AC 2007-775: CONTRIBUTION OF ENGINEERING MANAGEMENT & SYSTEMS ENGINEERING CONCEPTS TO ENGINEERING DESIGN

Yesim Sireli, University of North Carolina-Charlotte

Yesim Sireli is currently an assistant professor at the Engineering Management Program at the University of North Carolina at Charlotte. She earned her Ph.D. degree at the Department of Engineering Management & Systems Engineering at Old Dominion University, Norfolk, Virginia. She holds M.S. and B.S. degrees in electrical engineering, and has worked as an R&D engineer and a product development engineer. Her research interests include customer-oriented product innovation, design and development, decision analysis, business forecasting, and global product development. Dr. Sireli is a member of the ASEE, IEEE Engineering Management Society, Decision Sciences Institute, ASEM, Marketing Science Institute and the Honor Society of Phi Kappa Phi.

James Conrad, University of North Carolina-Charlotte

James M. Conrad received his bachelor's degree in computer science from the University of Illinois, Urbana, and his master's and doctorate degrees in computer engineering from North Carolina State University. He is currently an associate professor at the University of North Carolina at Charlotte. He has served as an assistant professor at the University of Arkansas and as an instructor at North Carolina State University. He has also worked at IBM in Research Triangle Park, North Carolina, and Houston, Texas; at Ericsson/Sony Ericsson in Research Triangle Park, North Carolina; and at BPM Technology in Greenville, South Carolina. Dr. Conrad is a Senior Member of the IEEE and a Certified Project Management Professional (PMP). He is also a member of Eta Kappa Nu, the Project Management Institute, and the IEEE Computer Society. He is the author of numerous books, book chapters, journal articles, and conference papers in the areas of robotics, parallel processing, artificial intelligence, and engineering education.

Martin Kane, University of North Carolina-Charlotte

Martin Kane earned his Ph.D. degree in Civil Engineering from Michigan State University (East Lansing, Michigan) in 1995. He also earned his BS in Civil Engineering (1990) and MS in Civil Engineering (1991) from the College of Engineering at MSU. Dr. Kane is currently an associate professor and Undergraduate Director in the Department of Civil and Environmental Engineering at the University of North Carolina at Charlotte. His research interests include Highway Operations, Transportation and Urban Planning, Human Factors in Transportation, Public Transportation, Traffic Engineering, and Aviation infrastructure. Dr. Kane is an Eno Fellow, and is a member of ASEE, ASCE, ITE, Sigma Xi, and Chi Epsilon.

Frank Skinner, University of North Carolina-Charlotte

Frank Skinner is currently the director of Industrial Solutions at the Department of Mechanical Engineering and Engineering Science at University of North Carolina – Charlotte. His industry positions include president of Robo-Tech Systems, Inc., senior market development engineer at GE and manager of engineering at Advanced Products Corp.

Contribution of Engineering Management & Systems Engineering Concepts to Engineering Design

1. Introduction

Engineering design is widely taught at colleges and implemented in industry as a stand-alone activity, rather than a part of the entire business system of a company. Product development consists of activities related to understanding customer requirements, collaboration with other functional areas in an organization such as marketing, sales and industrial design, as well as production design and manufacturing. As a part of this process, engineering design should reflect the results of a multifunctional team's work based on customer-focus, multidisciplinary design optimization, reduced cycle time, and ease of manufacturability. If planned and executed well, this design approach would serve businesses' expectations for high quality, low cost, and competitive products. As a result, today's engineers need necessary probabilistic decision-making and management skills to effectively work in a multidisciplinary project team, and to create designs based on the requirements of this larger system.

However, the typical engineering design curriculum does not include adequate discussion on probabilistic decision support and project management techniques. In addition, literature does not contain sufficient resources that are relatable by engineers from different disciplines and they also do not include adequate and/or useful examples for engineers from diverse backgrounds. This study suggests that new multidisciplinary educational material is needed, covering various stages of engineering design from a systems point of view. It starts with a summary of engineering design issues in industry and in higher education. After that, it proposes new educational material for engineering design to be incorporated into engineering curriculum. Finally, it discusses University of North Carolina at Charlotte's ongoing work in this context.

