
AC 2012-4130: A UNIQUE APPROACH TO CHARACTERIZING THE ENGINEERING DESIGN PROCESS

Ms. Lisa Guerra, NASA

Lisa Guerra has 25 years of experience in the NASA aerospace community. Guerra is currently working with the UTeachEngineering program. She recently completed a four-year assignment from NASA headquarters to establish a systems engineering curriculum at the University of Texas, Austin, as a pilot for national dissemination. Her efforts in systems engineering curriculum can be located at <http://space.nasa.gov/education/utearch/>. Guerra's most recent position at NASA Headquarters was Director of the Directorate Integration Office in the Exploration Systems Mission Directorate. In that position, her responsibilities involved strategic planning, international cooperation, cross-directorate coordination, architecture analysis, and exploration control boards. Guerra also spent three years at the Goddard Space Flight Center as Program Integration Manager for future high-energy astrophysics missions, particularly the James Webb Space Telescope. She began her career at the Johnson Space Center working for Eagle Engineering and SAIC, focused on conceptual design of advanced spacecraft for human missions to the moon and Mars. Guerra earned a B.S. in aerospace engineering and a B.A. in English from the University of Notre Dame. She received a master's of science degree in aerospace engineering from the University of Texas, Austin.

Dr. David T. Allen, University of Texas, Austin

David Allen is the Gertz Regents Professor of chemical engineering, and the Director of the Center for Energy and Environmental Resources, at the University of Texas at Austin. He is the author of six books and more than 200 papers in areas ranging from coal liquefaction and heavy oil chemistry to the chemistry of urban atmospheres. For the past decade, his work has focused primarily on urban air quality and the development of materials for environmental and engineering education. Allen was a Lead Investigator for the first and second Texas Air Quality studies, which involved hundreds of researchers drawn from around the world, and which have had a substantial impact on the direction of air quality policies in Texas. He has developed environmental educational materials for engineering curricula and for the University's core curriculum, as well as engineering education materials for high school students. The quality of his work has been recognized by the National Science Foundation (through the Presidential Young Investigator Award), the AT&T Foundation (through an Industrial Ecology Fellowship), the American Institute of Chemical Engineers (through the Cecil Award for contributions to environmental engineering and through the Research Excellence Award of the Sustainable Engineering Forum), the Association of Environmental Engineering and Science Professors (through their Distinguished Lecturer Award), and the state of Texas (through the Governor's Environmental Excellence Award). He has won teaching awards at the University of Texas and UCLA. Allen received his B.S. degree in chemical engineering, with distinction, from Cornell University in 1979. His M.S. and Ph.D. degrees in chemical engineering were awarded by the California Institute of Technology in 1981 and 1983. He has held visiting faculty appointments at the California Institute of Technology, the University of California, Santa Barbara, and the Department of Energy.

Dr. Richard H. Crawford, University of Texas, Austin

Richard H. Crawford is a professor of mechanical engineering at the University of Texas, Austin, and is the Temple Foundation Endowed Faculty Fellow No. 3. He received his B.S.M.E. from Louisiana State University in 1982 and his M.S.M.E. in 1985 and Ph.D. in 1989, both from Purdue University. He joined the faculty of UT in Jan. 1990 and teaches mechanical engineering design and geometry modeling for design. Crawford's research interests span topics in computer-aided mechanical design and design theory and methodology, including research in computer representations to support conceptual design, design for manufacture and assembly, and design retrieval; developing computational representations and tools to support exploration of very complex engineering design spaces; research in solid freeform fabrication, including geometric processing, control, design tools, manufacturing applications; and design and development of energy harvesting systems. Crawford is co-founder of the DTEACH program, a Design Technology program for K-12, and is active on the faculty of the UTeachEngineering program that seeks to educate teachers of high school engineering.

Ms. Cheryl Farmer, UTeachEngineering

Cheryl Farmer is the founding Program Manager and Project Director of UTeachEngineering. Funded through a five-year, \$12.5 million Math and Science Partnership grant from the National Science Foundation, UTeachEngineering offers a well-designed, well-rounded, and design-based high school engineering course that can be implemented at low cost in virtually any setting, as well as a variety of professional development programs for pre-service and in-service teachers who want to add engineering to their teaching portfolio. Prior to co-founding UTeachEngineering, Farmer spent several years managing programs for both K-12 and higher education. Before entering higher education, Farmer worked as a Project Manager in the environmental field. Her education includes graduate work in mathematics and business administration and a B.A. in mathematics and liberal arts, with highest honors, from the University of Texas, Austin.

