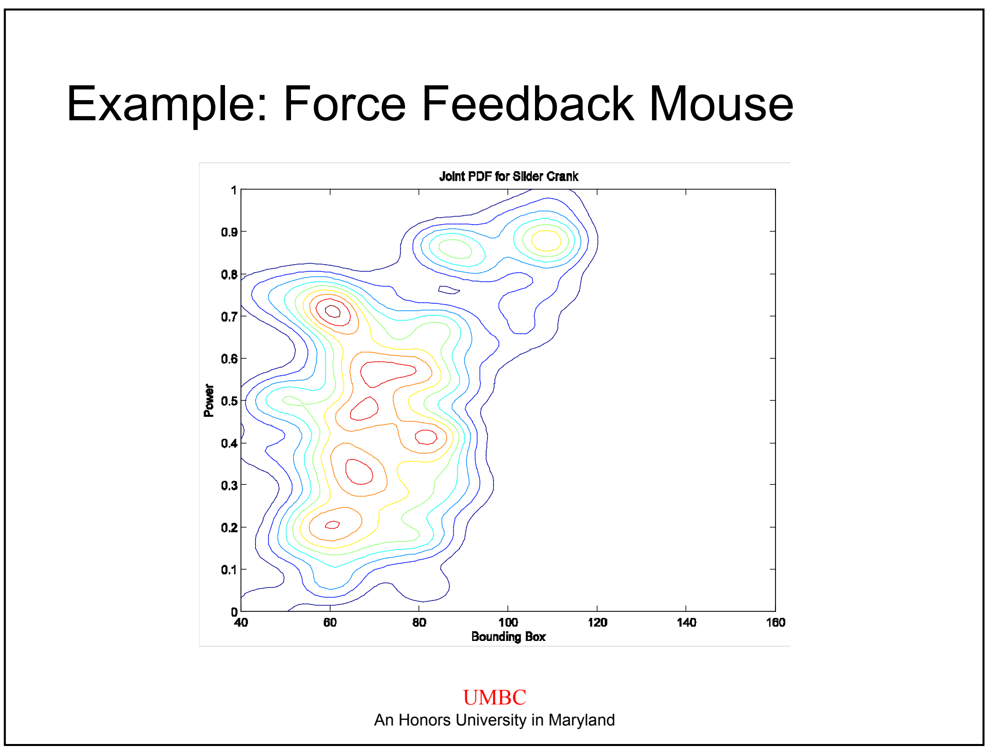
$$\sigma = cn^{1/(d+4)} \qquad c \in [0.01, 0.35]$$



UMBC
An Honors University in Maryland

Example: Force Feedback Mouse

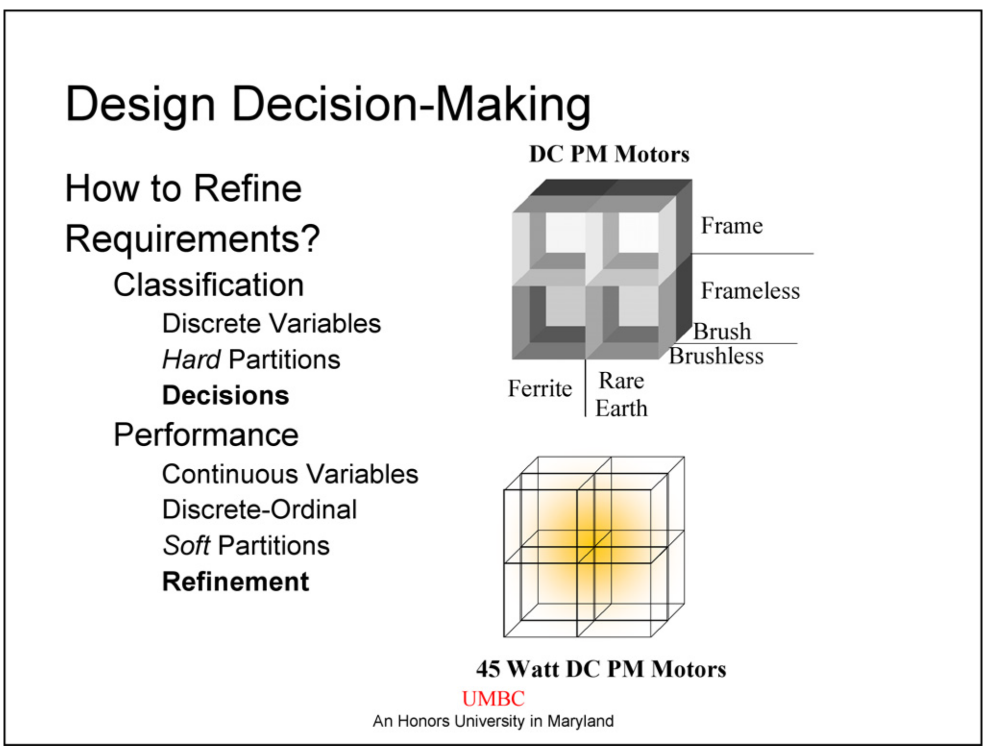
This plot shows a set of contours for a more manufacturing oriented case of a force feedback mouse. Here, the competing objectives are the power transmit through the mouse and its spatial volume. It appears that, for low-power designs there is little relationship between the two, but at higher power the mouse designs tend to get larger.



Design Decision-Making

At its heart, DBCD is a decision process. But a decision process needs options among which to decide. Here, we draw on the nature of the design-requirement space to identify possible sources of design options and types of decisions. For the discrete options required by formal decision theory, discrete design variables present the most obvious source of alternatives. Constraining a discrete variable to one (or a subset) of its possible values makes a ‘hard’ partition in the design space, deterministically removing some options from further consideration. These variables are called classification variables due to their general use to define design classes.

Uncertainty of continuous (or discrete-ordinal) variables could influence the decision made among the discrete design alternatives. Refining uncertainty in such performance variables might be of value if it makes decisions among classification variables more clear-cut. Reducing uncertainty in these variables produces a soft partition due to the generalization used to flesh out the design space.



Making Hard Partitions

For determining which values of a classification variable would likely produce the best design, we can apply expected value decision making. For this process, we need a a function that establishes design value (e.g., an optimization objective, a value function, a utility function, etc.), a set of discrete alternatives (i.e. the classification variables and their possible values) and a definition of the uncertainty in the problem (e.g., the design space joint pdf). For each possible decision, the expected value of the value function is calculated by integrating over all sources of uncertainty. The option that maximizes the expected value of the design is generally selected at the best option.

This process is normative: it provides a rational model for selection under uncertainty that is insensitive to how design options are packaged, the order of option presentation, etc. It provides a rational choice in situations where uncertainty cannot be reduced. But expected value decision-making does not reveal whether one alternative dominates all others or the situations in which the chosen alternative might be sub-optimal.

Making Hard Partitions

Expected Value Decision Making

$$option^* = \max_i \left(E\left[v(design \mid option_i)\right] = \int_U v\left(design \mid option_i, \mathbf{c}\right) dU \right)$$

Inputs

- Value Function (possibly uncertain)
- Discrete Options (possibly hierarchical): Classification Variables
- Uncertainty

Output

- Rational Choice

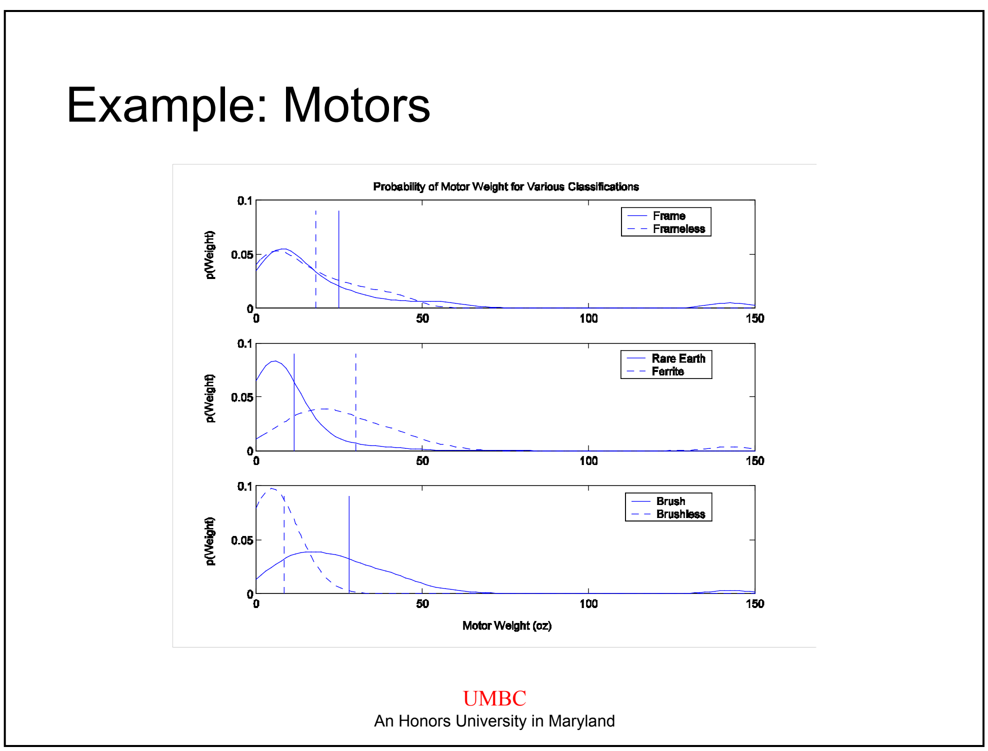
Issue

- Dominance

UMBC
An Honors University in Maryland

Example: Motors

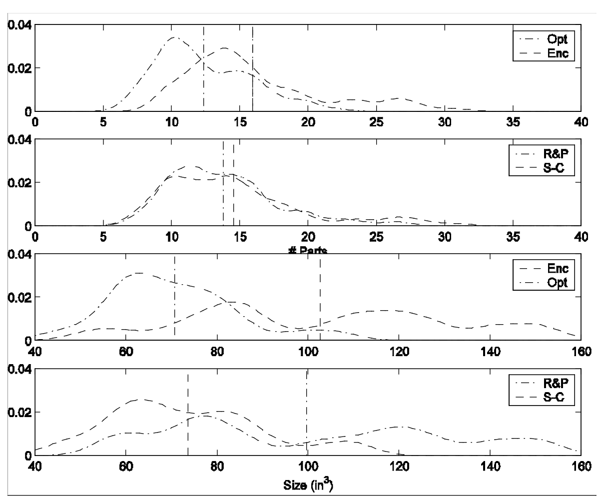
In the plots below, models for the mass of 45 Watt motors are plotted for different values of three classification variables: frame vs. frameless, ferrite vs. rare earth, brush vs. brushless. For each curve, the vertical line denotes the expected value of the pdf. To minimize motor weight, EVMD recommends frameless over frame, rare earth over ferrite, and brushless over brush. But it is clear than in none of these cases is one choice deterministically better than the other. By going with EVDM at this point, the designer is taking a chance that the resulting design will be suboptimal.



Example: Force-Feedback Mouse

Another example shows the number of parts (top two plots) and the size (bottom two plots) for a variety of force feedback mouse designs. The decisions to be made include both the type of position sensor – 2-D optical vs. 1-D encoder – and the type of actuator mechanism – slider crank vs. rack and pinion. Again, there is no dominance in the depicted decisions: optical and rack& pinion to minimize parts, optical and slider-crank to minimize size.

Example: Force-Feedback Mouse



UMBC
An Honors University in Maryland

Making Soft Partitions

To help clarify decisions among classification variables, we can evaluate how the resolution of design uncertainty might change the current best decision. If, at all points in the uncertain design space decision A is better than decision B, then there is no need to further resolve uncertainty. But, if there are ranges of uncertain variables for which the best decision is not that indicated by EVDM, there may be value to reducing the uncertainty in those variables. The expected value of perfect information (EVPI) is an upper bound on the value (expressed in terms of the values function) of completely reducing the uncertainty of a variable (i.e., selecting its value at random according to its probability density). Where EVPI is high, the designer might seek to resolve uncertainty.

Making Soft Partitions

Clarify Hard Partitions

Information Value: Information (a reduction in uncertainty) has value if it changes the optimal decision

$$EVPI\left[design \mid u_j\right] = \int_{\Omega_{u_j}} \begin{pmatrix} \max_i \left(E\left[design \mid option_i, u_j\right]\right) - \\ E\left[design \mid option^*\right] \end{pmatrix} P(u_j)\,du$$

Expected Value of Perfect Information

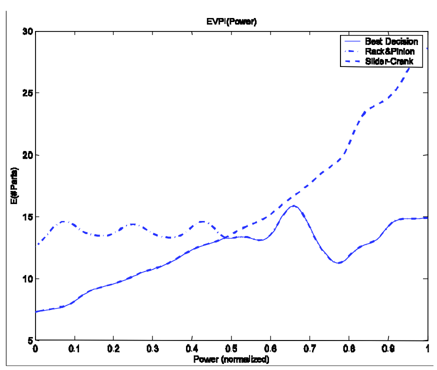
- Narrowing the range of a performance variable is a potential source of information
- Information has *value* if it might lead to different decisions
- EVPI is an upper bound on the value of reducing uncertainty: assumes it will be reduced to a deterministic value
- Calculating EVPI does *not* require design commitment

UMBC
An Honors University in Maryland

Requirement Refinement

In the below plot, the expected value of the number of parts given power is plotted for two values of the mechanism classification variable: rack & pinion and slider-crank. Recall that the rack & pinon is the preferred design from the standpoint of expected value; this plot show that, for high system power, the slider crank design is expected to require fewer parts. Until now, the designer has made no commitment with respect to system power; telling the system the exact power level will help make a better decision. Thus, information about power has value and should be pursued by the designer.

Requirement Refinement



Knowing how much power the mouse must transmit changes the type of mechanism that would be selected based on #parts

Uncertainty can be ***explicit*** (provide a pdf for a requirement) or ***implicit*** (get requirement pdf from joint pdf)

UMBC
An Honors University in Maryland

Measuring Design Freedom

Thus far, we have established methods for determining the value that can be derived from placing constraints on the design space in the form of decisions and requirement refinement. Generating this design value comes at a cost of design freedom – options removed from consideration could have been useful for resolving unforeseen issues downstream in the design process. Set-based design is more successful than 'anchor and adjust' design strategies because delaying commitment affords the design a better understanding of the full implications of all design decisions. Preserving design freedom is an important part of set-based design, measuring it is the first step.

A second implication of design freedom has to do with the unintended consequences of design decisions. In cases where the value function is complete, it captures all that is necessary in evaluating designs. But when the value function is incomplete, designers might 'decide away' performance for variables not currently in the design evaluation. Losing design freedom in these variables means that the designer has made an implicit rather than explicit decision.

Calculating design freedom in a probabilistic framework is a simple extension of Shannon's entropy definition from communication theory. Here, design freedom is derived from samples of the design space and normalized with respect to a uniform probability density. A design freedom of 1 means complete freedom, design freedom of 0 implies a deterministic choice.

Measuring Design Freedom

Communication Theory (Shannon):

Entropy – general measure of disorder in a probability density function:

$$H(u_j) = -\int_{\Omega_{u_j}} \ln\left(P(u_j)\right) P(u_j)\, du_j$$

Design Freedom – sampled entropy, scaled w.r.t. complete freedom (uniform density):

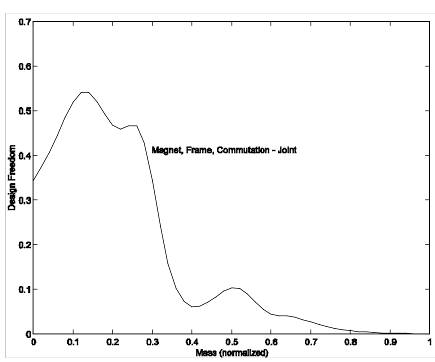
$$DF(u_j) = -\frac{\sum_{i=1}^{n}\left(\ln\left(P(u_{j,i})\right) - \ln\left(\sum_{i=1}^{n} P(u_{j,i})\right)\right) P(u_{j,i})}{\sum_{i=1}^{n} P(u_{j,i})}$$

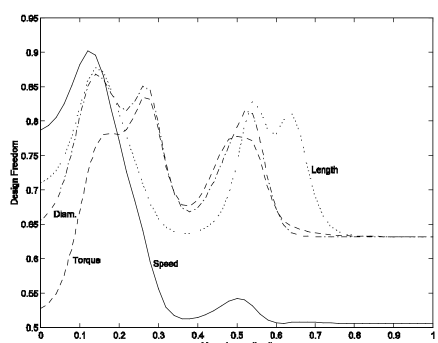
UMBC
An Honors University in Maryland

Setting/Refining Targets

For the motor example, one might want to set a target on motor mass early in the project, possibly to reduce uncertainty for other subsystem designers. Absent any value proposition for motor mass, one can determine how design freedom drops off the lower the mass target is set. For the discrete variables (plot on the left), the dropoff is not too severe when constraining the mass to less than 0.20 normalized mass. But for performance variables like torque (right plot), design freedom drops very quickly below about 0.15 normalized mass. Design freedom can aid in setting constraints by illustrating how achievable those constraints are and the degree to which they limit future choices.