2. Engineering Design Issues in Industry

Engineering design is a vital element of a company's business activities. It significantly affects a firm's product quality, its ability to satisfy customer needs, its competitiveness, and ultimately its profits. However, in spite of its status, in many cases the design process falls short of meeting business expectations. Major issues related to engineering design in industrial projects are summarized below, based on a variety of research available in literature.

Systems perspective: Engineering design is a part of the product development process and therefore a firm's entire business practice. However, it is often not planned and/or executed as an integrated sub-process of this larger system. For example, if the costs of the product design processes are not tied to the total cost of product development and manufacturing properly, the final product cost might be much higher than originally expected. This suggests that a systems point of view should be integrated into design activities, so that the outcome of the design process can serve the other business goals such as high profits and good company reputation[1]. Lack of systems perspective in design in general contributes to the inter-related issues identified below.

Consideration of customer needs in design: Customer-oriented product development is becoming more and more important due to globalization, increased competitiveness, rapid technological change and discriminating customers[2]. As a part of the product development process, engineering design should reflect the results of a multifunctional team's work on identifying technical design characteristics based on gathering and understanding customer expectations. For example, a product may not meet customer requirements if the marketing division in a company does not work as a team with the product development division. This may result in low profits since the target customer's needs are not incorporated to the design adequately.

Risk and uncertainty consideration in project planning: Risk factors related to the future implementation of a project, particularly large engineering projects, are often ignored or inadequately thought-out during the planning phase[3, 4]. For example, the amount of rework throughout the design process is often not considered or it is under-estimated at the planning stage.

Cost and schedule overruns: Due to shortening product life cycles, businesses are looking for ways to reduce product development time and to release their products to the market more quickly[5]. However, mostly as a result of poor consideration of risk and uncertainty in the planning phase, cost and schedule overruns are a big problem especially for large-budget projects. Flyvbjerg at el.[6] (2002) surveyed 258 such construction projects (including North America, Europe, and other geographical areas) and concluded that, for a randomly selected project, the likelihood of actual costs being larger than estimated costs is 86%.

Rework: Rework can be a major problem particularly for ineffectively planned design projects, and can add to cost and schedule overruns. Reichelt and Lyneis[7] (1999) studied a sample of ten large projects and concluded that the average budget overrun was 86% and schedule overrun 56%, due largely to excessive rework.

Global competition and innovation: Global competition adds cost pressures and reduces the amount of time companies have to bring products to market. This suggests that an engineering design process must produce competitive products faster. Time-to-market decreases an average of 5% to 10% each year[8]. In addition, more and more companies are paying more attention to innovation activities to gain a competitive edge, which expectedly puts further pressure on product design[9].

The brief literature summary above indicates that companies need to look at engineering design from a systems perspective, considering the relationship of this sub-process with other sub-processes such as marketing, sales and manufacturing. If a product does not deliver what the target customer wants at a reasonable cost with high quality, and if it is not released to the market on time with attractive features that set it apart from the competition, it is most likely a failed product.

All these issues put strains on engineering design and ask for engineers with better understanding of not only design but also the higher business goals of a company. It is evident that engineers cannot afford to operate as pure engineers any more. Babcock and Morse[10] (2002) report that, in the last decade, many companies have reduced the numbers and levels of management positions and have given more decision-making authority to teams at lower levels. Today's engineers need necessary probabilistic decision-making and management skills to effectively work in a multidisciplinary project team, and to create designs based on the requirements of the larger system. They need to make design decisions that will meet and exceed customer expectations, reduce the number of design changes and rework, provide easier manufacturability, and as a result, reduce cycle time, increase competitive advantage and decrease costs. Companies' need for such engineers should drive changes in engineering design education as discussed in the following sections.

3. Engineering Design Issues in Higher Education

U.S. university engineering programs have been mandated by accreditation organizations to add a "senior design" course to their curricula. These courses, also called "capstone" courses, are a student's last opportunity to use design skills learned in school on a substantial effort. In a senior design course, students create teams of two to ten participants (depending on the topic and the engineering department), identify a problem to solve or product to create, and spend one or two semesters completing their work. The ultimate goal is for students to demonstrate their skills by completing a project on time and with full functionality.

Unfortunately, some student groups do not complete the full functionality promised at the outset. They do not even complete working systems, only working subsystems[11]. Graduate students also experience similar problems with design and systems thinking. This study suggests that there are two issues that must be addressed to improve engineering design education as follows.

