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Design Education in a Research University

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**“design is what sets engineering apart
from the sciences”**

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Introduction

The word design can mean very different things in different Industry settings and in different University settings. In all cases there is a recognition that both the science and the art of engineering are important in the practice of engineering but beyond that views diverge. Industry needs engineers who perform well in collaborative design teams and Universities require students to excel as individuals first and foremost.

Industrial design philosophies range from classical form-follows-function to radical function-follows-form and the popular concurrent-form-and-function. Implicit is the notion that engineering design is about Products that are manufactured. That notion may change as the economy moves toward a Services economy and manufacturing moves from mass production to mass customization. But manufacturing is not going away, it is evolving as the economy changes and Services are embedded in Products.

Among Universities there are different educational models for research Universities and teaching Universities. These differences have virtually eliminated design from many research Universities. This White Paper is an attempt to define the pedagogical needs for design education in a research University given the changing needs of society for engineers in the 21st Century. A century where the traditional "Hypothesis" driven approach to science currently taught is evolving

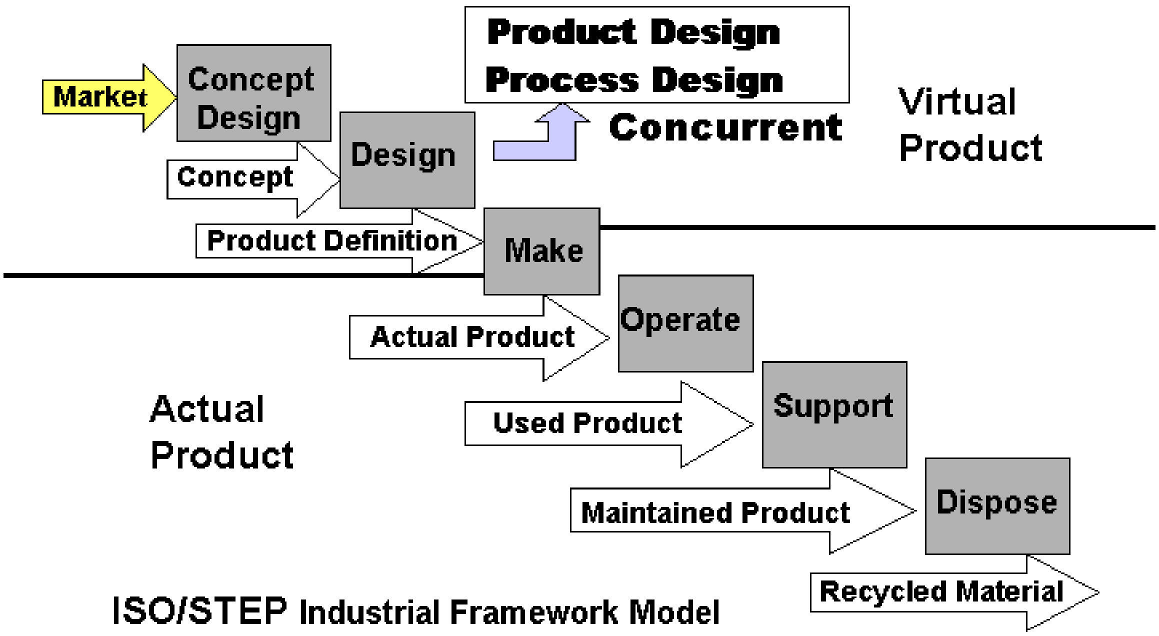
to include "Discovery" based methods being used so successfully to design new drugs and biomaterials.

Current Assessment

Industry

An ISO Industrial Framework Model covering the entire product life cycle for a manufactured Product was published in 1998. It was developed by representatives from several industries working in collaboration over nearly a decade. A figure from that document is adapted for this analysis to illustrate the role of design in several major industries; aerospace, automotive, shipbuilding and what are often called heavy industries. The ISO document develops this industrial framework in great detail for the Idealized Life Cycle Processes

Product Life Cycle Design Context



ISO/STEP Industrial Framework Model

needed to design, make, operate, support and dispose of a manufactured Product. Many disciplines are required and the level of detail increases as the product progresses from concept to production. The ability to simulate product performance and manufacturing processes has led many large companies to use virtual product design methods early in the design cycle to analyze hundreds of conceptual designs before making fundamental decisions. Once basic configuration and major component decisions are taken they are very difficult to change for economic reasons. As every manufacturer knows the cost of design changes go up exponentially with time.