A Unique Approach to Characterizing the Engineering Design Process

Introduction

While engineers frequently refer to “the engineering design process,” they rarely have the same representation of that process in mind. This paper describes an effort to generate a representation of the process that accurately describes engineering design at multiple levels, across engineering disciplines, and in industry and academia.

This design process representation was born of necessity when an interdisciplinary team of university engineering faculty, clinical engineering faculty (professionals with experience as both practicing engineers and secondary classroom teachers), engineering research fellows and learning sciences faculty came together in an effort to create design-based curriculum for students and teachers in high school. Realizing the differences in what individual team members meant by “the engineering design process”, a subset of team members undertook a process to clearly articulate a representation of the process that would be accessible to high school students, applicable in engineering teacher preparation courses, and authentic to the experience of professional engineers.

Background and Motivation

As part of a Math and Science Partnership (MSP) grant from the National Science Foundation (NSF), the UTeach*Engineering* faculty team from The University of Texas at Austin originally focused their efforts on preparing in-service teachers to teach engineering at the secondary education level. The teacher professional development consisted of a 6-week summer intensive program to learn the basics of engineering and how to apply those basics to hands-on engineering design challenges. In order to enable the teachers to learn and experience engineering design, the instructional faculty devised an engineering design process. Figure 1 illustrates this original engineering design process. Based on the classic “waterfall” approach to design, the process in Figure 1 shows a series of steps cascading in sequence — understand the problem, quantify the need, engineer the concept, embody the concept, implement the design, and finalize the design. The steps are connected with arrows showing the connection down the waterfall as well as up the waterfall, emphasizing the iterative nature of the engineering design process. For the summer teacher training, the Figure 1 process sufficed.

As the UTeach*Engineering* project’s MSP grant focus expanded to include the development of an engineering design course for secondary education, The University of Texas at Austin faculty team initially adopted the same process graphic for its high school course without consideration for the difference in the audience. The year-long course developed by the UTeach*Engineering* team introduced the waterfall engineering design process at the beginning with the intent for the students to apply it toward each new design challenge, whether designing a wind energy system or a robotic waste collector. Through the implementation of this pilot high school course, The University of Texas at Austin learning sciences faculty interviewed the students to gauge their

understanding of engineering practices. When questioned about the engineering design process, the student responses indicated the following:

- 1) They did not intuitively understand the process;
- 2) They did not internalize the process (unable to recite the steps after supposedly using it over the course of two semesters); and
- 3) The process appeared confusing to them.

In particular, response #3 highlighted the confusion of the many arrows looping back and forth between steps without clarity on when rework or iteration should occur.

Furthermore, the students discussed the confusion between the ‘embody the concept’ step and the ‘implement the design’ step. Why was prototyping part of implementation rather than embodiment? Why is software design embedded in ‘embody the concept’ as opposed to integrated in the entire system design? Lastly, the ‘finalize the design’ step included buzzwords about design — robust design and design for production — that appeared disconnected from completing a student design challenge. Given this specific feedback on the Figure 1 engineering design process, the UTeach*Engineering* team decided to rethink the communication of this critical engineering practice.