3.1 Inadequate Engineering Design Curriculum

A major reason for the unacceptable results in senior design and graduate projects mentioned above is that even though engineering design is a decision-making process under uncertainty, supporting probabilistic decision-making and management methods are rarely or inadequately taught in engineering colleges[12]. Students often lack the ability to identify what method to use or how to use it to make decisions at different phases of the design process[13]. In addition, students are not usually aware of how design activities interact with other business activities in a company.

For instance, at the Civil Engineering Department of University of North Carolina at Charlotte (UNCC), early in the senior design process students are given a few formal presentations on time management, scheduling, building codes, design loads, decision and probability theory and communication styles. However, the number of these presentations is relatively low, and the connection between engineering design and decision support and management methods is not adequately taught. As a result, these topics are usually met with indifference by the students as they are not able to "see" the connection with the conduct of their research and the issues related to the product development process, decision theory and probabilistic techniques. Students have difficulty with the concept that their project will not proceed smoothly. However, they usually experience some of the components discussed in these presentations when the project does not move forward as they envision (delayed), and they are not sure how to get back on track. The faculty believe that students should be more effectively exposed to the issues of risk and uncertainty as they will likely experience problems with the conduct of their project. Decision trees, for example, can be a helpful tool, but often the application to senior projects is too contrived and the students (and faculty) will not seriously consider how decision trees can be helpful. It becomes just another academic exercise. How can the issues of risk and uncertainty be integrated in a meaningful way into the senior design process? This is an area that could use improvement from the instruction side (i.e., faculty) as well as the application (i.e., students) side.

These issues are also observed at UNCC's Engineering Management Master's Program classes that accept graduate students from other engineering departments. Some of these students have difficulties with incorporating engineering management and systems engineering (EMSE) methods into pure engineering concepts at the beginning of the semester. However, once they successfully come to the end of the semester, most of them state that the EMSE methods are helpful to their work.

3.2 Inadequate Engineering Design Resources

Another important issue with engineering design education is that literature does not contain sufficient resources that are relatable by engineers from different disciplines. Many papers and books are based on a specific engineering area such as mechanical engineering. In addition, even when these resources cover a good amount of information, they do not include adequate and/or useful examples and case studies for engineers from diverse backgrounds (Selected examples: Eggert[14] (2005); Shigley et al.[15] (2004); Esche and Chassapis[12] (2003); Fernandez et al.[16] (2001)).

Furthermore, many students do not have the opportunity to work on a real problem. Even though only technical knowledge is not enough to prepare students for the real world, in a typical engineering curriculum students and faculty often do not have the chance to make design decisions based on actual problems[17, 18].

4. Proposed Work

The difficulties discussed in Section 3 show that, according to the UNCC's experience as well as selected experiences elsewhere in academic arena, a significant number of engineering seniors as well as graduate students have problems with at least systems thinking, integration of risk and uncertainty into design, and schedule overruns. Current teaching practices and educational material do not seem to be sufficient to help overcome these challenges. Consequently, it is safe to expect that similar problems will occur when graduates join the workforce, contributing to the industry problems mentioned in Section 2. This study proposes that new multidisciplinary educational material and an improved curriculum are necessary to equip engineering students with crucial design knowledge and skills from a systems perspective. Based on the industrial and educational engineering design problems discussed so far, the material should have the following characteristics.

1. This material must cover design-related probabilistic decision support and management techniques for various stages of engineering design such as concept development, design, optimization and verification with a clear systematic approach. Such methodology should guide students when and how to support their decisions throughout the design process without losing sight of the bigger system that is affected by that design. For example, conjoint analysis and quality function deployment (QFD) are rarely and/or inadequately taught in engineering curriculum. Based on the utility theory, conjoint analysis can help engineers to create product designs that are attractive to consumers and to differentiate the product from the competitors'[18]. QFD is another technique that expresses the importance of gathering, understanding and meeting customer needs and identifying the technical characteristics of the product based on those needs. It is well-documented that both are structured techniques and both can help businesses reduce cycle time, increase competitive advantage and decrease costs[19, 2, 20, 21, 22]. Therefore, both techniques are good candidates to be incorporated into engineering curriculum as decision support techniques in engineering design. Selected methods should be organized under various design phases mentioned above. For example, concept development phase may include Pugh's concept selection method, affinity diagram method, as well as survey methods for gathering voice of the customer (VOC). The design phase may deploy design or experiments (DOE) and/or QFD while the optimization phase can use design capability studies and tolerance analysis. Verification phase may include empirical tolerance design methods as well as statistical process control methods.