A weak link in many conceptual design processes are the functional models used even though advanced design teams have some of the best and the brightest engineers in the organization. They must be expert in their own discipline; mechanical, electrical, chemical, etc. and they must have a clear understanding of how these disciplines and financial models interact for the Product being designed. However, the models they use are often little more than spreadsheets. The transition from conceptual to prototype design requires moving from generic to specific Product and Process models requiring much more detail and actual not virtual data. This is a design team activity fraught with compromise and opportunities for human error as real world issues emerge in the building of the first prototype.

A more common problem in many design-build teams is poor communication between design and manufacturing and suppliers. This can lead to a cultural schism if engineers fail to understand that they share responsibility for the entire life cycle of their designs.

Poor communication also can result from legacy processes that while reliable when time is not critical, tend to break down when pressure builds to get to market faster and cheaper. As a business struggles to bring exciting new products to market on schedule and budget it takes a strong engineering team to transform a winning design into a successful Product; especially one that becomes a platform for many derivative Products, a Pentium chip architecture for example.

University

Engineering education at research Universities like UCI includes a few design classes but usually only as a branch of applied mathematics and not as something at the very core of the practice of engineering. Multidisciplinary design optimization is one of many mathematical tools that systems engineers' use but without a solid understanding of life cycle design requirements the tools are just as likely to create a disaster as a robust design. At the philosophical level it becomes a question of how to integrate the art and the science of engineering in the curriculum of a research University without sacrificing the research that sparks creative new endeavors.

Today at American research Universities, with the emphasis on science-based curricula, design and product life cycle design issues are given little serious classroom attention. Interestingly this is also an engineering weakness in many American product design teams as evidenced by lost market share and jobs when time-to-market, life cycle quality and warranty cost issues kill profits. The ability to turn the results of research into next generation Products and Services is

critical to financial health and the WSJ investment community measures company performance on exactly these issues. The American economy today is the engine that fuels much of the demand for engineers worldwide but our market share in aerospace and automotive not to mention shipbuilding has been in decline for years.

This does not mean that research Universities should educate engineers in life cycle design details but it does mean that more should be done to introduce life cycle functional requirements and to prepare students for the collaborative design environment found in the practice of engineering.

MIT and other American Universities have responded to Industry requests for design education in a variety of ways. Capstone projects with student teams designing and building electric cars, model airplanes, and mechanical robots are popular. Some have introduced degree programs in the "practice of engineering" usually at the Masters level. However, these "practice of engineering" programs do not seem to have attracted a large following. Case studies, "board" certification standards and similar experience critical aspects of engineering are still left to professional societies and standards organizations to develop and support

In Europe especially in German speaking countries design education is often at the department level. The Chair of Engineering Design is a title seen on papers at International Symposia like the 13th International Conference on Engineering Design. Most industries today are populated by large Global companies and in a

long career an engineer will definitely compete with and collaborate with engineers from many other countries.

In America the ASME Conferences on Design Theory and Methodology are popular and well supported by academia and the occasional industry researcher. Prof. Clive Dym from Harvey Mudd College was Paper Chair at the 2002 Conference. The Technical Program from the 14th ASME Conference is compared to the 14th International Conference on Engineering Design in the Appendix. They are similar. The papers are largely from Universities and a few industry researchers but rarely from advanced product design teams. The practice of engineering is conspicuous by its absence.

Design Education Requirements

Among those who have struggled with design education issues in Industry are people like Phil Condit, the CEO of Boeing. I have interviewed senior Aerospace engineers and Boeing engineers familiar with Condit's design education efforts to get their sense of what their industries future requirements are likely to be. Did sabbaticals by University Faculty at Boeing build lasting relationships? Were undergraduate or graduate student interns able to intern with advanced design teams in industry? What metrics did they propose to use to measure the success of a design education program?

International customers in Europe and Asia-Pacific have been interviewed as available to get their requirements with similar questions based the practice of engineering in those markets. A framework for domain-independent design education will be important for organizing

requirements and for developing a University program in design education. In Europe some argue for a philosophy in which the design process is seen as a sequence of state transitions. In Japan we are seeing changes from the “Taguchi” era Design of Experiments (DOE) methods to “stochastic” methods similar to those introduced at BMW in the 1990’s. Even the hard-core fans of Taguchi methods are introducing “robust stochastic” design methods.

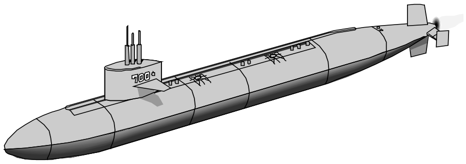
Industry Input:

Boeing, Ford, Honeywell, Lockheed-Martin, General Dynamics Electric Boat, General Electric, and others have provided papers, interviews and other materials that collectively form an initial requirements definition from industry. In what follows a brief synopsis of the major themes is presented with a few graphics from the papers repeated to make key requirements clear.