Setting / Refining Targets



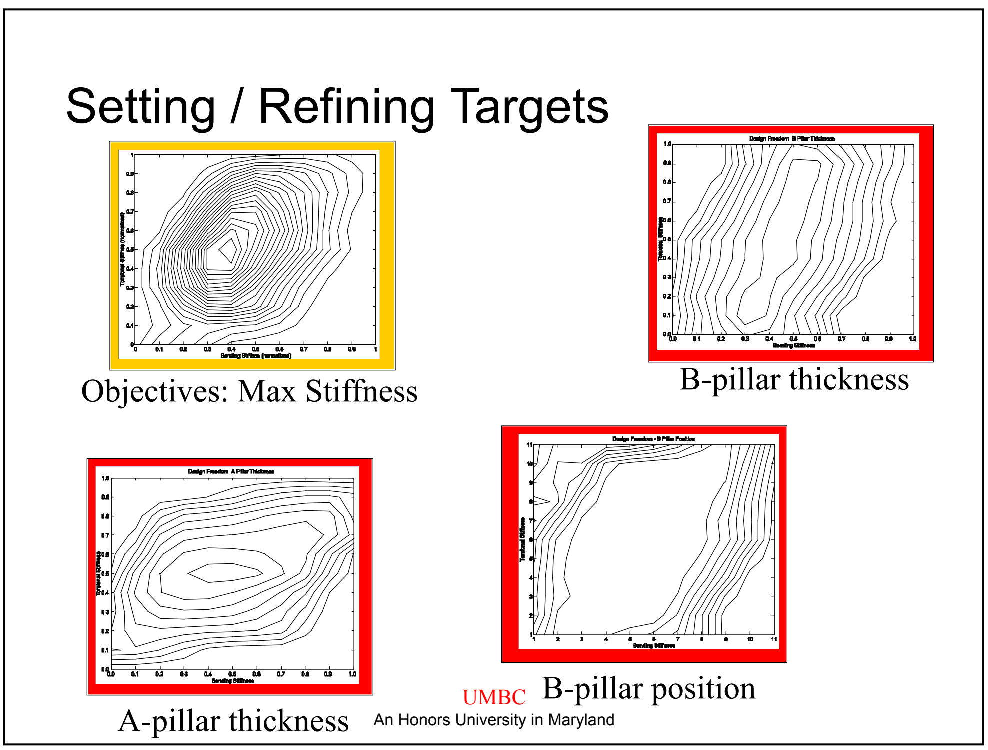


Discrete | Continuous

UMBC
An Honors University in Maryland

Setting / Refining Targets

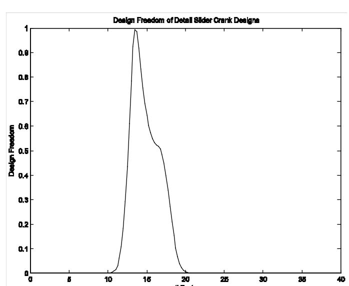
In this example, a sampled design space derived from 3125 finite element runs is depicted. The main objectives are to maximize both torsional and bending stiffness of a uni-body structure for a car. The first plot shows that, near the optimum value in the upper right there is little design freedom; backing off of the design targets can increase the number of ways in which the team can realize them. Other stakeholders, like manufacturing, might be interested in the constraints placed on wall thicknesses for various values of the design targets; styling might be concerned about the placement of the ‘B’ pillar. The below plots might help in the negotiation process as the team sets initial stiffness targets.



Design Freedom: Raising Issues

Finally, design freedom can be used to identify situations where decisions are implied by other actions. The plot below shows a narrow band in which the overall stiffness of the force feedback mouse linkage is under the designer's control. Below a certain part count, the designer has no freedom to choose stiffness; likewise above a certain level the freedom of stiffness is minimal. The loss of design freedom can be indicated to the designer without having any previous notion about the value associated with system stiffness – the loss of freedom along this dimension is enough to warn the designer about and implicit decision being made.

Design Freedom: Raising Issues



As we minimize part count, we make an implicit decision about the stiffness of the mechanism joints -> *Does the designer care?*

UMBC
An Honors University in Maryland

Summary

In summary, DBCD has been presents as a fundamental shift in the way design is viewed: away from a segregated view of requirement and attributes, toward a unified view in which any descriptive attribute for a design can become a requirement. This viewpoint is implemented in a probabilistic, mathematical framework that then yields to normative methodologies from decision theory: EVDM for selecting among the discrete, classification variables, and EVPI for refining uncertainty in the continuous, performance variables. Extending this process beyond typical decision-based design, measures of design freedom can help the designer to control the design process. Of particular note here is that the process of design does not preclude the generation of design space – measuring where and when it is lost can help to seed the creative process at the heart of design.

DBCD provides a normative methodology for conceptual design whose fundamental purpose is to support the design process. It provides aids for navigating among design abstractions, setting design targets, and preserving design space.

Summary

- A fundamental shift in the view of design space: commingled requirements and attributes
- A mathematical framework for modeling design space
- Normative Set-Based Design
  - EVDM: Selecting Designs
  - EVPI: Refining Requirements
  - Design Freedom: Managing Design Space
- Beyond Decision-Based Design
  - Designers *can* create design space
    - Where
    - When
    - How

UMBC
An Honors University in Maryland

Future Challenges in Innovation Practices: A View From Engineering Design Research

Ade Mabogunje
Center for Design Research
Stanford University
Stanford, CA

FUTURE CHALLENGES IN INNOVATION PRACTICES: A VIEW FROM ENGINEERING DESIGN RESEARCH

In a time when access to information is unrivaled compared to earlier times, have we become more creative as engineers or more conservative? Are today's engineers in the aerospace industries making more discoveries and innovations today when compared to engineers in the 1960s? What are the changes in work spaces, work practices, and management practices between then and now? It has been suggested that the information revolution is in reality more of a control revolution, and as managers we have unconsciously become more controlling as our knowledge of the domain has shrank relatively to the relevant knowledge. Bringing in a project on time and under budget has made the calendar and the spreadsheet about the only tools we understand. But management is not the only one to blame. As engineers we have become simply overwhelmed by the amount of important and relevant information that is out there and all too conscious of the limits of what we can do within the constraints of any given project. Is there a way out?

A CASE FOR ACCELERATING INNOVATION

Can we accelerate the rate at which we introduce new product and services? Is there a need for such acceleration? Do we have the know-how to do such a thing?

A Case for Accelerating Innovation

Is it possible to improve the rate at which we introduce new products and services?

THE NATURE OF DESIGN ENGINEERING

For the purposes of this presentation:

Forget for a while the numerous presentations and discussions about software and algorithms for design optimization. Let go of your association with the aerospace industry. Imagine you are the sole survivor of a shipwreck, and you have managed to swim to a small deserted island. What would you do?

Contextual Questions

What does design mean to us? What is design research? What is our approach to design research?

Our response to these questions will reveal several important features of design. It is a natural human instinct, some authors have argued that it is at the core of engineering, it is best to think of design as encompassing R&D and manufacturing. Design embraces thinking from art to science, and it is best "optimized" through competition and selection.

Design

- A natural human instinct (…homo innovaticus).
- The core of engineering thinking.
- Encompasses thinking from R&D and Manufacturing.
- Embraces thinking from art to science.
- Best "optimized" through competition and selection.

Science of artificial = Science of engineering

DESIGN RESEARCH

Design Research as a field of research in science and engineering is relatively young. The focus of our work is on ways to improve the creativity of engineering design and the effectiveness of product design and development.

The primary goal of NSF's Design Theory and Methodology Program is:

- ...to create a new generation of fundamental principles and generic methods which will enhance the design process and provide the basis for educating a new breed of design engineer.
- The results of fundamental research in this field can enhance design practice, improve design support systems, and strengthen the education of both practicing and future designers.
- ... the results of research in this field can improve the creativity of engineering design and the effectiveness of product design and development, leading to improved national productivity and international competitiveness.

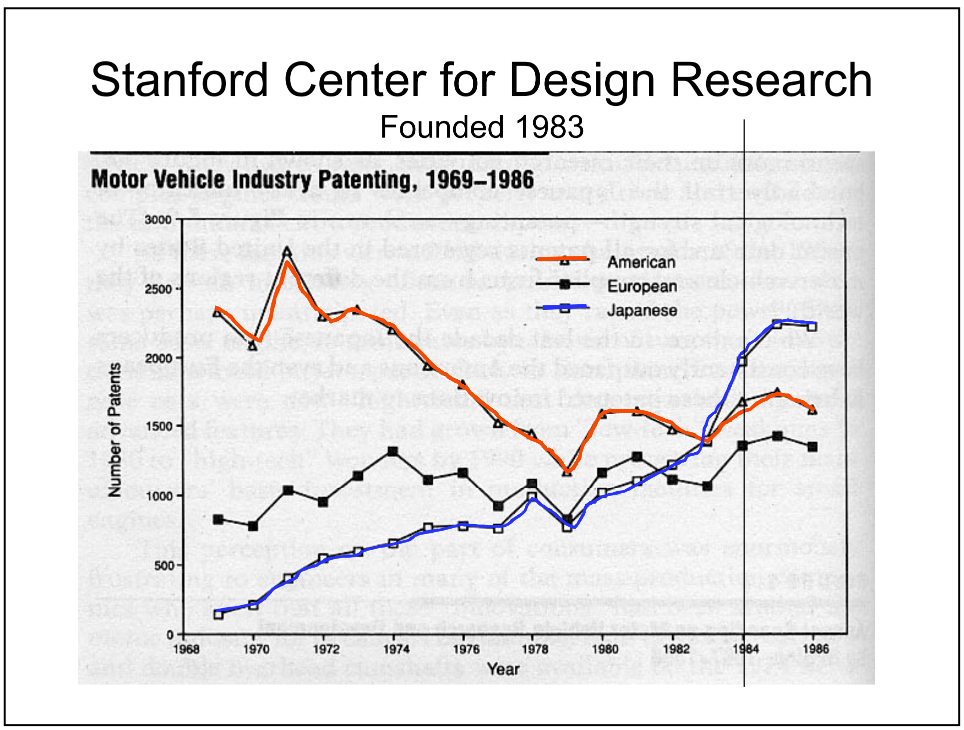
STANFORD DESIGN RESEARCH APPROACH

The Stanford Center for Design Research was founded in 1983, in response to a growing realization that Design was poorly understood in industry and academia. In industry, for example the Automobile industry, there was a great loss in market share to Japanese car manufacturers. In the university, very few courses existed that taught engineers how to do design.

At the Stanford Center for Design Research, our response was to pose two fundamental research questions:

What do engineers do when they do design?

How can we improve their process?



ENGINEERS OBSERVING ENGINEERS: REFLECTIVE AND REFLEXIVE RESEARCH

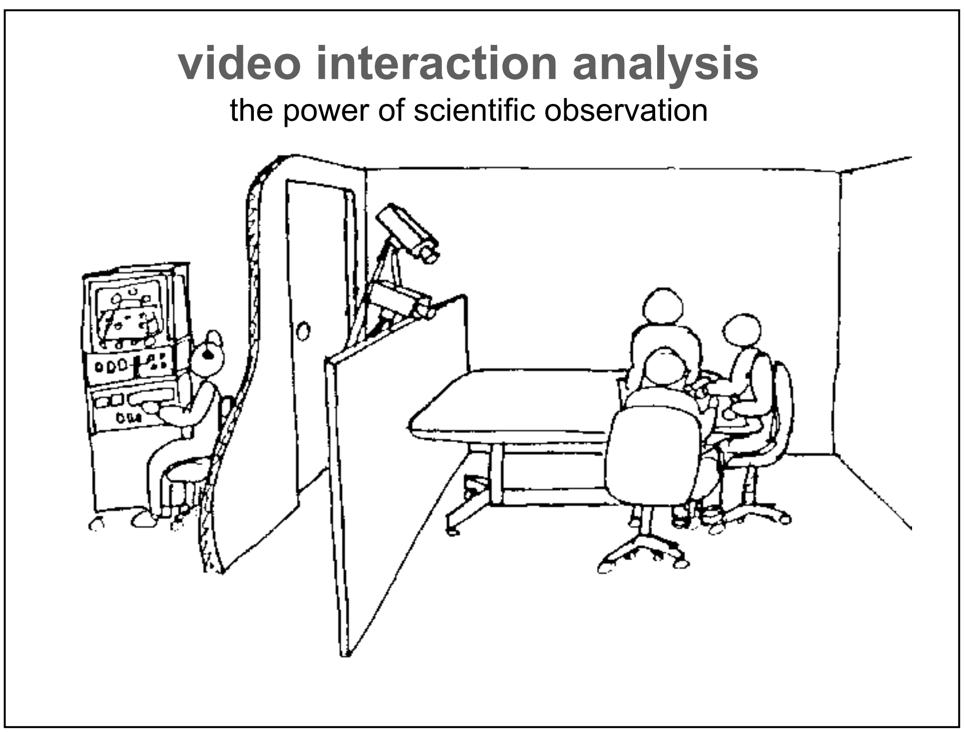
Thus in response to earlier scenario I described where you were the sole survivor of a shipwreck, we would be interested in:

what you would do (incl. why and how)

what you could do

what someone else in your situation would do

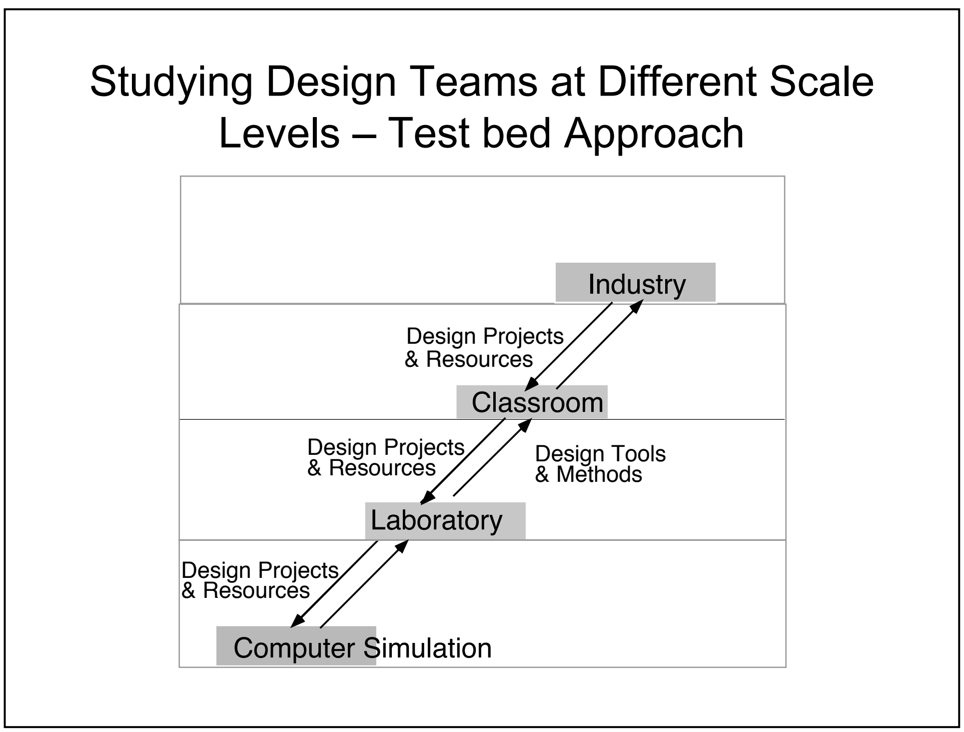
We use various observational techniques including video to observe Engineers and Designers at Work. Our primary concern is with the nature of their thinking, the computational tools they use, and the social protocols they develop to better meet the challenges they face.



MANAGING COMPLEXITY THROUGH SCALING AND DIMENTIONAL SIMILARITY

Engineering Design is a complex process. The technical artifact in most aerospace companies is complex and the organizations are complex. One approach to managing this complex whole is to think about them as separate entities. This approach works when the product and processes are well known, and the desire of the organization is that of reproducing previous work.

For innovative organizations, thinking of the artifact and the organization separately can be done artificially but is inefficient in practice. As in most engineering systems, the scaling approach will be more appropriate here. Thus our research practice is to observe the artifact and the organization at different scale levels, where the dimensions are level of complexity of the artifact and level of control in the organization. Each of these levels is called a test-bed.



THE KEY TO ACCELERATING INNOVATION

Our research suggests that the key to accelerating innovation is to focus on communication patterns in engineering design teams (See bibliography). In the rest of the presentation I will share with you sample material from research in our lab where we have systematically explored the fundamental questions I raised earlier and the results that have led us to this conclusion.

I will structure the slides in the following manner:

What do engineers do when they do design? Here I will present sample observations and early results

How can we improve their process? Here I will present some of the tools, methods, and approaches.

Towards the Innovative Organization? Here I will draw on extant literature to contrast Innovative organizations with Managerial ones. I will then indicate what our results have to say about ways to develop innovative organizations.

Approaches to Improving Performance

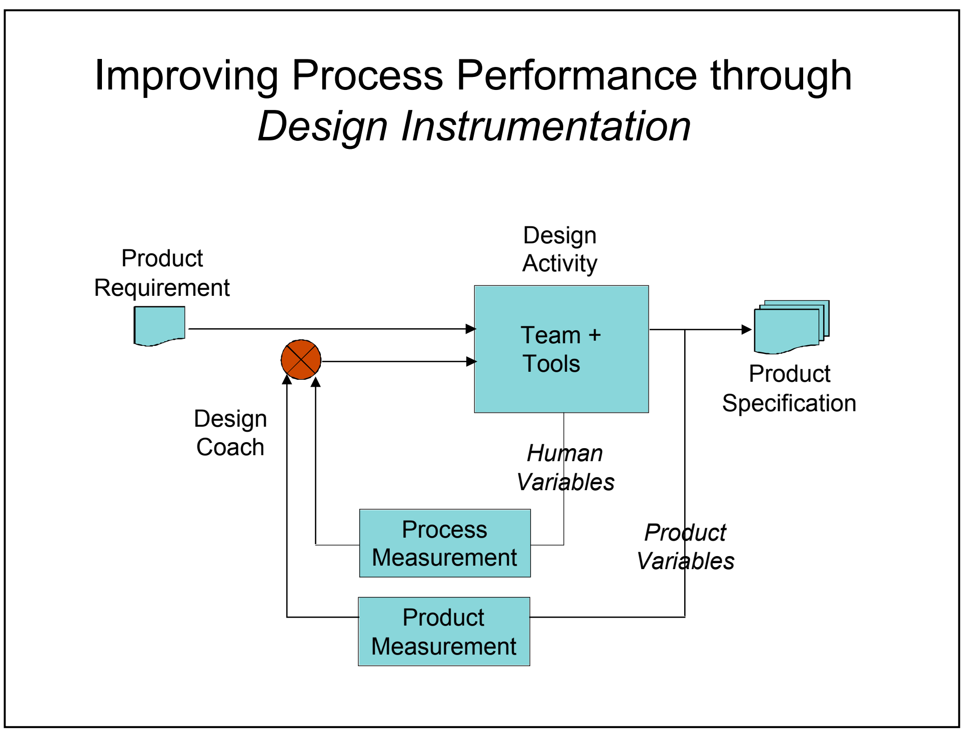
- Expert Systems
- Augmentation Systems
- Best Practices
- Design Optimization
- Decision support tools
- Simulation-based Design
- Industry Studies
- Laboratory Studies

DESIGN PROCESS INSTRUMENTATION

The focus on communication patterns of engineer has been embodied in an infrastructure for instrumenting the design process. This infrastructure , similar to a flight simulator allows us to observe the design process unfold in real-time and make suggestions for alternative courses of action through the use of expert design coaches.