2. Real examples and case studies should be provided to showcase the application of design-related decision-making methods at every step of the design process. These examples should involve different engineering disciplines such as electrical and computer engineering, civil engineering and mechanical engineering, as well as multidisciplinary projects.

3. Discussions on innovative design and engineering design's place in today's global business environment should be included. Global product development is an emerging concept that deals with development of products that are conceived and consumed in different countries and/or regions[23]. One of its challenges is about entering new global markets without adverse effects on the product development process since design, manufacturing and marketing across various time zones and cultures is a major problem. Today's engineering students need to be at least aware of the newest product innovation techniques and global challenges. Making use of such discussion in engineering design would equip them with an understanding of recent business challenges and ways to overcome those challenges.

This paper suggests that such material should be developed and integrated into engineering curriculum. Senior design and gradate students of engineering departments would be good candidates to receive this material as well as engineering management and systems engineering (EMSE) students.

4.1 Work Underway at UNCC and Future Directions

The College of Engineering (COE) at UNCC includes three main engineering departments: Electrical & Computer (ECE), Civil (CE), and Mechanical Engineering (ME). There is also an Engineering Management (EMGT) Program that is the foundation of the future Systems

Engineering & Engineering Management Department. One professor from the EMGT Program and three professors who are the senior design advisors of these engineering departments have proposed to work on creating the new educational material by taking advantage of UNCC's existing senior design program.

The current senior design program at the COE provides students with the opportunity to work on real-world design projects by working collaboratively with twelve industrial partners (such as General Dynamics, Lowe's Hardware, and Irwin Tools). However, challenges discussed in Section 3 still exist. If this proposed work is approved, it is anticipated that, first, most of the theoretical material including necessary EMSE concepts will be developed and taught to senior design students. After that, with the support of participating companies, real-world design projects will be defined for the senior design project groups, which will carry out those projects by applying proper decision EMSE techniques. These projects will serve as some of the real examples for the new educational material that demonstrate the implementation of selected methods. The final material will include a systematic engineering design methodology, real examples, and recent issues such as product innovation and global product development. It is expected that the material will be taught in engineering design and graduate classes at electrical & computer, civil, mechanical engineering as well as systems engineering & engineering management departments in the future.

4.2 An Initial Student Survey

A short student survey was conducted in an EMGT class to understand the effects of teaching EMSE-related topics to graduate engineering students. Although this was a limited survey that did not include a large number of participants in a variety of classes, its results are interesting to report nonetheless.

Quality and Manufacturing Management is a Master's and Ph.D. level class offered by UNCC's EMGT Program. It provides an in-depth study of current issues and advances in quality manufacturing management. Topics include quality concepts, total quality management, statistical process control and continuous improvement methods, introduction to design of experiments, quality function deployment, Six Sigma, and brief additional information about other management and decision support methods. The focus is thorough understanding and application of these topics and the class is offered to not only EMGT students but also graduate students from other engineering departments.

In Fall 2006, a relatively large number of students from other engineering departments signed on. For many of the non-EMGT students, this class was the first one they had ever taken from the EMGT Program. At the end of the semester, ten of those students who have worked on/are working on engineering design-related projects were surveyed to understand whether the EMGT topics discussed in this class were helpful to solve their design problems. Five of these students based their answers on design projects they worked on at the ECE Department. Three were from the ME Department, and the remaining two were from the CE Department. Nine out of ten indicated that they encountered major problems in their engineering design projects either as a senior design student or a graduate student working on a design project. Only one CE student did not recall any problems (this student had become an EMGT student but his undergraduate degree had been in CE). Those nine students also said that they now were able to comprehend the reasons behind those problems. After taking the class, they were also able to suggest appropriate EMSE methods that would have been helpful in solving or avoiding those problems.

