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Engineering Design Research

Results of a Workshop on Directions for Engineering Design Research
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Introduction

The challenges facing our world are quite substantial. Engineers have a key role to play in designing solutions. Current design practices must be continuously improved if they are to support the effective and timely development of such needed solutions. The purpose of this document is to define a set of research directions for the field of engineering design that will lead to our achieving the capabilities needed to address the challenges that we face.

The content for the document was generated at a workshop organized by the Advisory Board of the Design Society. In attendance were members of the Design Society Board of Management and Advisory Board and leaders of the Design Society Special Interest Groups. Their names are listed in Appendix 2.

The workshop participants identified three desired future states for the field of engineering design. To enable these states, they defined five domains for future research. A representative set of research areas within each domain was selected, and for each area an associated group of research topics was generated. The groups are intended to be representative but not necessarily complete.

Members of the Design Society have a long-standing tradition of addressing issues associated with current and future directions of the field of engineering design research. Examples include work by Finger & Dixon (1989a,b), Wallace (1997), Blessing (2002), Horvath (2004), McMahon (2006), Andreasen (2010), and Birkhofer (2011). While the content of this document is based on the results of the Design Society's 2011 workshop, earlier related contributions were consulted in preparation for the workshop and in writing this document.

Definitions

In this document, the terms "products" and "design artifacts" are used synonymously to mean the products, processes, services, and systems that engineers create. Successful products are those that satisfy customer, societal, and environmental needs in an economically viable way.

Future states

In “The Sciences of the Artificial”, Herb Simon asserts that “Everyone designs who devises courses of action aimed at changing existing situations into preferred ones.” Research in engineering design is conducted with the purpose of enabling preferred future states of design practice. Discussions at the workshop yielded three future states of design practice that must be realized if our designs are to meet the needs of future generations in timely fashion.

A. *Effective design:* Product development teams will deliver economically successful and socially viable products consistently and with much shorter development cycles.

Product development processes as currently practiced are laden with inefficiencies, uncertain information, and delays. At the same time, the need for socially sustainable products is becoming increasingly important. While estimates vary, it is generally understood that fewer than 1/3 of the products funded for development achieve their financial objectives. Resources are wasted and customer and societal needs are not met. Complex products require decades to mature. Given the rates at which technologies and competitive forces change, more effective product development processes must be created. Given the societal needs that must be addressed, and the costs of our failures in this regard, time to maturity for new solutions must be reduced. In this future state,

- Significant leaps in product value will be achieved by integrating the newest available technologies into both new and mature products. Aligning research, design, and product development processes with the creation and maturing of new technologies will enable the accelerated development of products to meet pressing needs.
- Rich virtual prototyping methods that allow the simulation, testing and iterative improvement of designs without requiring the building of physical prototypes will dramatically reduce the time and cost of achieving mature designs.
- Digital automation of the design process will speed up time consuming tasks of adapting or scaling existing components and systems, thus shortening the design process and freeing up time of engineers to devote to high-value activities.
- Globally distributed design teams will function effectively. This will increase overall process efficiency and product success rates in general and particularly in geographically fragmented markets, and will allow integration of the world’s best engineering talent into the innovation process regardless of the location of the engineers.

B. *Sustainable design:* The stream of new products and the processes for delivering them will be sustainable.

The rate at which energy arrives at the earth is set and the energy stored in the earth's buffers, while substantial, is fixed as is the availability of material elements. At equilibrium, energy, materials, and water will have to be conserved. New generations of engineering designers will spend progressively more of their design efforts addressing these constraints. In this future state,

- Designs will be based on the sustainable use of resources, addressing their long-term availability and cost, functionality, life-cycle environmental impact, and closed-loop recycling capabilities.
- Energy supply will be reliable, generated from sources that are available long-term, and without harmful by-products. Designs will be optimized to use minimal amounts of energy throughout their lifecycle.
- Clean water will be supplied by sustainable natural and technical sources. Products and processes will be designed to make minimum use of water and to minimize water quality degradation.

C. *Documented design:* Design and product development will be studied using a common set of accepted research methods. Best product development practices will be well understood and used pervasively in industry.

Today's standard product development processes are based more on precedent than on fundamental principles. As more effective processes are discovered, they must be codified, disseminated, practiced, and continuously improved. In this future state,

- Effective design practices will be identified in industry and developed through academic research.
- Research methods, domains, and standards in design will be clearly described and generally accepted. The research field will use a general taxonomy to describe research outcomes and design phenomena.
- An understanding of best practices and their use will be achieved both by professionals and by students.

Research Domains

The objective of the workshop was to identify research directions for enabling these future states. The topics proposed for future research fall into the five research domains described here.