Among the parameters that can be monitored are those related to the product, such as the function, the features and the performance; and those related to the human system such as development time, product novelty, learning, experiences of pleasure, fun and satisfaction, and experiences of anxiety and frustration.

By maintaining a dual focus on the human and technical side of product development we have been able to demonstrate a consistent pattern of exceptional design in one of the design test-beds we work with, the ME310 design course.



REFERENCES

This list consists of the Stanford doctoral dissertations that in sum leads us to understand the critical role communication patterns of Engineers will play in the process of accelerating innovation.

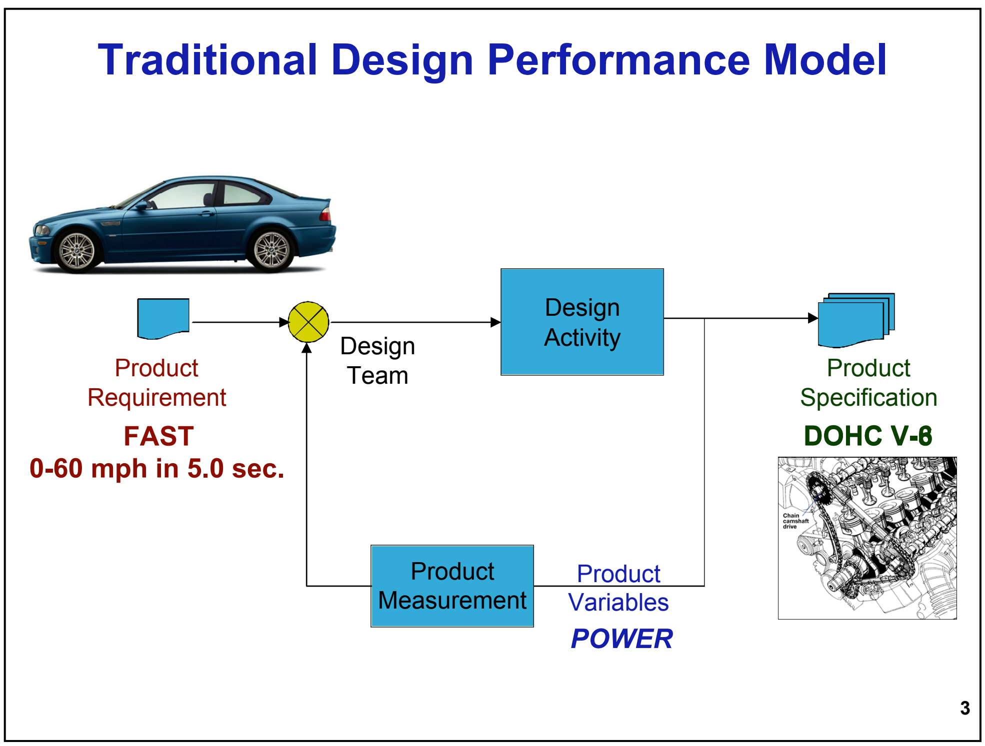
References

- 1989 - John Tang, Toward an Understanding of the Use of Shared Workspaces by Design Teams
- 1991 - Scott Minneman, The Social Construction of a Technical Reality: Empirical Studies of Group Engineering Design Practice
- 1996 - Vinod Baya, Information Handling Behavior of Designers During Conceptual Design: Three Experiments
- 1997 - Adegboyega Mabogunje, Measuring Conceptual Design Process Performance in Mechanical Engineering: A Question Based Approach
- 1999 - Margot Brereton, The Role of Hardware in Learning Engineering Fundamentals: An Empirical Study of Engineering Design and Product Analysis Activity
- 2000 - Tao Liang, Mapping Experience: Understanding Socio-technical Knowledge Sharing in Product Development Communities
- 2001 - Samuel Yen, Capturing Multimodal Design Activities in Support of Information Retrieval and Process Analysis
- 2002 – Ozgur Eris, Perceiving, Comprehending, and Measuring Design Activity through the Questions Asked While Designing.

Modeling Engineering Design Thinking and Performance As a Question Driven Process

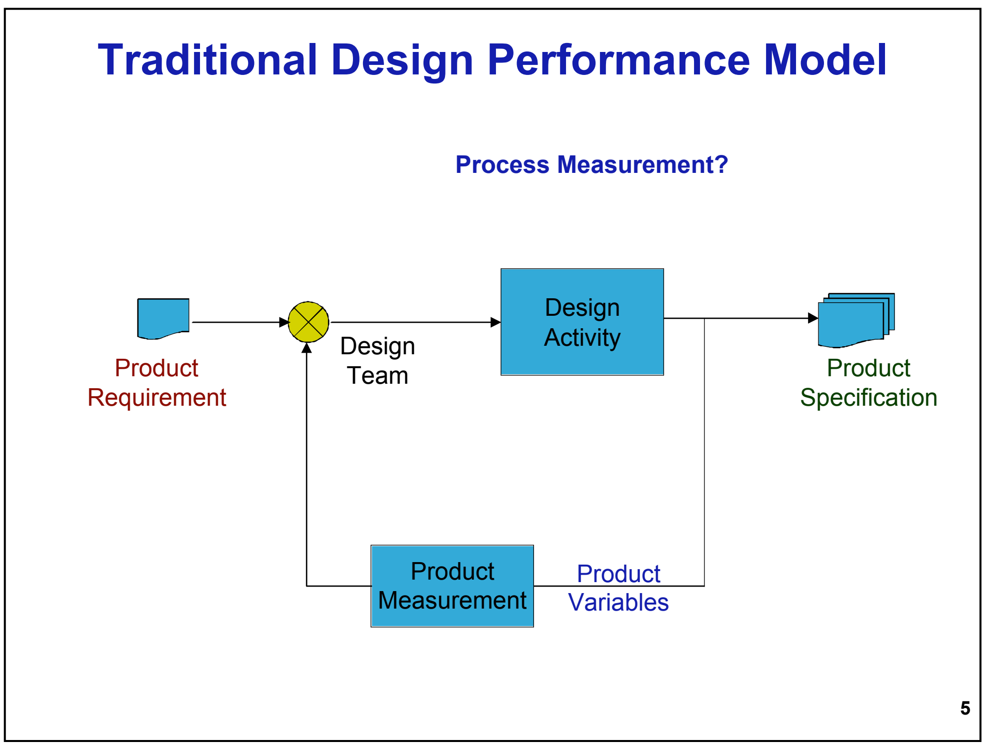
Ozgur Eris
Center for Design Research
Stanford University
Stanford , CA

Design teams transform product requirements into product specifications. Traditionally, as a performance dimension, engineering design teams are trained to focus on the product. They identify and monitor key performance variables associated with the product. This is the basis for iteration in the design process.

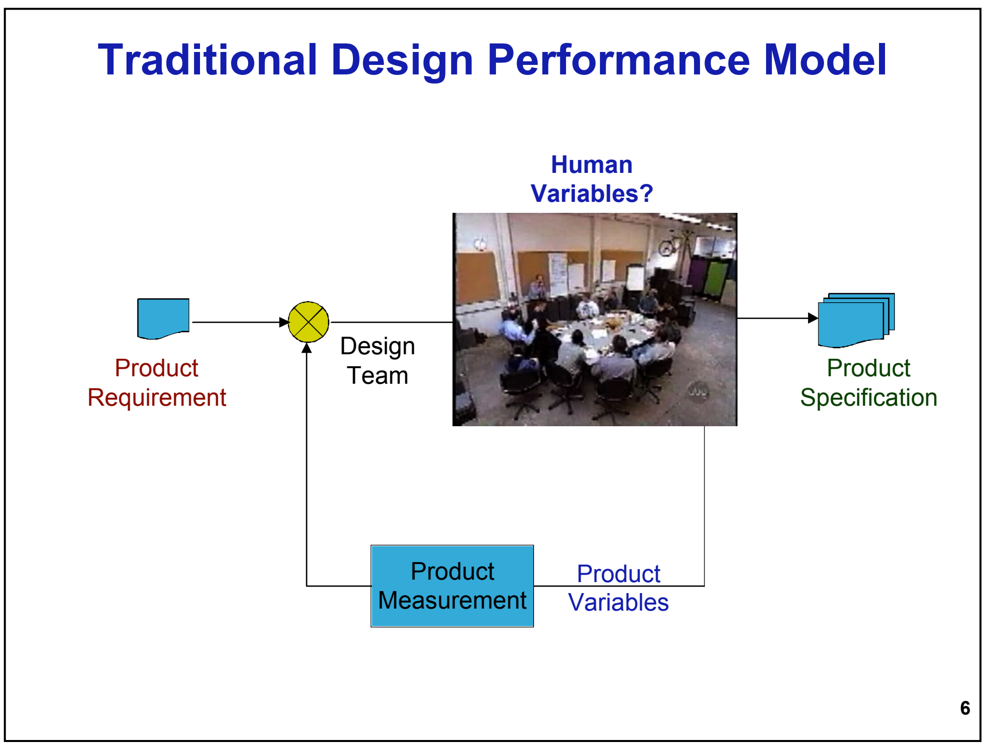


This video clip is an excerpt from a ABC network television program on the leading international design consultancy firm IDEO. The founder, Professor David Kelly, strongly emphasizes their expertise in the "design process" as a performance dimension over their expertise in a specific technical domain.

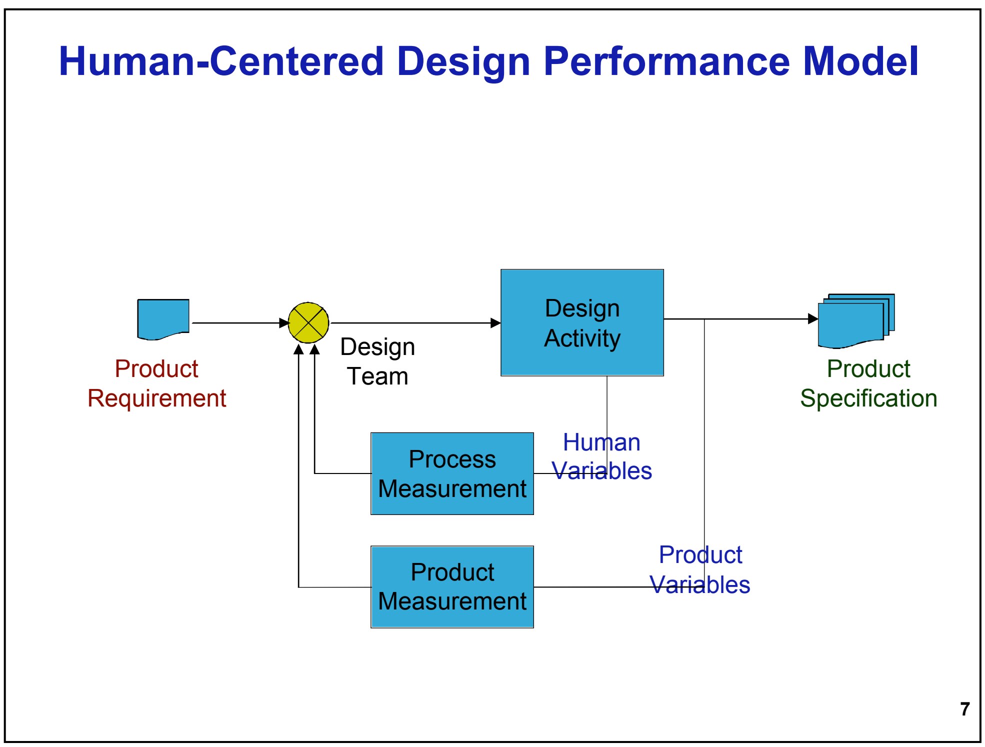
If David Kelly's point is valid, then how do we account for the performance dimension that is associated with the design process?



One way of accounting for the performance dimension associated with the design process is to consider the human variables in design activity. By "human," I am referring to the people who are directly involved in design activity and make up the design team, and not to the users.



Identifying and monitoring human variables would result in “process measurement,” which can then be treated similarly to product measurement and constitute the basis for a second feedback/iteration loop.



Identifying human performance variables is the main motivation behind this research. I conducted two sets of preliminary observations to accomplish this. I carried out the first set of observations at Ford's Dearborn vehicle development center, and the second set of observations at Stanford during a graduate level mechanical engineering design course.

During the observations, I initially paid attention to the decisions design teams were making. However, focusing on decisions resulted in an increased awareness of the influence of the questions that were being asked. Some questions seemed to influence pivotal decisions whereas other seemed to have no discernable impact and faded away. I attempted to create question-decision trees of design meetings in order to tease out such relationships. However, I quickly realized that our understanding of question asking processes of designers was limited, and decided to study the questions.

Motivation/Initial Observations

- Interplay between "Questions" and "Decisions"
  - Some questions have strong influence on pivotal decisions.
  - Initial Vision: Constructing question-decision trees in order to identify such influences.

8

On a conceptual level, the relationship between questions and decisions can be explained in terms of a duality: it is not possible to ask a question without making decisions, and to make a decision without asking questions.

Motivation/Initial Observations

A Duality between questions and decisions:

- **Every question operates on decisions** as premises since questions are formulated (goal, content, structure, timing, etc.) Questions are intentional and not arbitrary.
- Conversely, **every decision operates on questions** as premises since decision making entails dealing with choices that need to be generated, analyzed, and compared.

9

I made three key observations in the field, and built on them in constructing hypotheses related to the question asking behavior of design teams (will be discussed later in the presentation).

Key Field Observations

O1: The design teams spent a significant amount of time asking and discussing questions in order to:

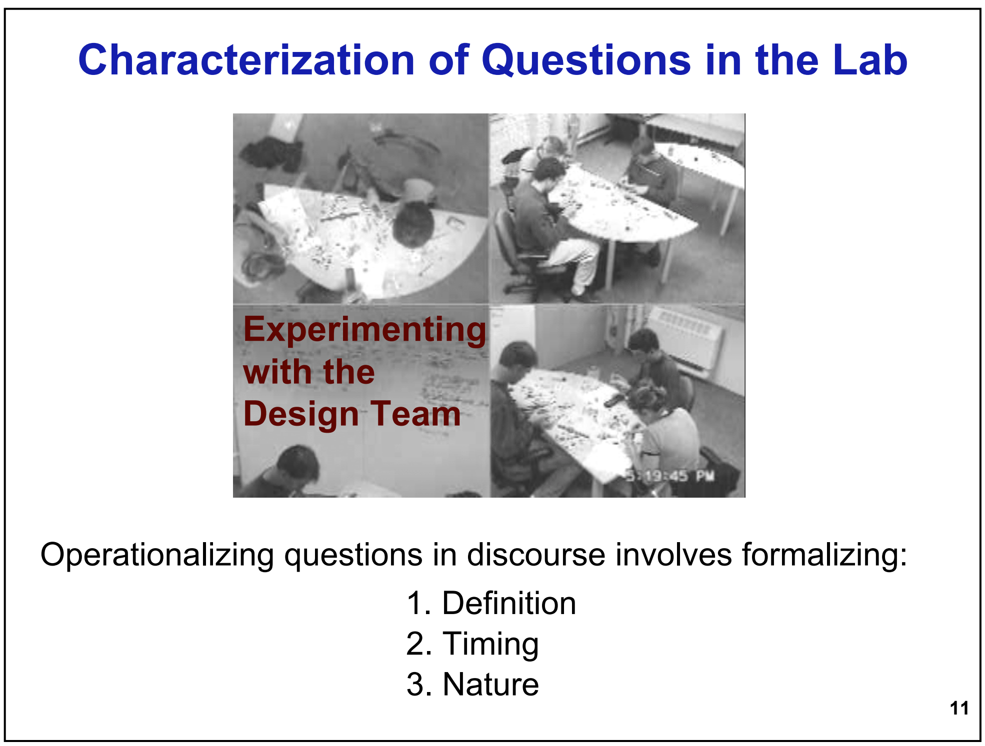
- reason about and explain phenomena,
- generate and negotiate design concepts,
- seek new information,
- verify and clarify facts and each others views,
- mediate social interaction.

O2: Meetings during which the teams asked more “good” questions yielded more progress (insights and discoveries).

O3: Working with existing artifacts and prototyping hardware had an effect on the nature of questions asked.

10

In order to test the hypotheses, I designed a quasi-controlled laboratory experiment, which required the operationalization (formalization) of three fundamental aspects of question asking.



I identified questions in the verbal discourse of the design teams participating in the experiment according to the definition and criteria listed above.

Definition of a Question in a Design Context

Verbal utterance related to the design tasks at hand which demand explicit verbal and/or nonverbal responses.