The survey asked two open-ended questions about the nature of these problems and the students' opinions about the EMSE methods that would have helped to overcome them. It should be emphasized that no multiple choice answers were provided in the survey and the participants provided their answers completely based on their own experience and opinions. Table 1 summarizes the design problems they encountered along with the number of survey inputs and suggested methods by the students.

According to Table 1, they described eight different problem categories based on their experiences on engineering design projects. The total number of inputs was 24. The most frequent problem was poor project planning and lack of understanding of how to plan and execute an engineering design project in a systematic way and lack of systems thinking (25% of all inputs). The students that provided these inputs also pointed out that if they had had any knowledge about quality function deployment (QFD), certain project management (PM) techniques, design of experiments (DOE), or some understanding of Six Sigma methodologies, they would have avoided or solved those problems.

The second category was about communication problems within the project team as well as the interaction of the team with outside parties (20.8% of inputs). They said they should have had better PM skills and QFD knowledge. The third category was a tie with 16.6% each. One was the project team's lack of knowledge about how to achieve an optimum number of design experiments at the beginning of the design process. They suggested that engineering design students should have DOE and robust design knowledge. The other one was about the outcome, or the final product, of the design project. They indicated that the product often did not meet pre-determined design goals when the project ended. They suggested DOE, robust design, cause-and-effect diagrams, and statistical process control (SPC) to overcome this issue. The following categories were poor scheduling (8.3%), poor budget planning (4.2%), relying on statistically unstable processes (4.2%), and inability of identifying design functions in multidisciplinary projects (4.2%). In addition to similar recommendations, they also suggested the integration of cost estimation/financial analysis concepts into engineering design.

Table 1. Survey results.

Engineering design project problem	Number of survey inputs to each category (Input percentage) Total number of inputs: 24	Helpful EMSE methods suggested by survey participants
1. Poor project planning and lack of understanding of how to plan and execute an engineering design project in a systematic way / Lack of systems thinking	6 (25%)	Quality Function Deployment (QFD) Project Management (PM) techniques Design of Experiments (DOE) Six Sigma methodologies (DMAIC, DMADV)
2. Lack / inadequacy of communication between team members and between the team and the outside parties	5 (20.8%)	PM techniques QFD
3. Inadequate or no information about how to achieve an optimum number of design experiments at the beginning of the design process	4 (16.6%)	DOE Robust design
4. Inability of the final product in meeting pre-determined design goals and specifications	4 (16.6%)	DOE Robust design Cause-and-effect diagrams Statistical Process Control (SPC)
5. Poor project scheduling / Inability to meet deadlines	2 (8.3%)	PM techniques
6. Poor budget planning	1 (4.2%)	PM techniques Cost estimation / financial analysis
7. Poor design due to unreliable measurements taken from an unstable process	1 (4.2%)	SPC
8. Inability in identifying design functions of a product in interdepartmental projects	1 (4.2%)	QFD DOE PM techniques

5. Conclusions and Future Work

Engineering design-related businesses face several challenges when it comes to the effects of design activities on the entire business system of a company. Largely due to lack of systems perspective, customer needs, and potential risk and uncertainties are not adequately incorporated in the design process. This contributes to a significant amount of rework as well as cost and schedule overruns. Relatively recent issues such as global competition and increasing need for innovation also put pressure on design activities. As a result, industry needs systems-thinking engineers who are capable of incorporating probabilistic product development and project management methods into engineering design.

However, a typical engineering design curriculum and available teaching material do not seem to be sufficient to provide such engineers to the industry. UNCC's senior design advisors as well as a number of other sources supported this argument based on senior design and graduate design projects. Additionally, a preliminary survey conducted at UNCC indicated that teaching certain engineering management and systems engineering concepts to all engineering students would help overcome the challenges mentioned above.

Consequently, this study suggested that new educational material is needed to be incorporated into engineering design curriculum (senior design and graduate level). This material should cover probabilistic decision support and management techniques, real-world design examples including multidisciplinary perceptions and additional discussions on global competition and product innovation. UNCC has a senior design program that provides actual projects to its students by means of participating companies. If approved, future work will be directed towards creating this material by taking advantage of the existing senior design program, and integrating it into senior design and graduate level engineering curriculum. Future work should also include more detailed research on other universities' engineering design curriculum.