One of their key requirements is realizing that in practice the design-build process for a company making products with 1000 parts is not adequate for a company making a product with 1,000,000 parts. Don Slawski at General Dynamics Electric Boat illustrated that point recently in the graphic below. His company builds submarines for the US Navy, a process that has more suppliers than many products have parts. How are the design-build processes different? Can a design-build process be found that scales up and down over a large range of product complexities? If not why not? This is an important pedagogical issue as well as an industrial issue that systems engineers struggle with daily.

Boeing 777:
50,000 Parts
550 Suppliers
50,000 Manhours

USN Submarine:
1,000,000 Parts
3,600 Suppliers
8,000,000 Manhours



Complexity is at the heart of the struggle. The Santa Fe Institute and others continue to search for a "DNA" like framework that reduces complexity with the help of a universal modeling language for engineered materials and processes. The OMG has a Model Driven Architecture effort ongoing based on their UML standard that addresses framework issues but not the domain specific issues. In effect leaving complexity to the user but with better tools and a framework to model complexity.

John McMasters, a Boeing Technical Fellow, has devoted years to writing about Aerospace industry engineering design education requirements. Boeing has experimented with Faculty industry sabbaticals and other ideas over the years. McMaster's papers, mostly in AIAA publications, describe many of these Boeing programs. After talking recently with Bob Spitzer it seems clear, at least to me, that Boeing does not feel it's message about design education is having the impact on Universities that they had hoped for.

Dave Wisler at General Electric recently published 12 aspects of engineering, normally learned only after graduation and that are critical to a successful career. His paper provides an insightful summation of differences in industry and academia that lead to this gap in the two cultures.

Industry	Academia
Team Oriented	Individual Oriented
Leverage Existing Work	Create Original Work
Contribute to Business	Contribute to Science
Must Produce	Must Publish
Worthwhile Market	Worthwhile Topic
Model Specifics	Model Fundamentals
Customer, Customer, …	Publish, Publish, …
For Profit	Not for Profit

Many colleagues like those mentioned have influenced my own thinking about design education. We see the problem in about the same terms but the solution is another matter. In recent years I have had the chance to observe medical intern education at a teaching hospital over a period of several months. It is definitely team based and practice oriented. The team leader is a practicing physician and usually a Professor of Medicine but not always. Many physicians take a few weeks annually to make rounds with interns and residents at teaching hospitals. My experience is limited to two University of California campuses but I am told the educational format is similar elsewhere.

That experience suggests to me that it may be possible to imitate the approach taken in medicine to bring the

practice of engineering into a research University. At least it should be considered. The Research Parks that surround most campuses (I am writing this White Paper at one) may offer an environment where a Design Center could provide a teaching environment in collaboration with industry commercialization and technology transfer projects. Something like that seems to be happening at MIT and at Cambridge and possibly elsewhere.