- A response constitutes an answer if it has been solicited by the questioner—a response which was not explicitly solicited does not constitute an answer.
- What is directly observable: Communication of the question as opposed to its "occurrence."

12

Formalizing the timing of a question entailed identifying the start and end of its communication.

Timing of Questions

- What can be observed directly
  - The start and the end of the communication of a question.
- What can be studied
  - Temporal relationships to other questions, i.e. Frequency, Progression and Interplay.

13

In order to formalize the nature of a question, I relied on published taxonomies of questions, which date back to Aristotle's Posterior Analytics. If a taxonomy abides by a unique differentiating principle, and is comprehensive, it can serve as a meaningful analysis scheme for coding the questions identified in discourse.

In this slide, four such taxonomies are inserted into the columns of a table. Categories which are semantically similar are placed in the same row. Aristotle's four fundamental classes are taken as the basis for the comparison. I would like to convey the following two points with this table:

1) The four taxonomies map onto each other. Therefore, any one of them can be taken as an initial coding scheme.

2) Graesser, after extending Lehnert's framework, used the resulting taxonomy to code questions he identified during tutoring sessions. He discovered a correlation between a class of questions, which he called "Deep Reasoning Questions" and learning performance (as measured by a test score after the tutoring session). Therefore, it made the most sense to use his framework as an initial coding scheme.

Review of Taxonomies of Questions

ARISTOTLE	DILLON [84]	LEHNERT [78]	GRAESSER [94]
Existence (Affirmation)	Existence/affirmation	Verification	Verification
	Instance/identification		
Nature (Essence/Def.)	Substance/definition		Definition
			Example
Fact (Attribute/ Description)	Character/description	Feature Specification	Feature Specification
		Concept Completion	Concept Completion
		Quantification	Quantification
	Function/application	Goal Orientation	Goal Orientation ■
	Rationale/explication		
	Concomitance	Disjunctive	Disjunctive
	Equivalence		Comparison
	Difference		
Reason (Cause/ Explanation)	Relation		Interpretation
	Correlation		
	Conditionality & Causality	Causal Antecedent	Causal Antecedent ■
		Causal Consequent	Causal Consequent ■
		Expectational	Expectational ■
		Procedural	Procedural ■
		Enablement	Enablement ■

■ Deep Reasoning Question (DRQ)

14

When I used Graesser's taxonomy to categorize the questions asked by the design teams, I was not able to categorize 15-20 percent of the questions, which were rather influential. After considering these questions in depth, I realized that this could be because the driving premise of a design situation is rather unique and might not have been a factor in the formulation of the reviewed taxonomies (the four taxonomies reviewed earlier are epistemological approaches and are concerned with "what we know.")

Extending the Taxonomies of Questions

- Underlying assumptions of the Taxonomies:
  - A specific answer, or a specific set of answers, **exist** for a given question.
  - Lehnert and Greaser also seem to assume that the answer is **known**.
- Driving premise of a Design situation:
  - Multiple **alternative known** answers as well as multiple **unknown possible** answers exist.
  - The questioner's intention is to **disclose** the alternative known answers, and to **generate** the unknown possible ones.

15

Further analysis of the questions I could not categorize led me to construct five new questions categories. I call these types of questions "Generative Design Questions." (Each question category will be discussed in detail.)

Extending the Taxonomies of Questions

ARISTOTLE	DILLON [84]	LEHNERT [78]	GRAESSER [94]	ERIS
Existence (Affirmation)	Existence/affirmation	Verification	Verification	Verification
	Instance/identification			
Nature (Essence/Def.)	Substance/definition		Definition	Definition
			Example	Example
Fact (Attribute/ Description)	Character/description	Feature Specification	Feature Specification	Feature Specification
		Concept Completion	Concept Completion	Concept Completion
		Quantification	Quantification	Quantification
	Function/application	Goal Orientation	Goal Orientation ■	Rationale/Function ■
	Rationale/explication			
	Concomitance	Disjunctive	Disjunctive	Disjunctive
	Equivalence		Comparison	Comparison
	Difference			
Reason (Cause/ Explanation)	Relation		Interpretation	Interpretation ■
	Correlation			
	Conditionality & Causality	Causal Antecedent	Causal Antecedent ■	Causal Antecedent ■
		Causal Consequent	Causal Consequent ■	Causal Consequent ■
		Expectational	Expectational ■	Expectational ■
		Procedural	Procedural ■	Procedural ■
		Enablement	Enablement ■	Enablement ■
				Proposal/Negotiation ●
				Enablement ●
				Method Generation ●
				Scenario Creation ●
				Ideation ●

■ Deep Reasoning Question (DRQ)

● Generative Design Question (GDQ)

16

What differentiates Generative Design Questions from the rest of the question categories is that they reflect **divergent** thinking. The reviewed question categories reflect **convergent** thinking.

Implications of the Extension

Convergent vs. Divergent Thinking Modes:

- When asking GDQs, the questioner can be seen to be **diverging from the facts to the possibilities** that can be generated from them. The answers are not expected to hold a truth-value.
- When asking DRQs, the questioner can be seen to be **converging from possibilities to the facts**. The answers are expected to hold truth-value.

17

I designed the experiment to test these four hypotheses. The most important one is the postulated relationship between the incidence of deep reasoning and generative design questions, and design team performance.

Hypotheses Derived from Field Observations

H1: Question timing, type and content are descriptors of design process. They are informative enough to serve as a roadmap to the design thinking and processes of teams.

H2: DRQ+GDQ asking rates of design teams can be taken as a design performance metric.

H3: Working with hardware influences the question asking behavior of design teams.

H4: There is significant correlation between the frequency of discoveries made by design teams and their performance.

18

Short description of the design scenario used in the experiment. It is relevant to note that almost all of the graduate students who were subjects had more than two years of industry experience.

Experiment Description

The Bodiometer Exercise:

- Design and prototype a measurement device to measure the length of various body contours.
- 36 mechanical engineering graduate students designing in teams of 3 for 90 minutes.
- Half of the teams were provided with the prototyping hardware at the beginning, the other half, approximately 30 minutes into the exercise.

19

Description and illustration of the Proposal/Negotiation Generative Design Question category.

Generative Design Questions

GDQ Category	Proposal/Negotiation
Definition	Questioner wants to suggest or negotiate a concept.
Example	How about attaching a wheel to the body?
Significance	Proposing an idea in the form of a question promotes consideration and feedback. Negotiation promotes synthesis.

20

Description and illustration of the Scenario Creation Generative Design Question category.

Generative Design Questions

GDQ Category	**Scenario Creation**
Definition	Questioner wants to construct a scenario and consider possible outcomes.
Example	What if the device was used on a child?
Significance	Accounting for possible outcomes generates and refines design requirements.

21

Description and illustration of the Method Generation Generative Design Question category.

Generative Design Questions

GDQ Category	**Method Generation**
Definition	Questioner wants to generate procedures of achieving a specific goal.
Example	How can we keep the wheel from spinning?
Significance	Operating with a specific goal generates a set of methods for implementing concepts.

22

Description and illustration of the Ideation Generative Design Question category.

Generative Design Questions

GDQ Category	Ideation
Definition	Questioner wants to generate as many concepts as possible without a specific goal.
Example	What can we do with magnets?
Significance	Operating without a specific goal frees associations and drives concept generation.

23

Description and illustration of the Enablement Generative Design Question category.

Generative Design Questions

GDQ Category	**Enablement**
Definition	Questioner wants to identify as many resources as possible that enable a concept.
Example	What allows you to measure distance?
Significance	Identification of multiple resources promotes surveying and learning from existing design features.

24

In order to test the hypothesis outlined earlier which postulates a relationship between the incidence of deep reasoning and generative design questions, and design team performance:

1) All deep reasoning and generative design questions that were asked by the twelve design teams were identified.

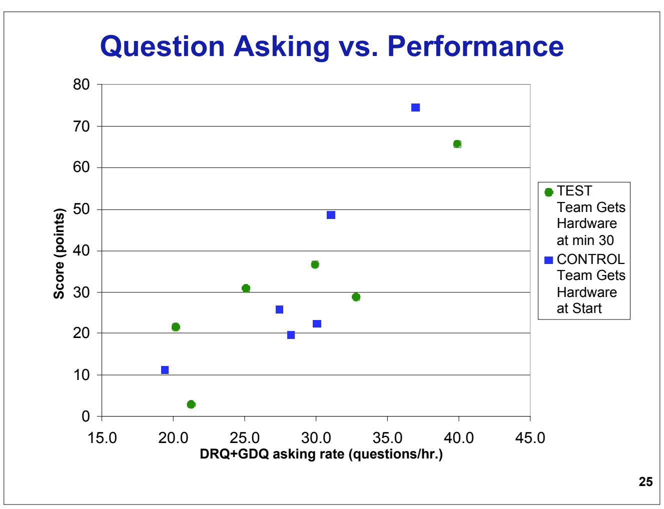
2) Performance of each team was measured by using two independent methods: i) A score indicating the degree to which each team met a set of design requirements related to accuracy, manufacturability, usability and price that were provided at the beginning of the experiment.

ii) A subjective rank ordering of the prototypes by three Stanford mechanical engineering faculty.

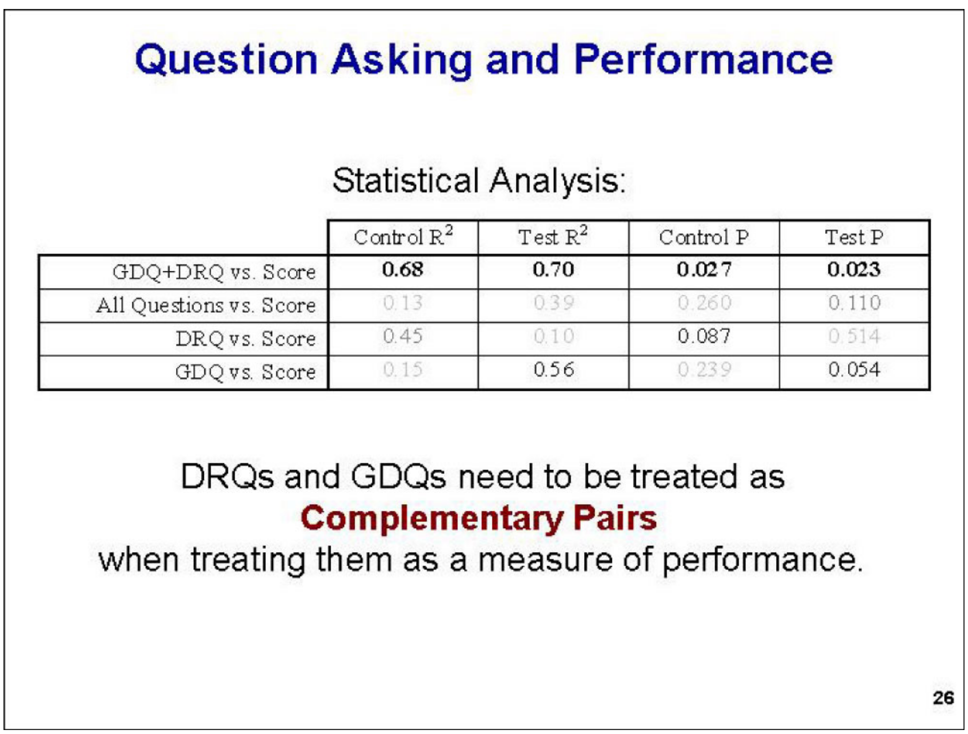
These two methods yielded results that correlated strongly. Therefore, only the first metric was used for evaluation. The combined deep reasoning and generative design question asking rate of each design team was plotted against its score. A linear correlation is visible.

Note: There was a control and a test group in experiment. In the interest of time, I will not discuss the difference between them. For a detailed discussion, please see the following reference:

Eris, Ozgur. Effective Inquiry for Innovative Engineering Design, Kluwer Academic Publishers, Boston, 2004.



Statistical analysis yielded strong correlation between the incidence of GDQs and DRQs and performance. There was no significant correlation when all of the questions or just the DRQs or the GDQs were considered. This suggests that deep reasoning and generative design questions are strongly related and need to be considered in conjunction.



Asking deep reasoning and generative design questions can be treated as a mechanism for managing convergent and divergent thinking modes during design activity.

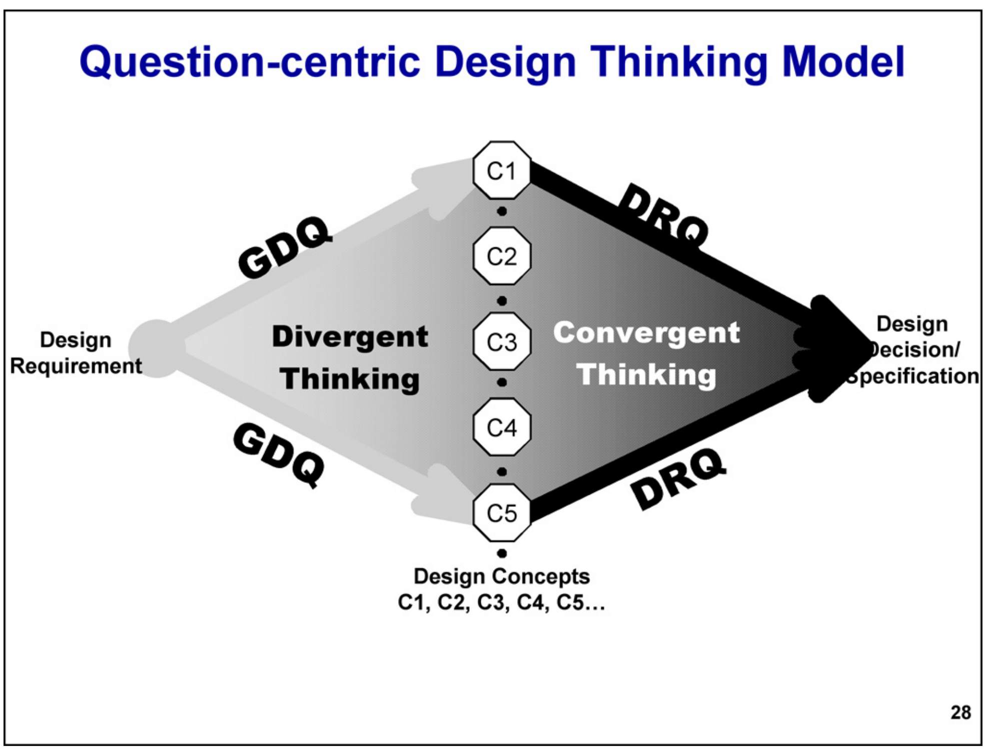
Question Asking as a Mechanism for Managing Convergent-Divergent Thinking

- During conceptualization, GDQs are instrumental in preserving or increasing conceptual ambiguity by:
  - reframing existing understandings that establish context,
  - generating alternatives,
  - creatively negotiating design concepts.
- During implementation and assessment, DRQs are instrumental in reducing conceptual ambiguity by:
  - reiterating goals,
  - focusing on deliverables,
  - seeking and establishing causality,
  - reducing the number of alternatives.

27

High performance design teams realize the importance of managing conceptual ambiguity, and use the GDQ and DRQ instruments in a balanced fashion to operate at the necessary level of abstraction throughout the design process. Therefore, the manifestation of convergent-divergent thinking in the question asking and decision making processes of design teams in the form of Deep Reasoning and Generative Design Questions constitutes a performance dimension in design activity.

The resulting design thinking model illustrates the transformation of design requirements into design concepts through Generative Design Questions, and the transformation of those concepts into design decisions and specifications through Deep Reasoning Questions.



Two potential applications are: constructing a method which promotes effective question asking and using it as a pedagogical tool, and treating the key findings of this research as requirements for the design of engineering design information systems.