REFERENCES

[1] Reilly, J. J., "Cost estimating and risk-management for underground projects," Proc. of International Tunneling Association Conference, Istanbul, May 2005.

[2] Cristiano, J. J., Liker, J. K., and White, C. C., III, "Key factors in the successful application of quality function deployment," IEEE Transactions on Engineering Management, vol. 48, no. 1, pp. 81-95, February 2001.

[3] Miller R. and Lessard, D., "Understanding and managing risks in large engineering projects," International Journal of Project Management, vol. 19, pp. 437-443, 2001.

[4] Bashir, H. A. and Thomson, V., "Metrics for design projects: A Review," Design Studies, vol. 20, pp. 263-277, 1999.

[5] Bayus, B. L., "An analysis of product lifetimes in a technologically dynamic industry," Management Science, vol. 44, no. 6, 1998.

[6] Flyvbjerg, B., Holm, M. S., and Buhl, S., "Underestimating costs in public works projects," Journal of American Planning Association, vol. 68, no. 3, pp. 279-295, Summer 2002.

[7] Reichelt K. and Lyneis J., "The dynamics of project performance: Benchmarking the drivers of cost and schedule overrun," European Management Journal, vol. 17, no. 2, pp. 135-150, 1999.

[8] Boswell, B., "Putting global product development to work," Machine Design, July 21, 2005.

[9] Afuah, A., *Innovation Management, 2nd Edition*, Oxford New York, 2003.

[10] Babcock, D. L. and Morse, Lucy C., *Managing Engineering and Technology, 3rd Edition*, Prentice Hall, 2002.

[11] Conrad, J. and Sireli, Y., "Learning project management skills in senior design courses," Proc. of Frontiers in Education (FIE) Conference, October 19-22, 2005. Indianapolis, IN.

[12] Esche, S. K. and Chassapis, C., "Integrating concepts of decision making and uncertainty into engineering design education," Proc. of Frontiers of Education Conference, vol. 3, pp. S3B1-S3B3, 2003.

[13] Radhakrishnan, R. and McAdams, D. A., "A methodology for model selection in engineering design," Transactions of the ASME, vol. 127, pp. 378-387, May 2005.

[14] Eggert, R. J., *Engineering Design*, Pearson Prentice Hall, 2005.

[15] Shigley, J., Mischke, C. and Budynas, R., *Mechanical Engineering Design, 7th Edition*, McGraw Hill, 2004.

[16] Fernandez, M. G., Seepersad, C. C., Rosen, D. W., Allen, J. K., and Mistree, F., "Utility-based decision support for selection in engineering design," Proc. of ASME Design Engineering Technical Conference and Computers and Information in Engineering Conference, September 9-12, 2001.

[17] Muci-Kuchler, K. H. and Weaver, J. M., "Using industry-like product development projects in mechanical engineering capstone design courses," Proc. of ASEE Annual Conference and Exposition, pp. 15249-15264, 2005.

[18] Dunn-Rankin, D., Bobrow, J. E., Mease, K. D., and McCarthy, J. M., "Engineering design in industry: Teaching students and faculty to apply engineering science in design," Journal of Engineering Education, vol. 87, no. 3, pp. 219-222, July, 1998.

[19] Pullman, M. E., Moore, W. L., and Wardell, D., "A comparison of quality function deployment and conjoint analysis in new product design," Journal of Product Innovation Management, vol. 19, no. 5, pp. 354-364, September 10, 2002.

[20] Fung, R. Y. K., Law, D. S. T., and Ip, W. H., "Design targets determination for inter-dependent product attributes in QFD using fuzzy inference," Integrated Manufacturing Systems, vol. 10, no. 6, pp. 376, Bradford, 1999.

[21] Khurana, A. and Rosenthal, S. R., "Integrating the fuzzy front end of new product development," Sloan Management Review, vol. 38, pp. 103-120, Winter 1997.

[22] Lyman, D., Buesinger, R. F., and Keating, J. P., "QFD in strategic planning," Quality Digest, pp. 45-52, May 1994.

[23] Dias, A. V. and Galina, S. V. R., "Global product development: Some case studies in the Brazilian automotive and telecommunication industries," 4th International Conference on Technology Policy and Innovation, August 28-31, 2000.