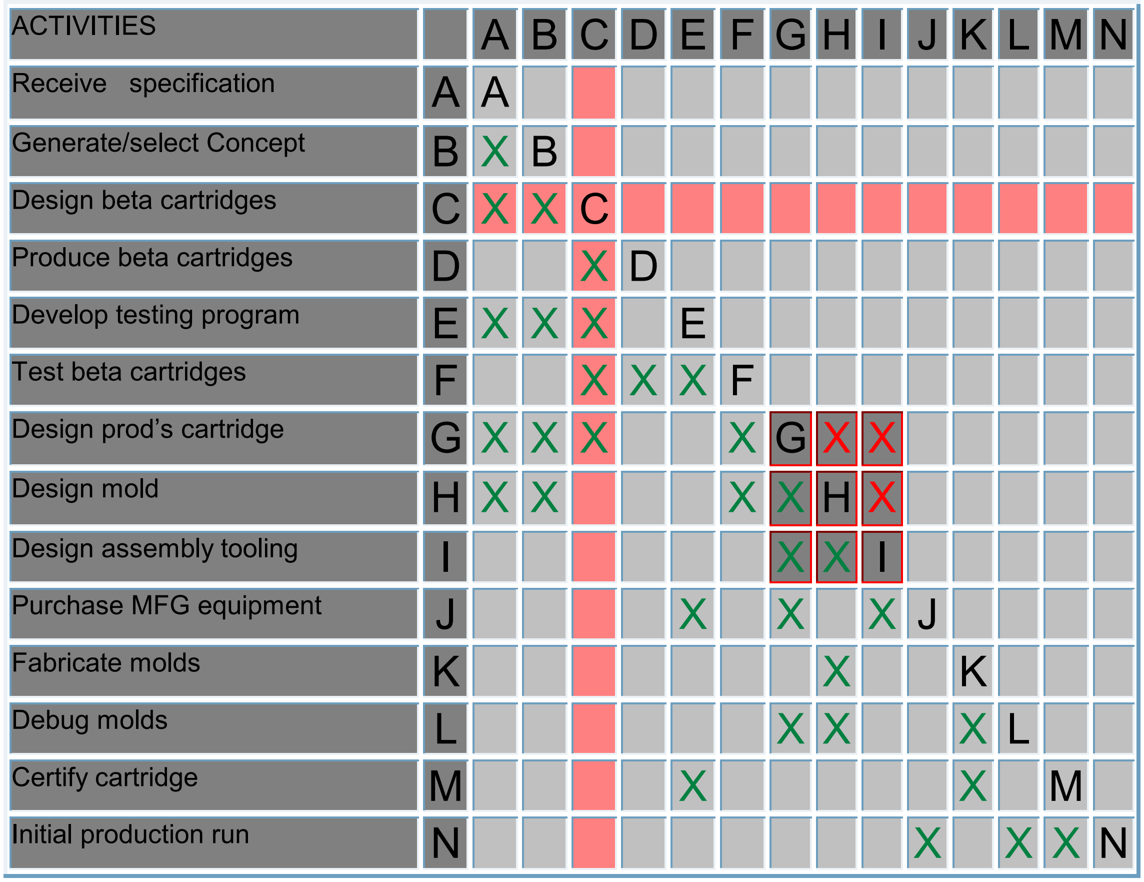
Academic Input:

Rather than interviewing Universities or ABET for academic design education requirements I selected two well-known research Universities, MIT and Cambridge, with successful ongoing design education programs and "leveraged existing requirements" from their programs as Dave Wisler would say. This was the only way to complete the White Paper in a timely manner. Other program requirements can be added over time.

MIT Design Structure Matrix

The industry representatives I met with all had favorable things to say about MIT's efforts to strengthen design education. In many cases they recommended the MIT Design Structure Matrix (DSM) methodology as representing an approach that they were sponsoring. It uses a systems analysis and project management tool that functions as a directed graph. The methodology has evolved over several years and annual Workshops are held with industry participation. Many applications of the DSM methodology are based on Excel spreadsheets, which make DSM applications easy for industry to implement.

A sample DSM from the MIT Web site tutorial (Ulrich and Eppinger, 1999) is shown below.



ACTIVITIES		A	B	C	D	E	F	G	H	I	J	K	L	M	N
Receive specification	A	A													
Generate/select Concept	B	X	B												
Design beta cartridges	C	X	X	C											
Produce beta cartridges	D			X	D										
Develop testing program	E	X	X	X		E									
Test beta cartridges	F			X	X	X	F								
Design prod’s cartridge	G	X	X	X			X	G	X	X					
Design mold	H	X	X				X	X	H	X					
Design assembly tooling	I							X	X	I					
Purchase MFG equipment	J					X		X		X	J				
Fabricate molds	K								X			K			
Debug molds	L							X	X			X	L		
Certify cartridge	M					X						X		M	
Initial production run	N										X		X	X	N

X’s mark the existence and the direction of information flow from one activity in the project to another. Rows track input information flow and the columns output information flow. X’s are color coded green to indicate FORWARD information flow and red to indicate FEEDBACK information. In effect the DSM is an information network or “knowledge network” for the project.

A typical industry application at Lockheed Martin TAS makes the rows in the spreadsheet IDF0 cells which their customer the US Air Force uses to track project

performance. The methodology is capable of treating design iterations stochastically, which is increasingly important in risk management. The pedagogical requirement here is not about learning to use DSM tools except maybe as a technology transfer process. It is about learning system level planning methods for organizing design-build activities for any project and about introducing robust design concepts.

Cambridge – Engineering Design Centre

After the recent 2003 SAE Collegiate Design Series: Aero Design West competition I reviewed the UCI entries and talked to the students about their projects and visited with faculty participants. It was great to have UCI Mechanical Engineering students involved in actual design-build projects. It was also clear in talking to the participants that they had not been exposed to design-build concurrent engineering methods and essentially had used a "discovery" science approach. We do learn best from our mistakes and there were lots of "if I had it to do over insights" discovered by all the teams. In my opinion prior exposure to design-build methods would have enhanced the Senior Design Project learning experience as it has at Cambridge. Their Engineering Design Centre program started in 1991 and has developed into a research center for advanced design methods. They have three strategic objectives, Research, Technology Transfer & Exploitation, and Education. The Education track includes both undergraduates and postgraduates.