1. Designers

Successful design depends on designers having and using essential design knowledge and skills. Skills include both individual cognitive processes such as engineering reasoning, creativity, and knowledge acquisition, and group skills such as communication and collaborative teamwork. The structure of the environment in which designers will work is also important. The study of designers and design teams will provide guidance for improving design processes and their adoption.

2. Design artifacts

Product quality, cost, and development time are strongly dependent on such factors as engineering specifications, product architecture, testing protocols, design modularity, and technology maturity. Our understanding of the dependencies among these factors is limited. There are many opportunities to better understand how to improve the design of the product during the design cycle.

3. Design processes

We are experiencing the evolution of product development from an informal to a structured set of processes. There is a great deal yet to be learned about the effectiveness of these processes, their proper sequencing, the coupling among them, and their sensitivity to uncertainties.

4. Design tools

Designers depend heavily on analytical, organizational, and representational tools, particularly computational tools, to support development of successful products. Our ability to represent, analyze, and improve design performance characteristics is constrained by the limited availability of effective design tools. Cost savings and reliability improvements are two of an array of desired design outcomes that can be achieved through employment of effective design tools.

5. Design education

To make use of improvements in our understanding of design artifacts and processes, we must codify this understanding effectively. This design knowledge will be taught to a wide range of people, from students to seasoned design professionals. We must understand how to align our educational pedagogies with these various learning styles and needs.

Research Areas

Workshop participants proposed a representative set of research areas within each research domain. These areas are mapped to the desired future states in the Table below. Research topics within each area are listed in the appendix.

Future States Design Research Domains and Areas	A. Effective design	B. Sustainable design	C. Documented design
1. Designers			
1.1. Cognitive processes of the individual	●		●
1.2. Team processes	●		●
2. Design Artifacts			
2.1. Design artifact value	●		●
2.2. Modeling of design artifacts	●	●	
2.3. Measuring the impact of design on society.		●	
2.4. Designing specific types of artifacts	●		
3. Design Processes			
3.1. Management of the design process	●		●
3.2. Design for the product life cycle		●	●
3.3. Designing for different types of artifacts	●		●
3.4. Design theory generation			●
3.5. Specific design practices	●	●	●
3.6. Requirements management	●	●	●
3.7. Inclusive design	●		●
4. Design Tools			
4.1. Communication technology	●		
4.2. Design automation	●		●
4.3. Virtual prototypes	●		●
4.4. Digital-immersive design environments	●		
5. Design education			
5.1. Professional education		●	●
5.2. University education		●	●
5.3. Understanding design research			●

Literature

Finger & Dixon (1989a)	A review of research in mechanical engineering design. Part I: Descriptive, prescriptive, and computer-based models of design processes, Research in Engineering Design, vol. 1, no. 1, pp. 51-67, 1989
Finger & Dixon (1989b)	A review of research in mechanical engineering design. Part II: Representations, analysis, and design for the life cycle, Research in Engineering Design, vol. 1, no. 2, pp. 121-137, 1989
Wallace (1997)	Product Development and Design Research, ICED 1997, Tampere
Blessing (2002)	What is this thing called Design Research?, CIRP 2002, Hong Kong
Horváth (2004)	A treatise on order in engineering design research. Research in Engineering Design, vol. 15, no. 3 pp. 155-181, 2004
McMahon (2006)	Design Research Challenges for the 21st Century, Rigi 2006, Heraclion
Andreasen (2010)	Design Research - past, present and future, NordDesign 2010, Göteborg
Birkhofer (2011)	The Future of Design Methodology, Springer, London, 2011
Simon (1996)	The Sciences of the Artificial, Chapter 5, MIT Press, 1996

Appendix 1: List of Research Topics

The following Table expands the Table on the previous page to include a detailed, representative list of research topics for each of the research areas.

Design Research Domains, Areas and Topics
1. Designers
1.1. Cognitive processes of the individual 1.1.1. Design cognition 1.1.2. Design thinking 1.1.3. Motivating designers 1.1.4. Design skills 1.1.5. Design behavior study 1.1.6. Design as primary human behavior 1.1.7. Individual creativity 1.1.8. Language of creativity
1.2. Team processes 1.2.1. Teamwork in design 1.2.2. Design communication 1.2.3. Design knowledge and collaboration 1.2.4. Workspaces to support design 1.2.5. Team creativity 1.2.6. Multi-disciplinary design
2. Design Artifacts
2.1. Design artifact value 2.1.1. Effort required for specific designs 2.1.2. Societal and economic benefits of specific designs 2.1.3. Operational model of value creation and value capturing networks
2.2. Modeling and simulation of design artifacts 2.2.1. Modeling and simulation of different types of artifacts • Product • Process • System • Service • Hybrid 2.2.2. Modeling and simulation of aspects of design artifacts • Uncertainty modeling and capture in design • Modeling and managing complexity in design • Functional representations • Product architectures • Modularity and platforms
2.3. Measuring the impact of design on society 2.3.1. Impact of design on society: What is the "full societal cost" of design artifacts and technologies? 2.3.2. Benefit: What is the "full societal benefit" of design artifacts and technologies