Applications

- Pedagogical: a methodology to inform students of the importance of questioning in design thinking
- Design Information Systems:
  - Interacting with the Knowledge System = Asking Questions of the Knowledge System
  - Capturing and retrieving Design Rationale

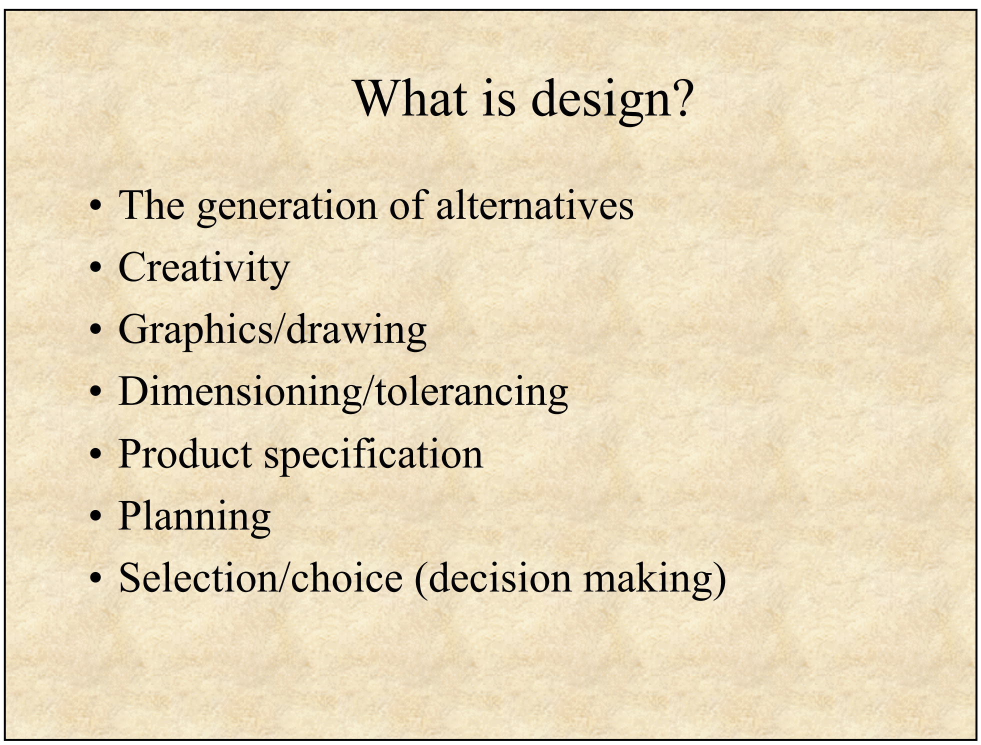
29

Design Education for the Aerospace Workforce

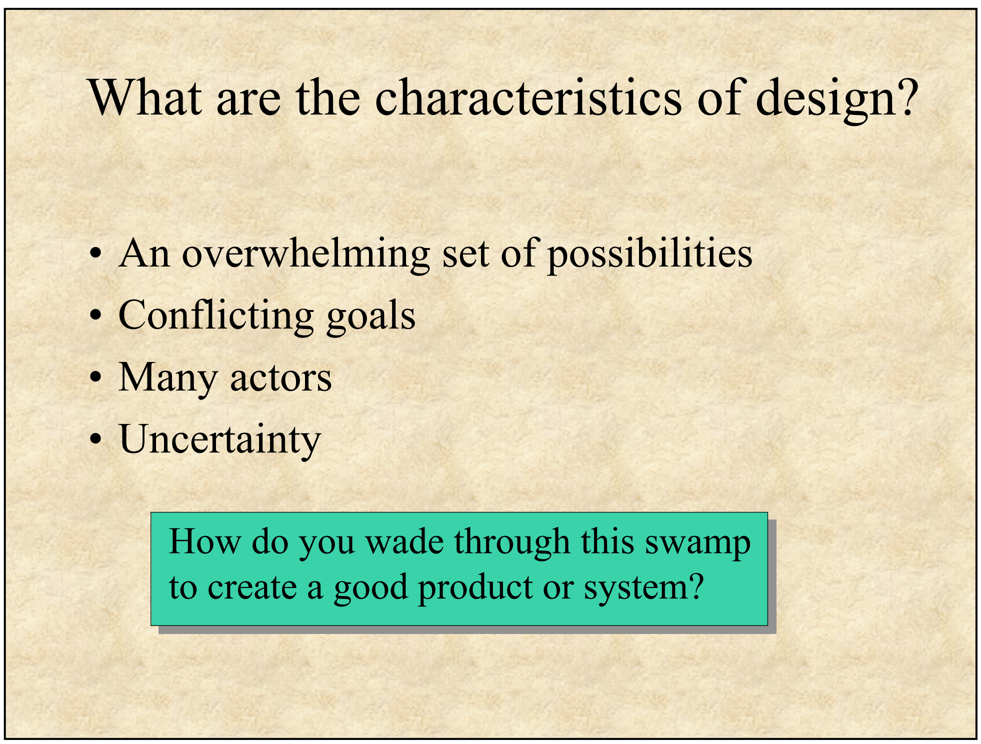
George A. Hazelrigg
Division of Design, Manufacture, and Industrial Innovation
National Science Foundation
Arlington, VA

Design is what defines engineering as an activity separate from the sciences. Yet design, while practiced for millennia, is perhaps the least well defined of the "engineering sciences," and many people would insist that it is not a science at all. I want to take a few minutes to put design in perspective and discuss where we might go with design education.

To be sure, engineering educators and practicing engineers alike cannot agree on what is design. Some people feel that an important element of design is the generation of alternatives, some insist that design is creativity, others look upon design as a process of graphics and drawing (now really CAD), while others add to that dimensioning and tolerancing. Certainly, design would include some elements of product specification and planning. And I certainly would argue that design involves a good deal of selection or choice, that is, it involves a good deal of decision making. We could argue that design encompasses at least this circle of activities, and perhaps more.



Now, what are the characteristics of design? As we have seen by the presentations so far, design presents an overwhelming set of possibilities, and dealing with this set is one of the things that makes design such a complex activity. But, in addition, the designer usually faces what appear to be conflicting goals, the presence of many actors—design is done by teams—and always a great deal of uncertainty. I'll come back to the issue of uncertainty. The underlying question is then, how do you wade through this swamp to create a good product or system?

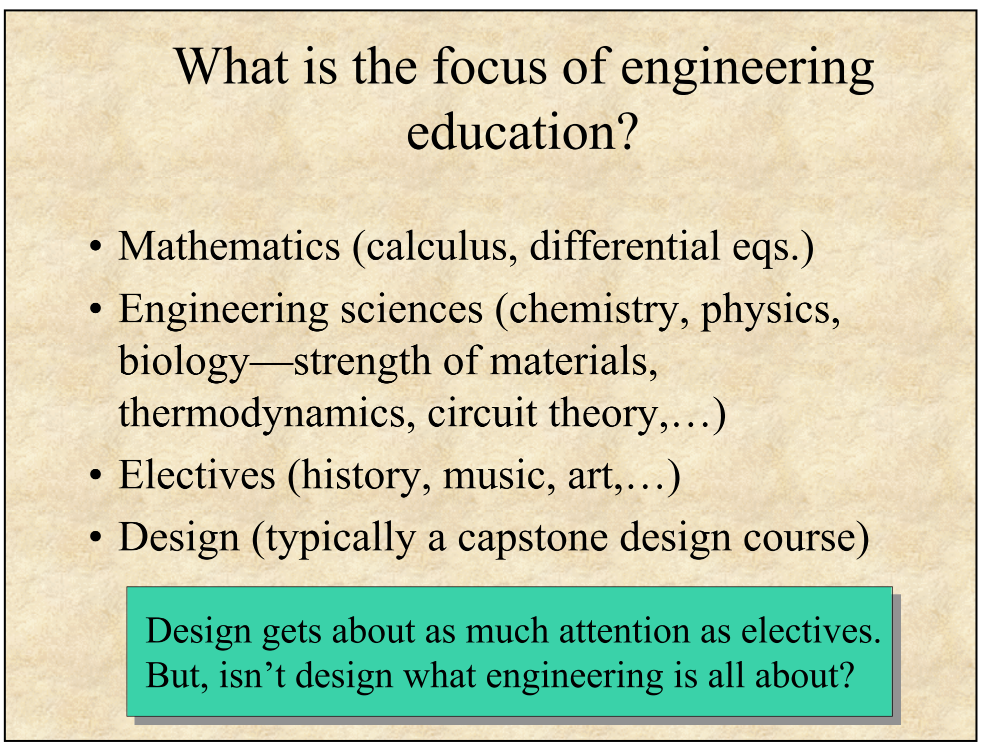


Uncertainty is pervasive in all of design. You see, design is a matter of making choices in the present to achieve goals or desires set for the future. And you simply cannot predict the future with certainty. Think about what it would mean if you could. For an airplane, you would know when it would fly, and when it would be broken, how many passengers would be on each flight, when it would crash, how and why, and how much money the producing company would make as a function of its design. So the implications of all design decisions would be clear. Outcomes would be assured, and it's hard to think of a reason for poor design decision making. But life just isn't like this. All real decisions—design decisions included—are under uncertainty.

What is the meaning of uncertainty?

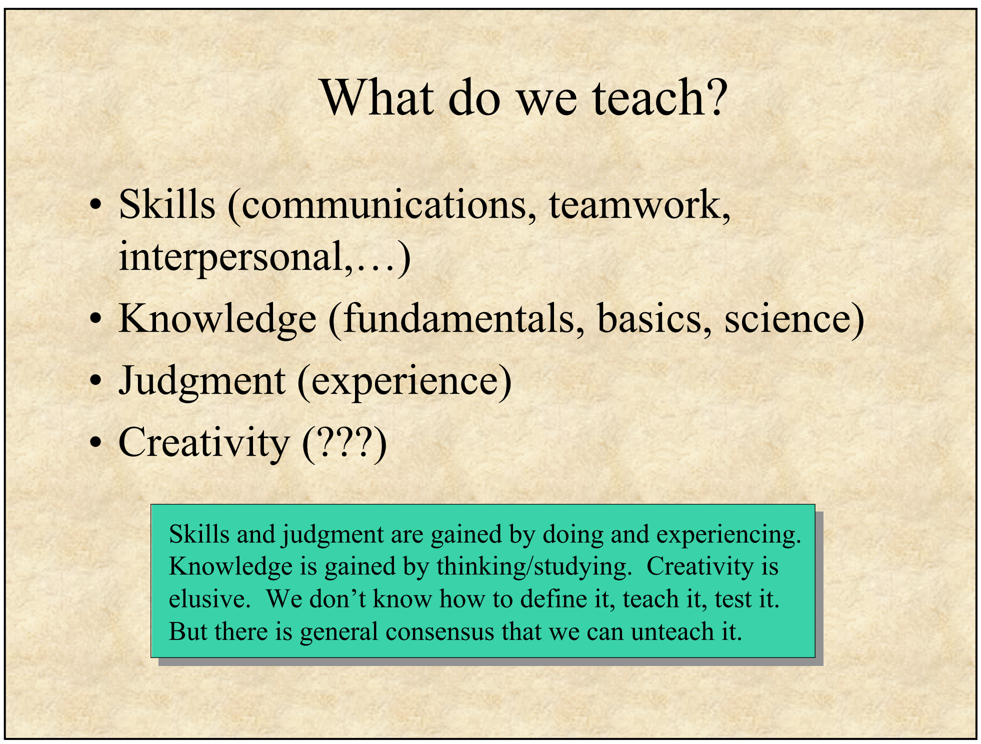
- You cannot know the future with certainty
- If you could:
  - Success/failure would be obvious
  - Implications of choices would be clear
  - Outcomes would be assured
  - There would be no technical reason for poor design decision making
- But all real decisions are under uncertainty

Recognizing that design is the defining element of an engineering education, let's take a look at what we teach. Our engineering curricula include a good deal of mathematics, mainly focused on calculus and differential equations—the mathematics for modeling physical systems. We provide some 20-25 credits of math. Then, of course, we have the engineering sciences, which begin with fundamental courses in chemistry, physics and biology, and proceed into the more specialized sciences such as statics, kinematics, thermodynamics, strength of materials, and so on. Students get some 70-80 credits of the sciences. We sprinkle in some electives—not much in the usual engineering curriculum as there isn't much time, maybe 12 credits. And finally, we have a capstone design course—6 credits. This is what interests me: design is what engineering is all about, design is what defines engineering, design is the main reason why students enter engineering, and we devote less attention in the engineering curriculum to design than we do to the electives.

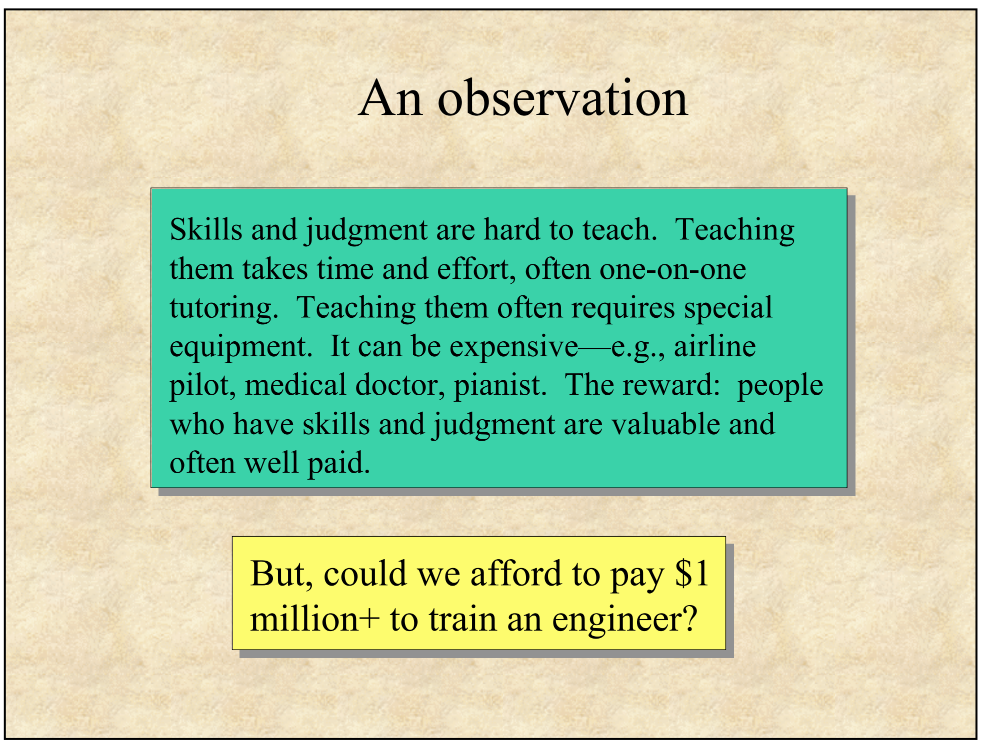


We can classify what we teach into four broad categories. We can teach skills: playing piano, riding a bicycle, teamwork, communications skills and so on. We can teach knowledge: the laws of nature, facts, relationships and causality. We can teach judgment. And then there's creativity. I have question marks on creativity, as I have my doubts about teaching it. I feel that we really can't define creativity clearly, we don't know it when we see it, we have no validated pedagogy for creativity education, and we don't know how to test for it to see if we have done any good at teaching it. About the only thing I have heard agreement on is that we are pretty good at unteaching it. So let me leave creativity out of this discussion.

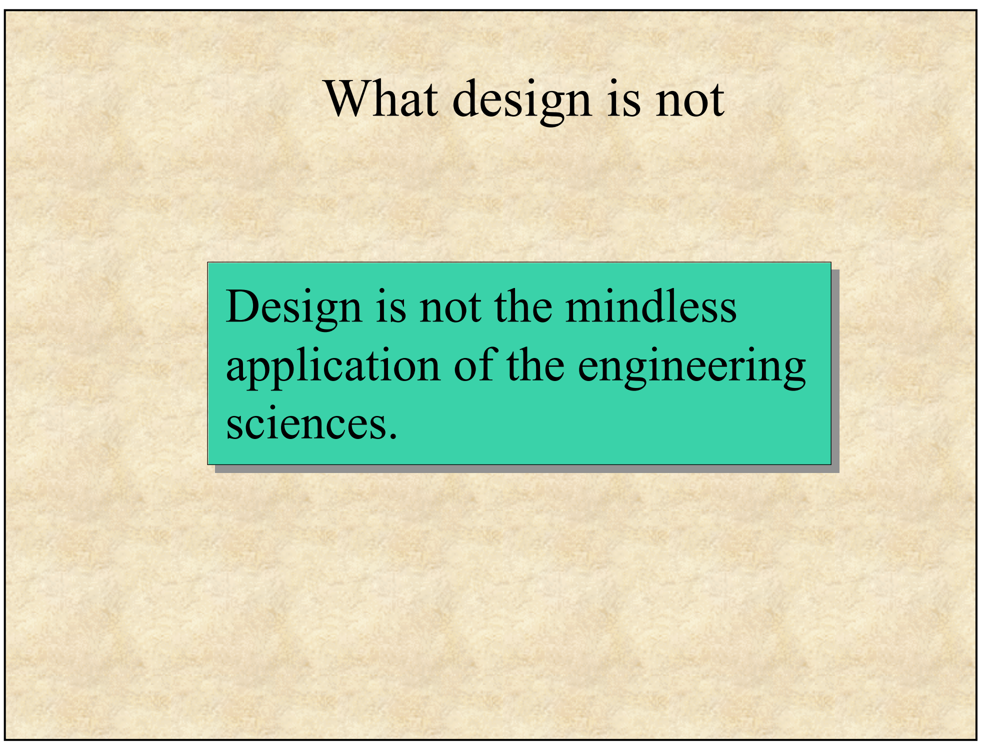
Skills and judgment are gained through experience, often through one-on-one tutoring. Knowledge is gained by thinking and studying. Knowledge is what we teach in lecture classes, and it is taught mainly by reducing concepts to theories and then presenting these theories and their applications.



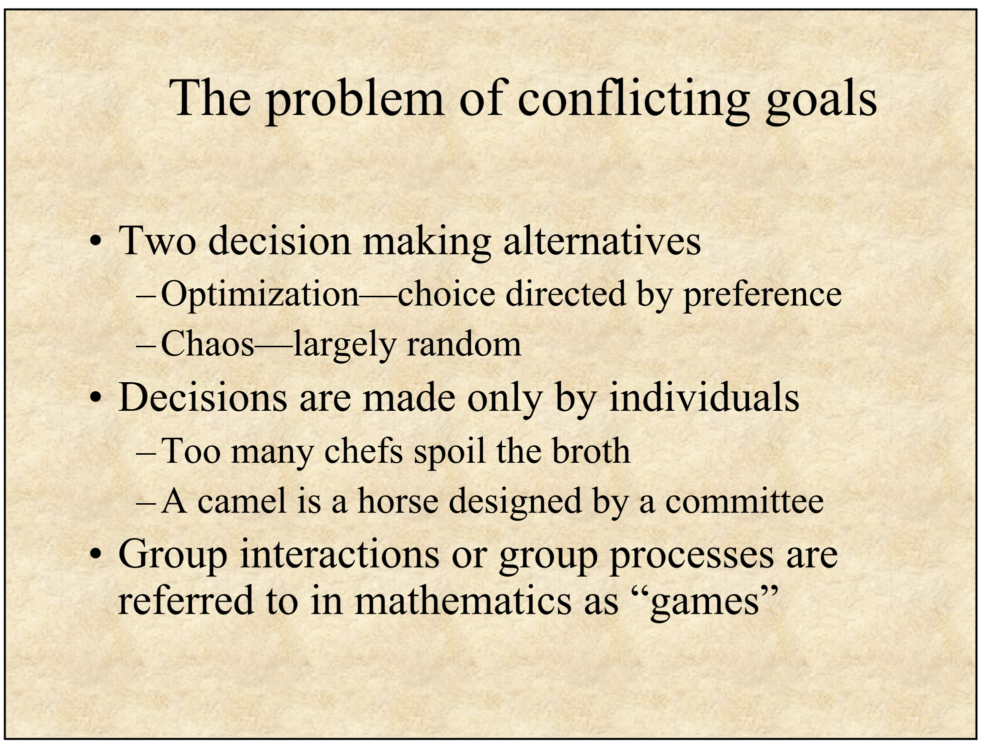
The bottom line here is that skills and judgment are hard to teach. Teaching them can take quite a bit of time—even decades. It can require special equipment and tutoring, and it can be very expensive. To train an airline pilot may cost $2-3 million, for example. But the reward is that people who have skills and judgment are valuable, and they are often quite well paid. The question is, could we afford to spend something in excess of a $1 million to train each engineer? Then, could we afford to pay them well enough to justify this educational expense?