SAE 2003 Colligate Design Entries

UCI Senior Design Projects Demonstration Day

The Cambridge Engineering Design Centre program is rich in pedagogical content with major industry collaborative program support including lecturers from industry. I did not find another four-year design education program at a major research University like the one at Cambridge. MIT's DSM program seems to me more software tool oriented than pedagogical.

The Cambridge EDC program is summarized below,

Research

- Themes
  - Design Synthesis
  - Design Optimization
  - Design Evaluation
  - Knowledge Management
  - Process Improvement
  - Inclusive Design
  - Research Methodology
  - Materials Selection
- Sectors
  - Aerospace
  - Healthcare
  - Architectural
  - Product Design
  - Projects (56 active projects)

Education

First Year

At Cambridge the first year teaches the communication skills needed in design and introduces basic product design topics at the conceptual design level. There are eight (8) engineering application lectures by industry experts in the first year. Courses include,

- Geometric Design
- Product Design
- Structural Design

Engineering Application Lectures

Second Year

The second year features an integrated design project where students work in multidisciplinary design teams. There are again eight (8) engineering application lectures by industry experts. The second year courses provide case studies for industry projects too large for student teams to attack.

Integrated Design Project
Mechanical Design, Manufacture & Management
Design of a Jet Engine
Design of a Fast Transistor
Engineering Application Lectures

Third Year

In the third year students undertake two 80-hour projects in the four weeks after exams. The aim of these projects is to work in greater depth on the Build phase of the design process and to use CAE tools to analyze and optimize their designs. The projects offered are taken from,

Design Projects
Computer-Based Projects
Fieldwork Projects
Foreign Language Projects

Fourth Year

In the fourth year about half of a student's time is spent on a major open-ended project, often undertaken in collaboration with industry. The other half of the final year is devoted to domain specific "taught modules" of which about 70 are available from the Engineering Design Centre. They can be collected into the following categories,

Major Design Project
Design Methods (Research)
Design Case Studies
Materials and Process Selection

White Paper Recommendations

The White Paper recommendations are the authors and have not been approved by UCI or any other organization. All of the recommendations would have to go through UC processes to implement that are beyond the scope of the White Paper. Having said that I did undertake the White Paper with indications of UCI interest in Design Education as a member of the Dean's Engineering Advisory Board.

1. UCI should work toward an Engineering Design Center with strategic objectives much like Cambridge's but with Themes and Sectors taken from the Dean's master plan for the Henry Samueli School of Engineering. Research, Education, and Technology Transfer & Exploitation are good strategic objectives that can be interpreted to fit UCI specific needs.

2. At the graduate level Engineering Design Center objectives should focus on Technology Transfer & Exploitation in collaboration with existing UCI Research Centers and their Industrial partners.

- **Collaborative Design Teams**
  - **Teaching Design Laboratory**

3. At the undergraduate level the focus should be on Education programs beginning with courses and seminars that introduce life cycle design concepts including Application lectures from industry.

- **Life Cycle Design Concepts**
  - **Understanding Engineering Projects**

- **Case Studies – Components, Assemblies, Systems**
  - **Industry Advanced Design Participation**

- **Design Philosophies, Methods and Practice**
  - **Integrating Art and Science in Practice**

Development of Themes appropriate to UCI is beyond the Scope of this White paper. My recommendation would be to have a forum like the EAB collaborate with the Dean and Center Directors to identify specific Themes. That activity could go on in parallel with a Design Education program for undergraduates.

Appendix

1. ASME 14th international Conference on Design Theory and Methodology, 2002 Montreal

   Technical Program

   Creativity and Innovation in Design
   Decision-Based Design
   Design Science and Design Lexicons
   Representation Theory in Design
   Distributed Design and Web-Based Design
   Design of Large Scale Systems
   Design for the Life Cycle; DFX
   Cognitive Theories of Design
   Validating Design Methods
   Design Pedagogy

2. ICED 14th International Conference on Engineering Design, 2003 Stockholm

   Technical Program (abridged)

   Methods Application
   Knowledge Management
   Innovation & Customer Demands
   Concept Modeling
   Requirements Specification
   Design Management
   Product Conceptualization
   Creating Product Families
   Collaborative Design
   Model Based Configuration
   Design Teams
   Management of Complexity

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