Design Research Domains, Areas and Topics
2.4. Designing specific types of artifacts 2.4.1. Designing specific technologies and machinery 2.4.2. Designing to meet specific needs 2.4.3. Designing for specific industries
3. Design Processes
3.1. Management of the design process 3.1.1. Designing design processes 3.1.2. Performance and value measurement and management of design 3.1.3. Metrics and quantitative assessment of design processes 3.1.4. Design change management 3.1.5. Product development strategy 3.1.6. Benchmarking the design process
3.2. Designing for the product life cycle 3.2.1. Design for X (lifecycle: manufacturing, assembly, testing, use, recycle, value chain, business model, entire lifecycle…) 3.2.2. Design to X (properties: cost, time, quality, flexibility) 3.2.3. Design for green and sustainable products
3.3. Designing for different types of artifacts 3.3.1. Designing products • Product architecting and design methods • Product platform design, modularization and product family design 3.3.2. Designing processes 3.3.3. Designing systems • Complex system design • Multi-disciplinary systems 3.3.4. Designing services 3.3.5. Designing hybrid artifacts • Product-Service design • Product-System-Service design
3.4. Design theory generation 3.4.1. Researching of design methods 3.4.2. Design theories and approaches 3.4.3. Validating design theories and methods 3.4.4. Design theory and formalism 3.4.5. Design process representations 3.4.6. Organizational understanding of product development

Design Research Domains, Areas and Topics
3.5. Specific design practices 3.5.1. Design tactics and methods 3.5.2. Design traceability 3.5.3. Evaluation and decision making 3.5.4. Flexibility and reuse in design 3.5.5. Design risk management 3.5.6. Product innovation 3.5.7. New technology infusion 3.5.8. Analogies in design 3.5.9. Bio-inspired design 3.5.10. Socially responsive design 3.5.11. Design for social innovation 3.5.12. Conservation of material and energy in design 3.5.13. Industrial Design 3.5.14. Inclusive Design • Collaborative and participatory design • Co-Design • Universal design
3.6. Requirements management 3.6.1. Helping the customer understand their requirements 3.6.2. Understanding the customer requirements 3.6.3. Requirements trade-off and tradespace exploration 3.6.4. Stakeholder orientation and integration 3.6.5. Engagement of society in defining needs and requirements
3.7. Inclusive design 3.7.1. Collaborative and participatory design 3.7.2. Designing for appeal (aesthetics, attraction, beauty) 3.7.3. Industrial design 3.7.4. Human-centered design 3.7.5. Interactivity in design 3.7.6. Design for all 3.7.7. Design for emotion and experience 3.7.8. Universal design 3.7.9. Emotional design

Design Research Domains, Areas and Topics
4. Design Tools
4.1. Communication technology 4.1.1. Open innovation and web-based design
4.2. Design automation 4.2.1. Intelligence-based design 4.2.2. Artificial intelligence in design 4.2.3. Design optimization
4.3. Virtual prototypes 4.3.1. Digital representation of design 4.3.2. Digital modeling and simulation methods 4.3.3. Functional modeling in design
4.4. Digital-immersive design environments 4.4.1. Representing qualitative aspects of designs 4.4.2. Representation of design information
5. Design education
5.1. Professional education 5.1.1. Improving design practices in industry
5.2. University education 5.2.1. Understanding the educational experience in design 5.2.2. Defining learning goals in design education 5.2.3. Developing design curricula 5.2.4. Case studies of successful learning in design 5.2.5. Measuring the success of design education 5.2.6. Understanding and optimizing the societal impact of design education 5.2.7. Consolidation of design research methods, taxonomy and domains
5.3. Understanding Design Research 5.3.1. History and evolution of design research 5.3.2. The role of design research in the future 5.3.3. Consolidating current state of design practice 5.3.4. Developing consolidated teaching material (e.g. textbooks)

Appendix 2: List of Workshop Attendees

Mogens Myrup Andreasen

Petra Badke-Schaub

Lucienne Blessing

Jean Francois Boujut

Marco Cantemessa

Gaetano Cascini

Amaresh Chakrabarti

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Steve Culley

Alex Duffy

Steven Eppinger

Bill Ion

Udo Lindemann

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Tim McAloone

Chris McMahon

Margareta Norell

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