Now, despite all that I have heard, even from academic department chairs, I want to make one thing perfectly clear, design is not the mindless application of the engineering sciences. In my mind, design encompasses much more than the engineering sciences. It is more than a multi-disciplinary activity, it is an omni-disciplinary activity—it includes all conceivable disciplines.



One of the things that designers believe that they have to deal with is the issue of conflicting goals. This is a notion that has stymied progress in design for some time. First, let me say that there are really only two kinds of decision making: decision making that is essentially based on optimization—the choice is directed by the desire to maximize against some preference, such as, I want to make money and more is better; and a process of chaos—essentially decision making by flipping a coin. There really is nothing in between. To understand this, it is important to note that decisions are made only by individuals. We've all heard statements such as these that refer to the chaos that results from group interactions. Groups, in fact, don't "make" decisions. Rather, they have an emergent behavior that is the result of the decisions of the individuals who comprise the group, *and* the rules by which the members of the group interact. The field of mathematics that deals with group processes is called game theory. It was introduced by the famous mathematician John von Neumann and the economist Oskar Morgenstern in their seminal book "*The Theory of Games and Economic Behavior*." I'll come back to this shortly. But suffice to say that all group interactions are, to some extent, chaotic.



So, if groups always behave somewhat chaotically, why do we use groups in engineering design? Well, first of all, the job is just too big for one person. One person won't live long enough to design every piece of a jumbo airliner. And one person doesn't have the knowledge to do it successfully anyway. But more than this, designs often have to satisfy a group—consumers, for example—and it seems logical that the design process could benefit from the insights of a group of designers.

The need for group processes in engineering design

- One person can't do it alone
- We have to satisfy a group
  - Insights gained from members of the group should help, right?

But there are severe pitfalls of group processes that have important, and often negative, impacts on engineering design. First, although it might not seem so, unless a group is led by a dictator, the results of the group process are essentially random, that is, they are chaotic. This is hard to comprehend, especially for people who believe that they have recently had a "good" group experience. After all, many group processes seem so well organized and directed. But, clearly, the results of a group interaction depend critically on the rules of the interaction. Just think of a sports event. Team A wins, team B loses. But the result could have been quite the opposite if some little rule—a penalty rule, for example—had been different. Of course, you might think, what we need is to assure that group interactions simply proceed under a good set, the "right" set, of rules. This is the key issue—the rules—and it is addressed by Arrow's Impossibility Theorem. Kenneth Arrow is a Stanford economist who won the 1972 Nobel Prize in economics for the work he did in his PhD thesis in 1951. His work has been well vetted by a number of highly qualified experts, and it really bears paying attention to.

The pitfalls of group processes in engineering design

- Unless the group is led by a dictator, the results are essentially random—chaotic
  - This is hard to comprehend—group processes often appear well organized and directed
- Clearly, the results of a group interaction depend upon the rules of the interaction
- The key issue is addressed by Arrow's Impossibility Theorem

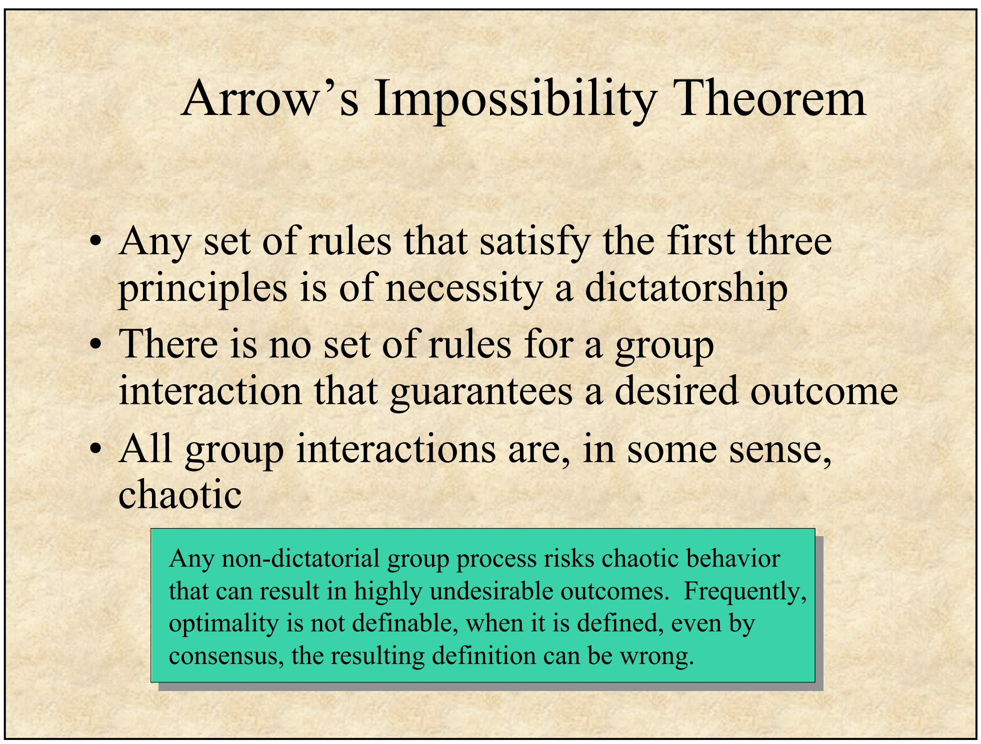
Arrow focused on voting as the key group process. But voting is the essence of choice in a group process. It is how groups develop their emergent behavior. So Arrow postulated that the rules by which the group evolves its behavior should have certain rather obvious characteristics: (1) If everyone in the group prefers alternative A, then the group should choose A. (2) If the group agrees that A is preferred to B, and the group agrees that B is preferred to C, then the group should agree that A is preferred to C. (3) If the group is asked to express a preference between A and B, the result should not depend on the presence or absence of alternatives C or D or E. And, finally, (4) that more than one person in the group should have a say—that there is no dictator in the group who gets to make all the decisions irrespective of the preferences of the others in the group. These characteristics are pretty straight forward. The first seems obvious by examination. The second is needed for the group to be able to agree on a choice. If A is preferred to B and B to C, but C is preferred to A, there is no best choice for the group. Every alternative possesses a better alternative. And the third condition is needed to affect any choice, because additional alternatives, however irrelevant, can always be added. So these characteristics are really basic to rational group behavior. Without them, a group cannot behave in a rational way.

What are the right rules for a group interaction?

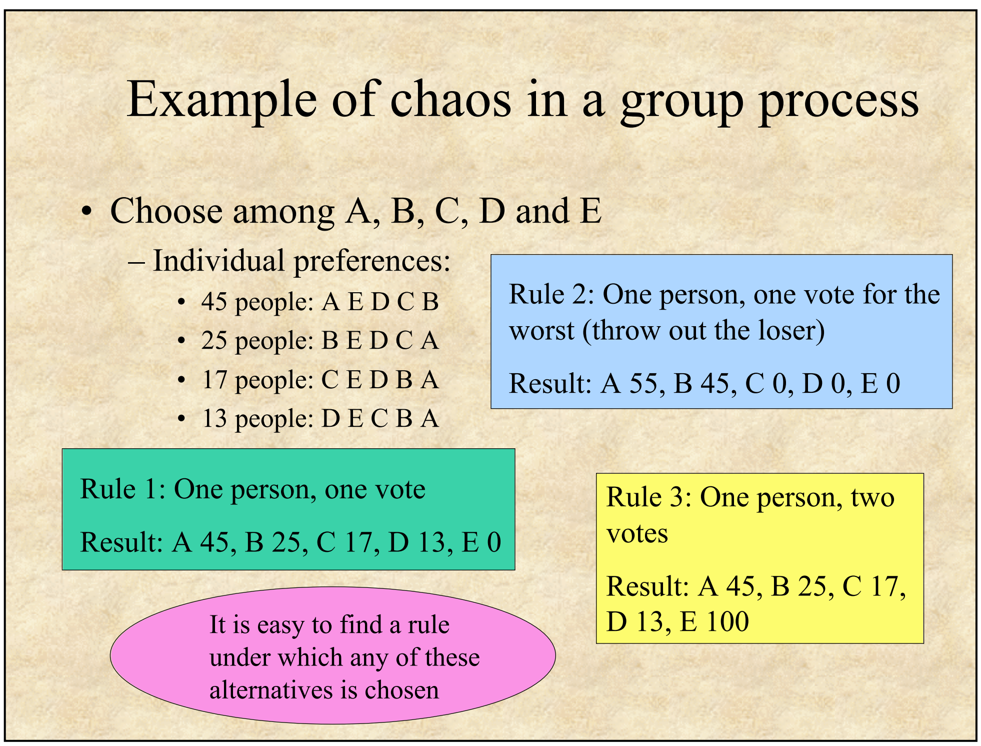
- Principles:
  - If everyone in the group wants A, the group chooses A
  - If the group would choose A over B, and B over C, the group would also choose A over C
  - If the group is asked to choose between A and B, the choice does not depend on whether C (or D or E) is also on the table
  - Everyone in the group gets a say (no dictator)

But Arrow’s Theorem provides us with the alarming truth: any set of rules—ANY SET—that satisfies the first three characteristics is of necessity a dictatorship. That is to say, no set of rules exist or can be found to exist that enable a group to have rational behavior. All group interactions are, in this sense, chaotic. What this means is that the behavior of a group depends as much on the rules of the interaction as it does on the individuals who make up the group, their preferences, and what they bring to the group. Optimality for the group is frequently not definable and, even when it is, no set of rules exist to assure that the group’s behavior is, in any sense, optimal.

This has profound implications for engineering design, because what it says is that one can never be sure that a design that is the result of “teamwork” is the best possible design, the worst possible design, or anything in between. Indeed, one can be pretty certain, especially given the myriad of design possibilities, that any group design will be well off optimal. This is a strong case for dictatorial design, or at least for making a strong attempt to minimize the group-choice aspect of design.

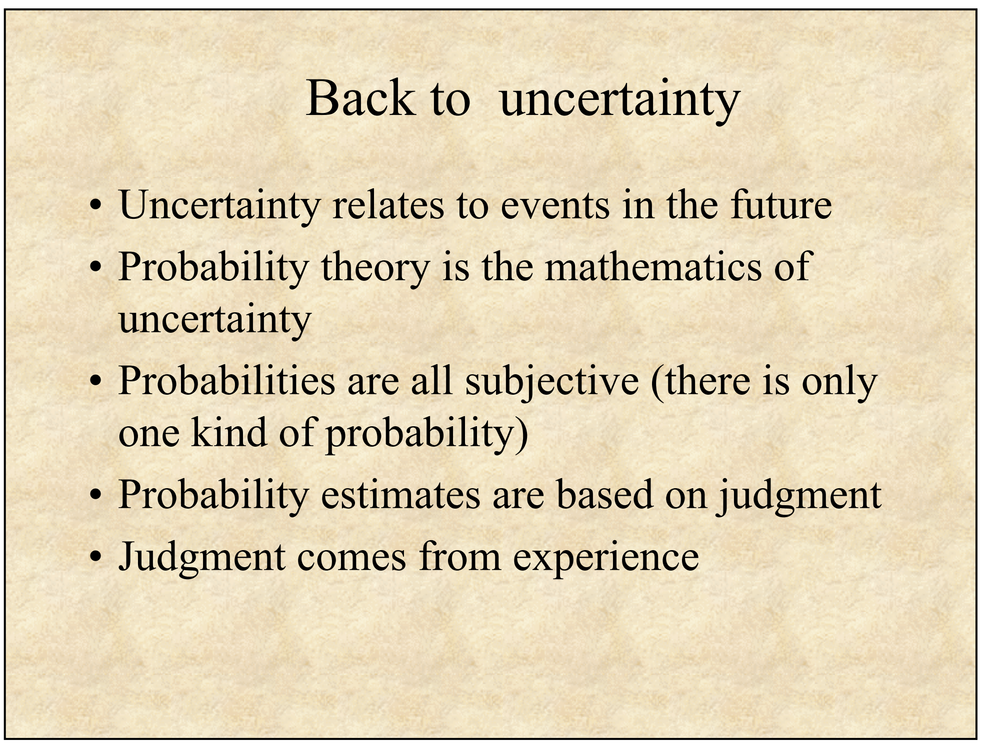


I know that, for all of you who have had great teamwork experiences, this stuff is really hard to believe. So I need to leave you with an example. Suppose a team of 100 people are trying to decide among five alternatives: what color should we design this thing—red, green, blue, orange, yellow (A, B, C, D, or E)? Let's say the preferences of the 100 individuals are as given: for example, 45 people like these in the order A, E, D, C, B (A is best, B is worst). 25 prefer the order BEDCA, 17 prefer CEDBA, and 13 prefer DECBA. Now, if the group decides to pick their preferred color by a one-person-one-vote procedure, it's easy to see that A is the winner by a wide margin. Of course, everyone would walk away happy with the process, and confident that it was a good process, although many people, as individuals, would be dissatisfied with the result. On the other hand, if the group decides to throw out the worst color before moving on, then clearly A would be thrown out. Or, if the group decided to allow each person two votes (vote for the two colors you like best), then E would be the winner. You see, the winner depends on the voting rule used, not upon the preferences of the people voting. And you can verify for yourself that it is actually easy to find a voting rule under which any of the five alternatives is the winner, all without changing the preferences of the voters. The choice of voting rule introduces chaos in the result. But—Arrow's Theorem—there is no correct voting rule. So you are doomed to endure chaos if you want a group process.

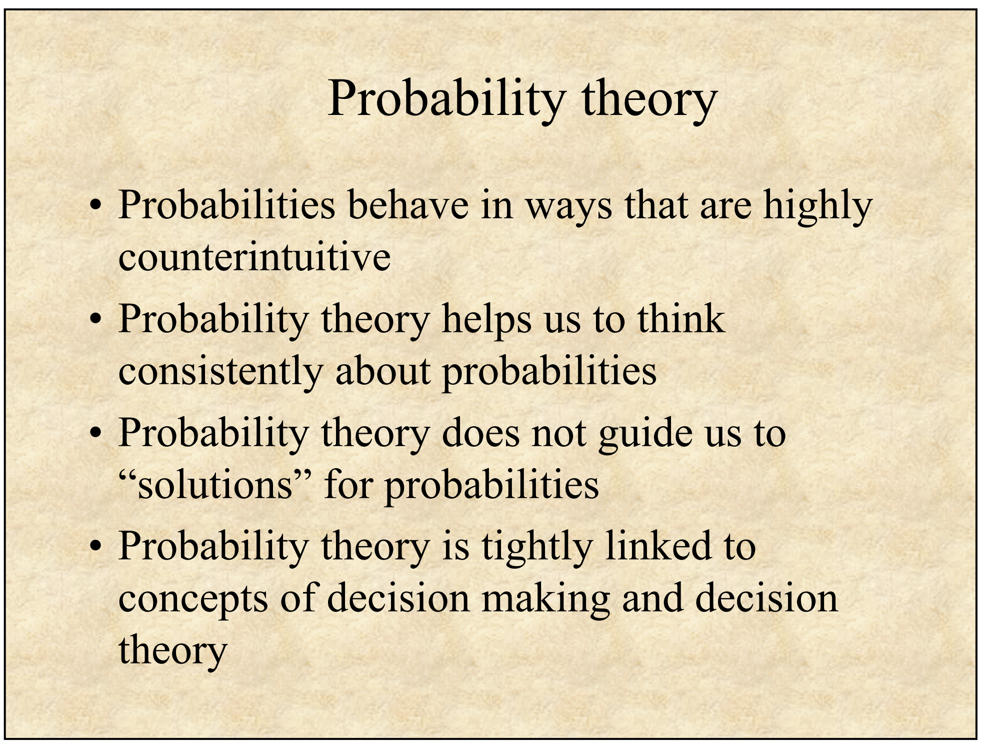


Now let me come back to uncertainty. Uncertainty is a term that we use to refer to events that are in the future, and only to events that are in the future. Probability theory is the mathematics of uncertainty. Because probabilities relate to events that are in the future, we have no data on them—EVER! Ergo, ALL PROBABILITIES ARE SUBJECTIVE. There just is no other kind of probability. Probability estimates are based on judgment, not on data. Data may be used to influence our judgment, but the data are never on the event in question. They may be on similar events, but never on the future event. What this means is that it is futile to say, "I don't have the necessary data to estimate that probability." You never do and never will. What you need is judgment, and judgment comes from experience.

So, engineering design involves dealing with uncertainty. Understanding of uncertainty comes from judgment, and judgment comes from experience. But our engineering curricula don't focus on design experience, so we largely fail to teach judgment.



I need to add a few words about probability theory. Probabilities behave in ways that are highly counterintuitive. What probability theory does is to enable us to think consistently about probabilities. It does not guide us in any way toward "solutions" for specific probability numbers. Another thing about probability theory is that it is closely linked to decision making. After all, the main reason for thinking about probabilities is that we care to make decisions, and we want our decisions to be consistent with what we know and what we want. Putting probabilities into the context of decision making imposes severe restrictions on them. I urge you to look up the Dutch Book. The Dutch Book is a bookie who makes bets in such a way that he always wins. And the Dutch Book mathematics shows that ONLY Kolmogorov probability provides a self consistent framework for decision making. ALL other approaches, such as fuzzy logic, fail the test of self-consistency in the context of decision making.



So, let's start to wrap up our thinking here. The key to good design is good decision making. But all real decisions are under uncertainty and risk. So good decision making demands a good understanding of uncertainty and risk. A good understanding of uncertainty and risk comes from good judgment. Good judgment comes from experience, and gaining experience takes time and it is expensive. So, how can we educate good design engineers without it taking decades and costing a fortune?

Good design

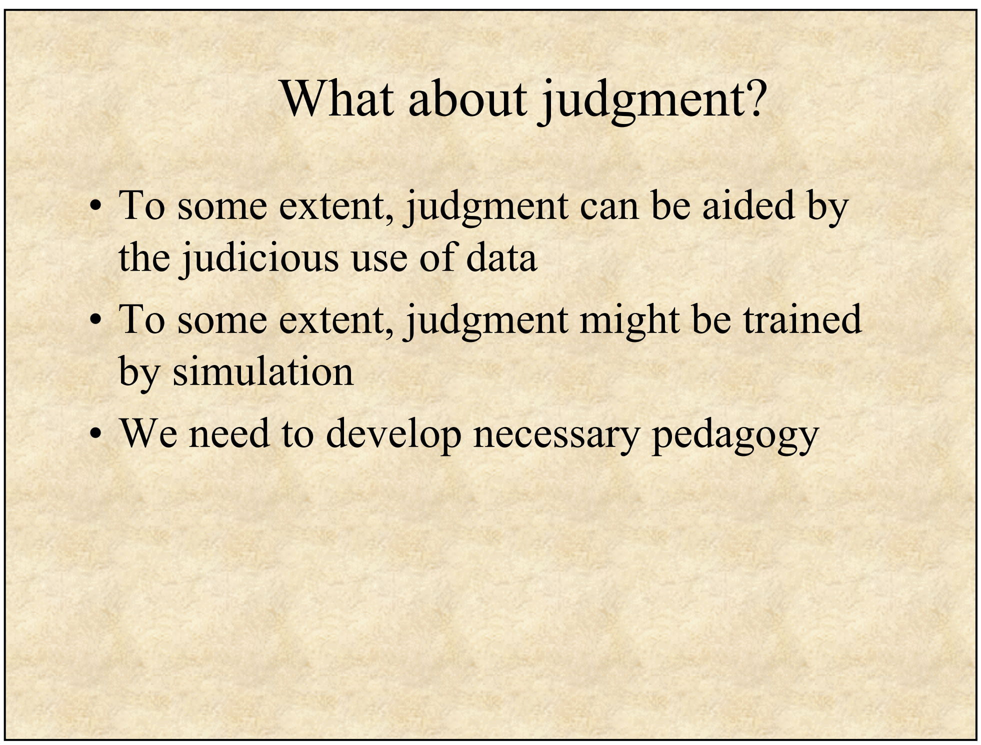
- The key to good design is good decision making
- Good decision making demands a good understanding of uncertainty and risk
- Good understanding of uncertainty and risk comes from good judgment
- Good judgment comes from experience
- Gaining experience takes time and it is expensive

We have observed that the teaching of skills and judgment is time consuming and expensive, while the teaching of knowledge is relatively quick and cheap. Now the trick is that we can convert skills to knowledge through the development and teaching of theory. For example, one way to teach addition would be to present the student with column after column of numbers and ask the student to memorize the column and the results. But there are infinite columns of numbers to memorize, and the process will take eons. On the other hand, addition can be reduced to theory—a set of rules—which, when learned allows the student to do addition. And these rules can be quite compact and simple to learn. The same is true with design. The development of a theory of design, that is, a theory of design decision making under uncertainty and risk, and the teaching of this theory will obviate the need for much of the skill and judgment demanded by our current approach. In short, a unifying theory enables us to use one or a few case studies to impart the necessary skills and judgment that, without the theory, would take many cases and years of experience.

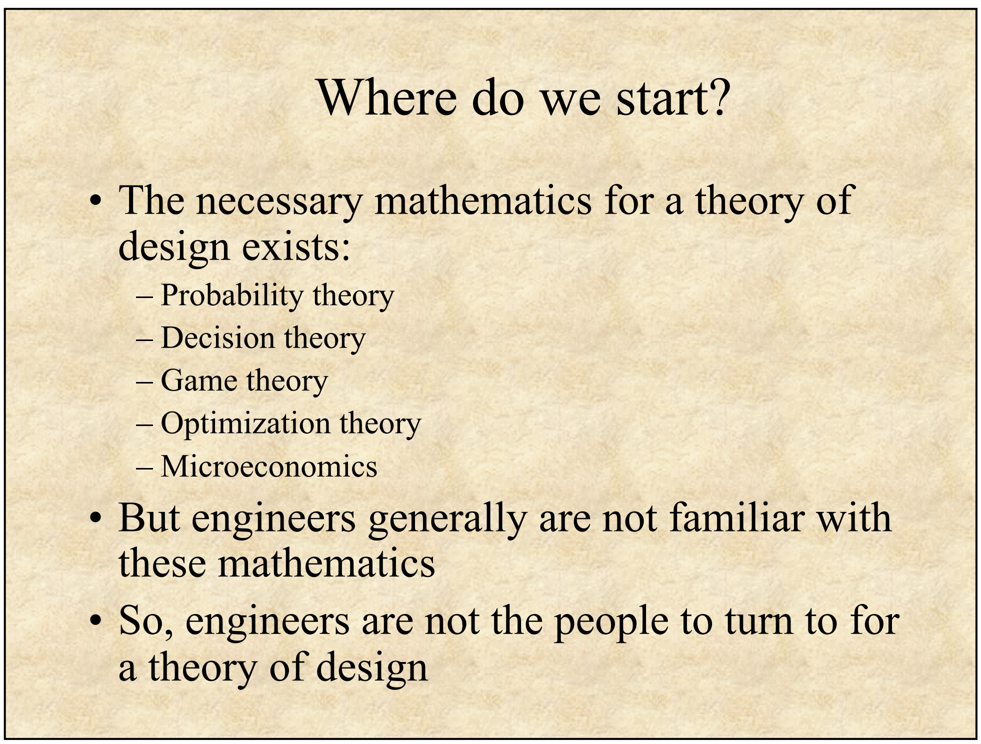
An alternative

- The teaching of skills and judgment is time consuming and expensive
- The teaching of knowledge is quick and cheap
- Skill can be converted to knowledge through the development of theory—knowledge of the fundamentals
- Development of a theory of design will greatly enhance design education

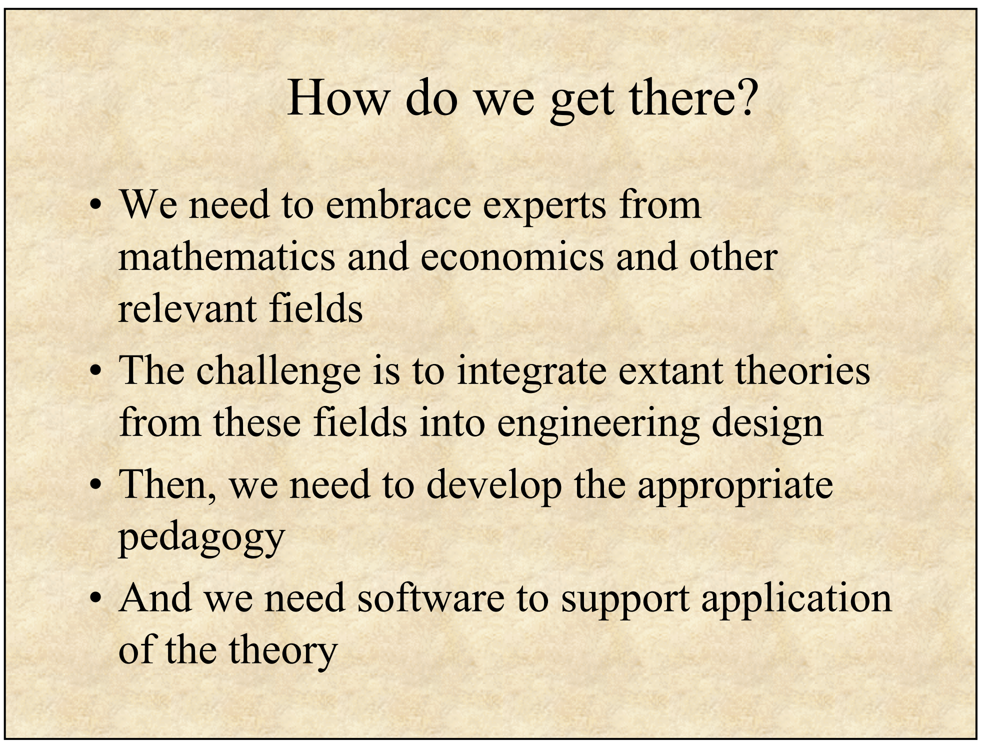
What about judgment? Can we effectively teach judgment in a compact experience? I believe that judgment can be aided by the judicious use of data, and it might be trained by simulation. I would call for development of the necessary pedagogy to improve the teaching of judgment in the engineering curricula.



So, where do we start? Fortunately, we don't have to develop any new theory. It already exists, and has for quite some time. The necessary mathematics include probability theory, decision theory, game theory, optimization theory, and microeconomics, to mention several. The problem is that engineers are generally not familiar with these mathematics, and they don't see their applicability. So, engineers are not the people to turn to for the development of a theory of design. Let's face it, engineers have had over 50 years to develop a theory of design, and they haven't done it yet. So, why would we choose to believe that they will in another 50 years.



What we need to do is to embrace experts from other fields, such as mathematics and economics, and ask their help in developing a theory of design and supporting pedagogy. The challenge is to integrate extant theories from related fields into engineering design. Although this is straight forward, it is not trivial. It will take drastic revision in our thinking and wholly new ways of approaching design. For example, I contend that we will throw out the concept of requirements altogether, and replace them with preferences. Requirements offer no decision guidance whatever among alternative designs that meet the requirements. Preferences provide guidance across the full range of alternatives. Nor will it be trivial to implement a theory of design as it can be computationally intensive. Thus, support software will greatly aid in the necessary transition.

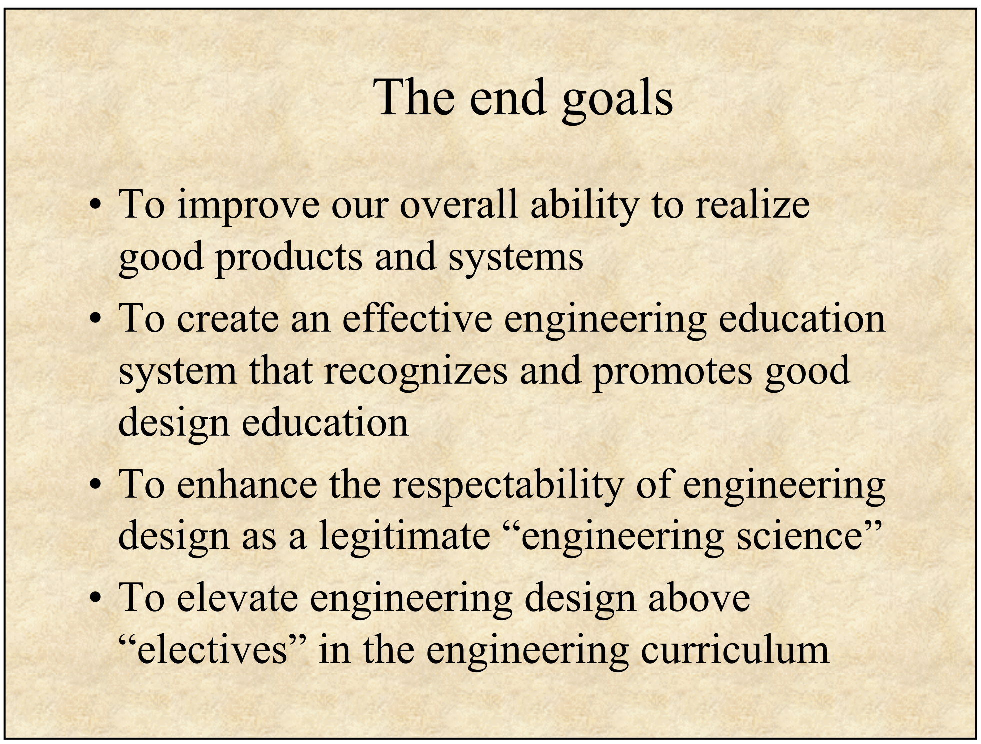


Nor is it the case that no progress has been made to date. An underlying theory of design has already been proposed. Called “decision-based design,” the theory is based on the mathematics of decision theory. This theory is slowly gaining acceptance, however, it leads to approaches that are far afield from the conventional, requirements-based approach, and it demands a full rethinking of our approach to design. The development of support software could well pace much of the transition to decision-based design.

Progress to date

- An underlying theory and framework has been proposed for “decision-based design”
- It is slowly gaining acceptance
- Its implementation will depend on the development of support software and the continued development of supporting theories (demand theory, simulation theory, optimization theory, etc.)

So, in my mind, the way to improve design education is to provide a theory of design that allows us to move design away from a skill and judgment-based activity and toward a knowledge-based activity. Not only will this improve our overall ability to realize good products and systems, but it will allow us to create an effective engineering education system that recognizes and promotes good design education. One of my personal goals has been to elevate the respectability of engineering design as a legitimate "engineering science," and I look forward to the day when the emphasis on engineering design in the engineering curricula matches the emphasis we currently place on electives.



Teaching Design Across Disciplines

Blaine Lilly
Ohio State University
Columbus, OH

I mention my background here because I believe it's relevant to how I approach teaching. My experience as an apprentice tool and die maker at General Motors 25 years ago has affected how I view teaching and learning. My goal as a teacher has been to try to bring part of the "one on one" apprenticeship experience into my classroom in one of the largest universities in the U.S.

Background

- Tool and die maker, General Motors
- BS and MS in mechanical engineering
- PhD in industrial and systems engineering
- Biases:
  - Undergraduate education is crucial
  - Manufacturing and design are inseparable
  - "Hands on" experience is invaluable

This slide is just intended to give some idea of the size of Ohio State, which is one of the largest campuses in the country. While we are not one of the elite schools, we nevertheless turn out thousands of engineers who go on to careers in industry, government, and academia.

More than football:

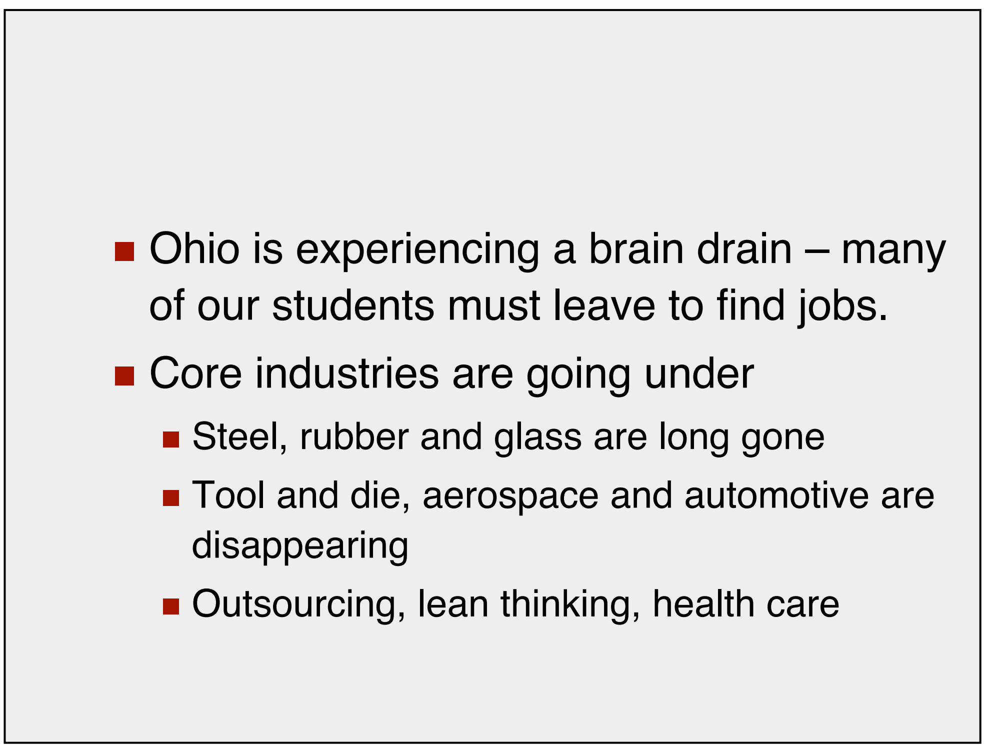
- Ohio State is **large**:
  - 50,000+ students on Columbus campus
- College of Engineering:
  - 5500 undergraduates – 15% of OSU total
  - 1500 graduate students – 80% international
- Sixteen degree–granting programs

Like most state–supported schools over the past decade, Ohio State is struggling to maintain our quality in the face of relentless annual budget cuts. Our situation is made worse by the fact that we must compete in the legislature for funding with nine other state universities, each of which has a local constituency. As a result, although we're the "flagship" university for the state, we do not have the same clout that a Purdue or a Penn State has in their respective states.

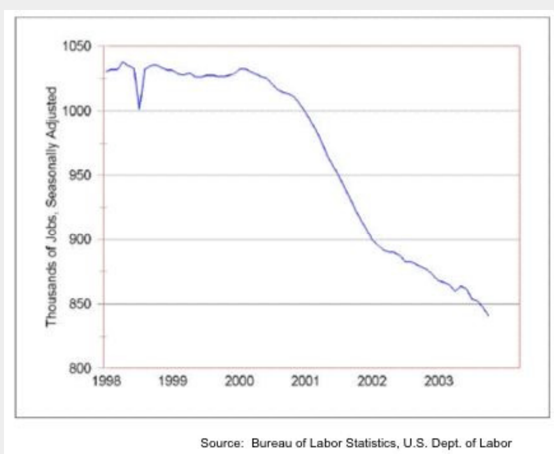
The bigger picture

- State support has declined steadily
  - FY 2003: $2.7 billion total budget
  - State of Ohio provides $471 million
- Ohio has 9 other state universities that compete for funding.

This slide and the next slide are merely intended to provide context for what is happening in our region. While the numbers are for Ohio, the picture is much the same in Michigan, Illinois, Pennsylvania, and West Virginia. The traditional industrial heartland of the U.S. is dying, and very little is being done to reverse these trends.



Manufacturing in Ohio



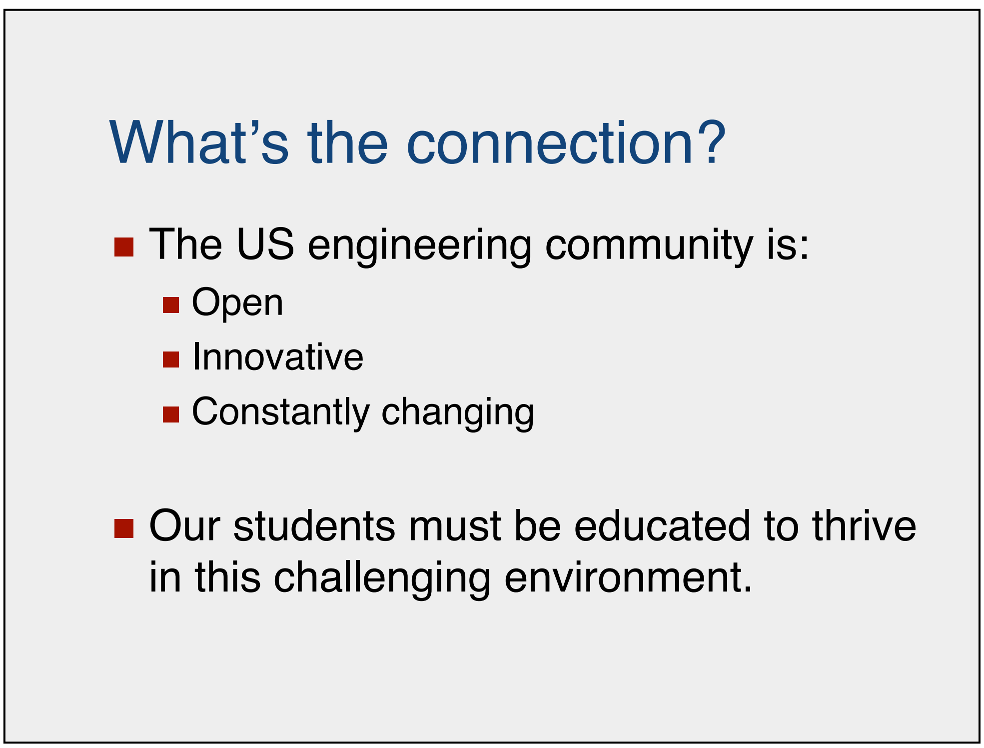
179,000 jobs lost since July 2000

Here I attempt to make a connection between the environment I teach in and the role played by product design. I firmly believe that good product design is intimately related to a strong manufacturing economy. It's impossible to do product design effectively without a good understanding of manufacturing processes. When a nation loses its manufacturing prowess, as England did in the 1950's, then technological prowess will also follow. The question for us as educators is, what can we do?

Why does this matter?

- Product design and manufacturing are inseparable.
- If manufacturing leaves, design will follow – consider England vs. Germany.
- As educators, what should our response be?

The solution I've come up with is this: the U.S. clearly cannot compete in the "widget world", where we try to manufacture low–cost goods competitively. China will own those markets for years to come. Our only hope is to concentrate on high–end products. Along with that, we need to train our young engineers to be open–minded, innovative, and aware that they can never stand still. We must make our students understand the world they're entering, and the need to keep abreast of it.



I think our narrow, focused view of engineering must change. This is a tough sell to professors, who are rewarded for being specialists. Specialization is of course necessary for Ph.D's, but we need to understand that at least 90% of our students will never go further than a Masters degree, at most. We need to expose our undergraduates to the tools they'll need to survive in a world where breadth of knowledge is as important as depth.

Challenges

- We must find ways to:
  - Demolish the silos
  - Expose students to the big picture
  - Provide exposure to
    - Business
    - Economics
    - Language
    - Psychology
    - Industrial Design

This course has been developed slowly over the past ten years, and is the only course in the College of Engineering at Ohio State that deals with the issues I’ve mentioned. The course has been very heavily subscribed for several years, and has had consistently high evaluations from the students.

ME/ISE 682: Fundamentals of product design

- Students from ME, ISE, EE, Aero, WE, Material Science, Architecture, Ind Design
- Seniors, first–year grad students
- Four credit hour technical elective
- 40 students per quarter, three per year
- 3 hours lecture, 2 hour lab per week

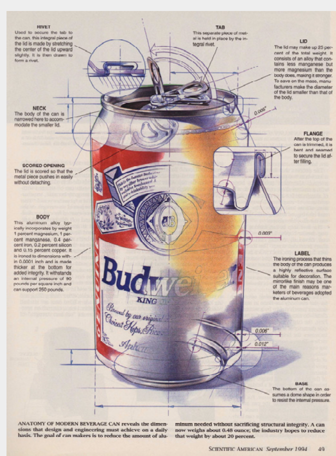
This slide is self explanatory. The overriding goal is to put what they've learned for four or five years into some logical context, and get the students to understand something of the history of engineering, and the importance of design.

My approach

- Teach with artifacts
- Maximize hands–on experience
- Multi–disciplinary focus
- Relate to engineering history
- Fill the gaps
- Embed design in context

I use this example in many classes to point out the importance of constraints on design. In this case, the fact that 300 million cans are produced in the US every day leads them to understand how material costs can drive a design. A very good reference here is the article by Hosford in the September 1994 Scientific American.

An artifact they know well…



More artifacts

I have made extensive use of the Kodak single–use cameras in the classroom. The cameras are cheap, but are highly engineered objects. I've used these to teach freshmen, seniors, and NASA engineers, and every group can find something about the cameras to relate to.

Uses for cameras:

- Product portfolios
- System architecture
- Design for manufacture
- Injection molding
- Intro to statistics – freshman engineering
- Lean assembly methods

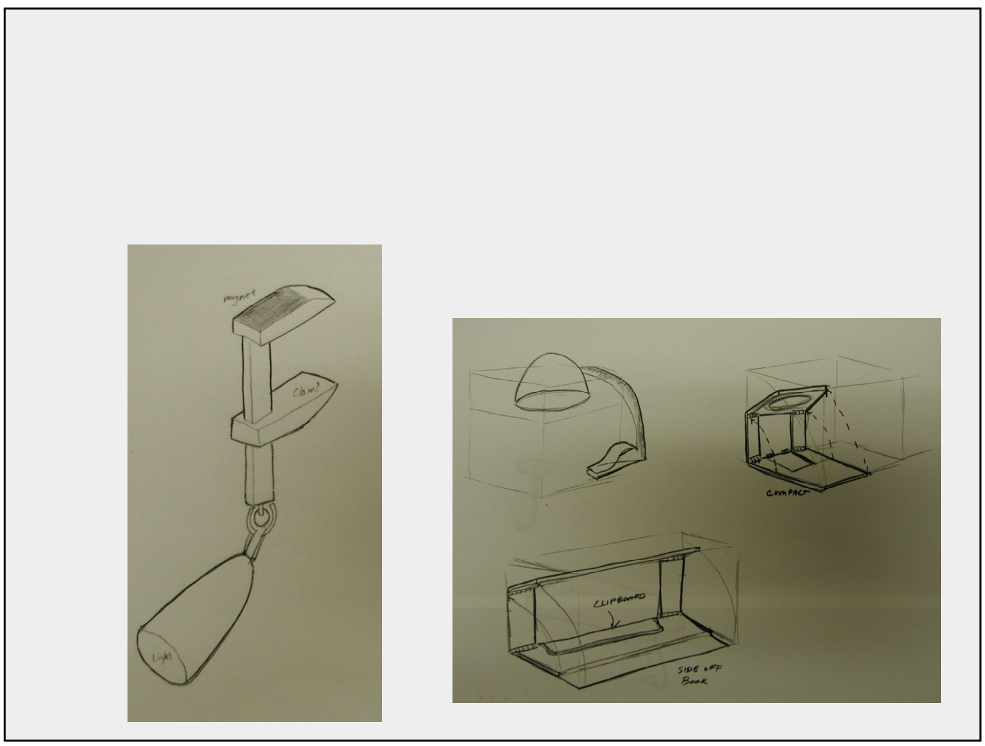
Here we use hundreds of disassembled cameras in a lab to teach the students the principles of lean vs mass assembly. The students often have done similar exercises with paper airplanes, etc., but find that assembling real devices makes the exercise much more interesting.

I also believe that engineering students need to spend more time in the early stages of design, meaning conceptualization. I have worked with colleagues from Industrial Design to teach my engineering students how to sketch quickly in three dimensions for the purposes of communication and ideation. Even a few hours training can lead to quite a bit of improvement in these skills.

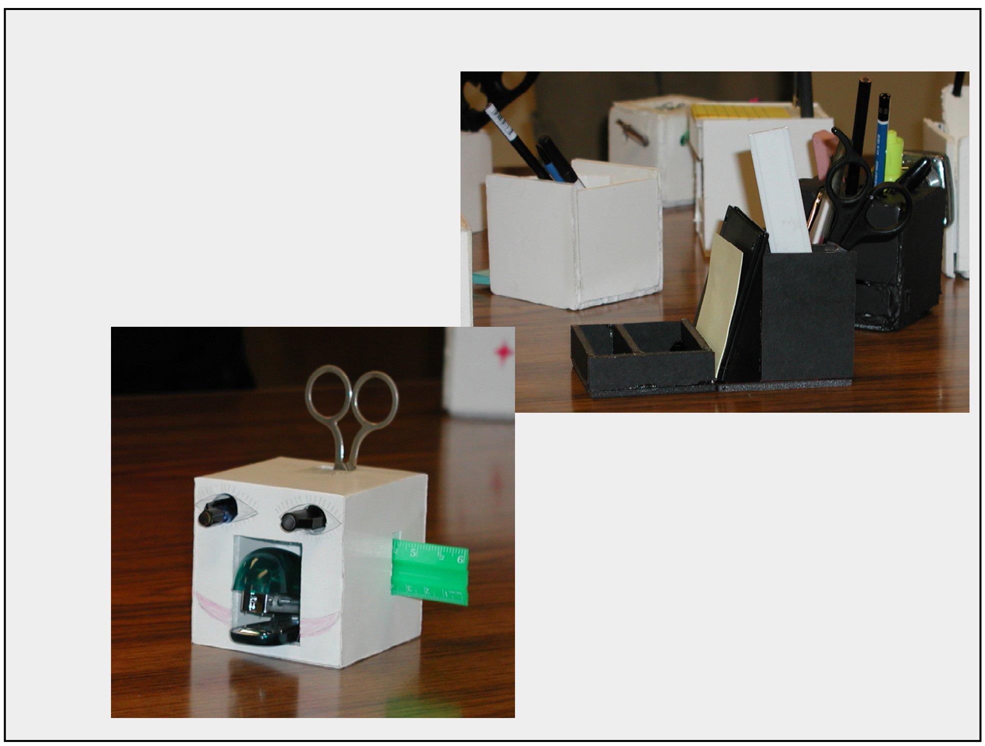
Maximize "hands on"

- Students typically have little exposure to "hands on" design experiences.
- Curriculum is heavy on analysis, light on design
- I emphasize:
  - Perspective sketching for ideation
  - "Quick and dirty" prototype building
  - Product disassembly and analysis

Example sketches from students after six hours of training.



Following the sketching exercise, the students build three dimensional prototypes from foam core and other cheap materials. The point here is to get them to see their ideas in three dimensions. I believe that this exercise is a necessary complement to learning CAD skills.



This slide is self explanatory, and these days, I'm preaching to the choir. I think it's very useful to bring design and architecture students into engineering classes such as this one, because they show the engineering students that there are other valid ways to approach problems. The engineering students typically enjoy the interaction, as well.

Multi–disciplinary focus

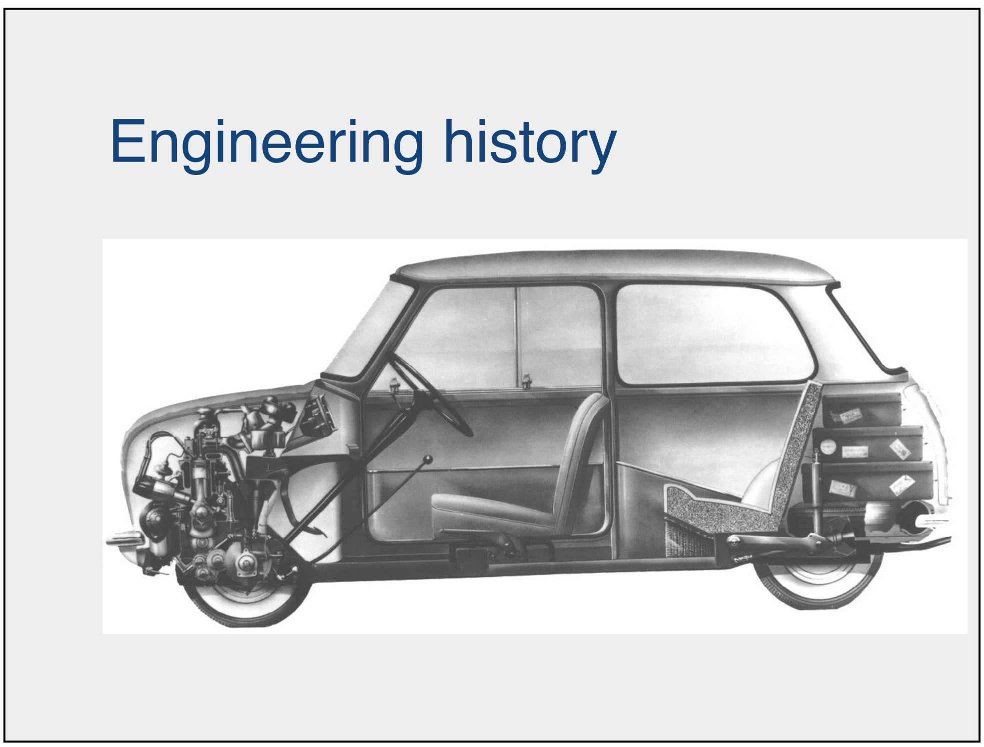
- Teaching to engineers, architects, and industrial designers can be constraining.
- Student teams are mixed by discipline.
- ID and architecture students add "yeast" to the student teams.
- Students typically enjoy the interaction.

A few brief thoughts on the discipline of industrial design. ID as a discipline has changed in the past decade or so, with much more emphasis placed on designing artifacts that work well and are environmentally sound, in addition to looking good. My interactions with industrial designers have been very positive.

The ID perspective

- Emphasis on ideation and creativity
- Willingness to iterate early on
- “Get physical fast”
- Scenario modeling
- Cognitive engineering: human – machine interface

The original Mini, designed by Alex Issigonis. A fine example of designing within strict constraints.



I see my product design course as an opportunity to plug some of the gaps in our program at OSU. Many tools and techniques current in industry are overlooked in the university, and here I list some of the tools that I expose the students to.

Fill the gaps

- Concept generation and selection techniques
- QFD methods
- System architectures
- Functional decomposition
- Boothroyd–Dewhurst DFMA
- Lean manufacturing

Where we intend to go from here. The next logical step is to develop a program in product design at the M.S. level, and institute a minor for undergraduates in design.

What's next?

- Create an interdisciplinary design program at the M.S. level
- Interdisciplinary minor in design
- Year–long senior design projects

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01- 07 - 2004	Conference Publication	

4. TITLE AND SUBTITLE	
Innovative Design of Complex Engineering Systems	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Ahmed K. Noor, compiler	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER 755-80-00-01
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23681-2199	**8. PERFORMING ORGANIZATION REPORT NUMBER** L-19032
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	**10. SPONSOR/MONITOR'S ACRONYM(S)** NASA
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) NASA/CP-2004-213244

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 38
Availability: NASA CASI (301) 621-0390 Distribution: Standard

13. SUPPLEMENTARY NOTES
Noor: Center for Advanced Engineering Environments, Old Dominion University
An electronic version can be found at http://techreports.larc.nasa.gov/ltrs/ or http://ntrs.nasa.gov

14. ABSTRACT

The document contains the proceedings of the training workshop on Innovative Design of Complex Engineering Systems. The workshop was held at the Peninsula Higher Education Center, Hampton, Virginia, March 23 and 24, 2004. The workshop was jointly sponsored by Old Dominion University and NASA. Workshop attendees came from NASA, other government agencies, industry and universities. The objectives of the workshop were to a) provide broad overviews of the diverse activities related to innovative design of high-tech engineering systems; and b) identify training needs for future aerospace work force development in the design area. The format of the workshop included fifteen, half-hour overview-type presentations, a panel discussion on how to teach and train engineers in innovative design, and three exhibits by commercial vendors.

15. SUBJECT TERMS
Aerospace systems; Innovative design; Design education; Design thinking; Design practice

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	285	(301) 621-0390

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18