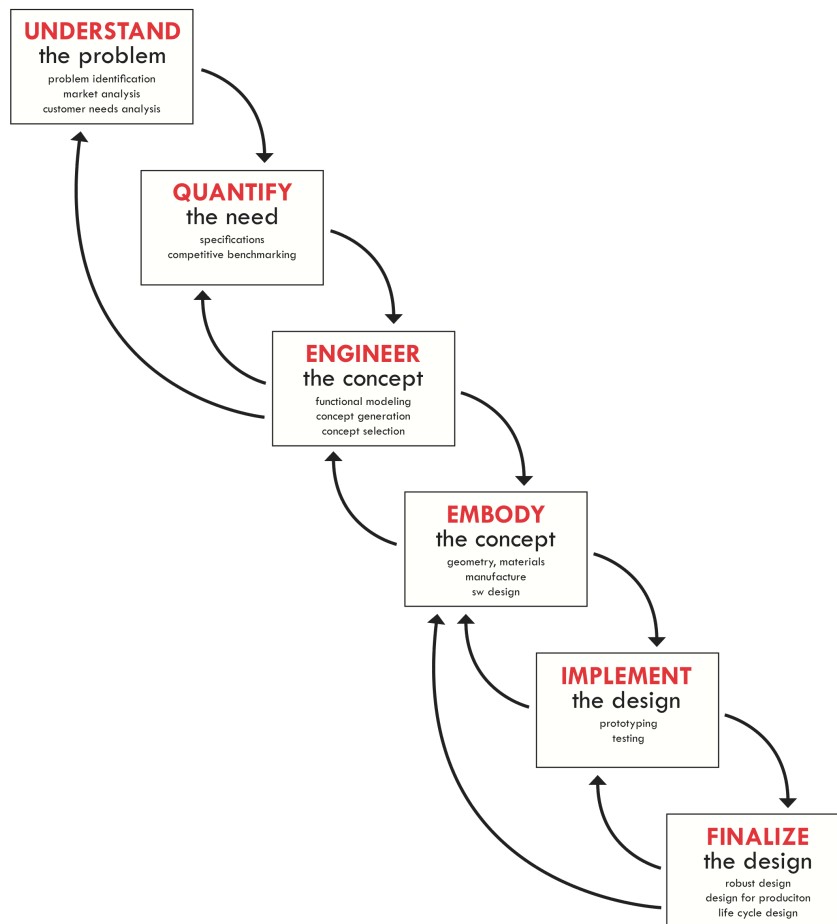


Figure 1 — Original Engineering Design Process Used for In-Service Teacher Professional Development.

Methodology

Rather than edit the existing engineering design process graphic or start with a clean sheet, the UTeach*Engineering* team initiated a benchmarking exercise. A selection of eleven unique cross-disciplinary representations was selected to reflect the engineering design process in professional, post-secondary and K-12 settings. Each representation consisted of the specific steps in the process as well as a graphical means of displaying the steps, including loop, list, web, and loop plus linear flow. These graphical approaches are simply illustrated in Figure 2, including a generic version of the original waterfall process.

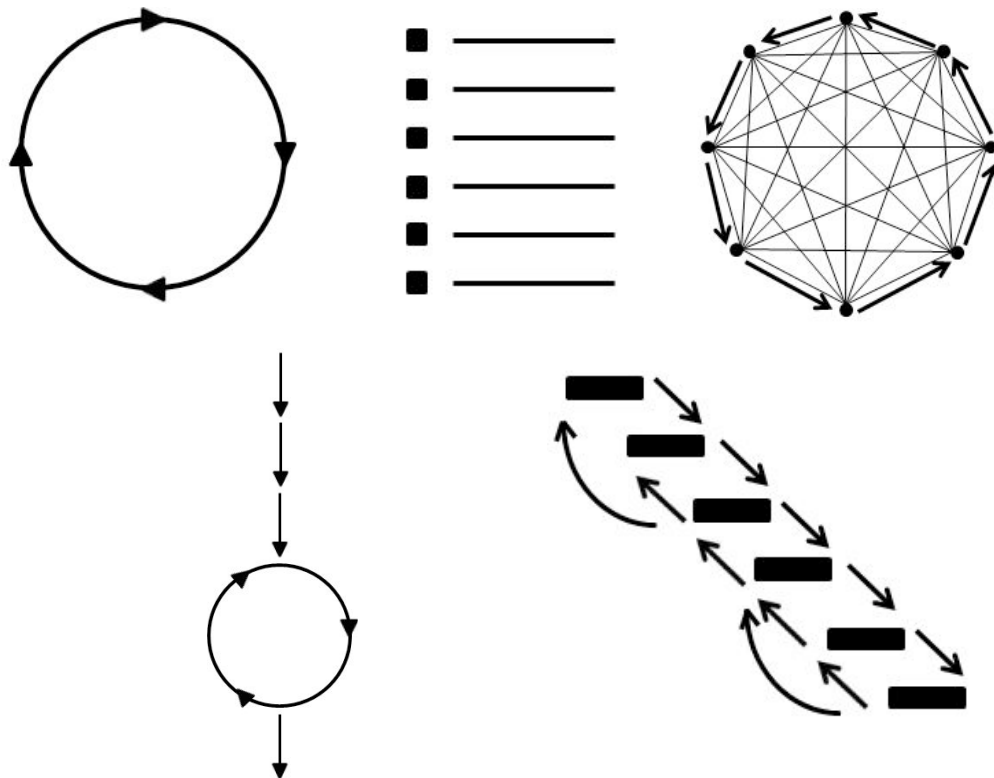


Figure 2 — Generic graphical representations of the engineering design process, including loop, list, web, loop plus linear flow and the waterfall.

The most common graphical representation identified was the loop, with six of the eleven sources using it to describe the engineering design process. The loop construct implies a nonlinear approach to engineering, a more creative and organic method to progressing through one's work. These representations also include arrows around the loop or a single sweeping arrow, signifying the direction of the work as well as the iterative nature of the engineering design process. The sources for the six loop-defined processes are listed below:

- 1) Engineering the Future¹ — a full-year course to introduce beginning high school students to the world of engineering and technology.

- 2) Teach Engineering.org² — a digital resource for math and science teachers to introduce engineering into the K-12 classroom.
- 3) TryEngineering.org³ — an online resource for students and teachers to enable engineering learning and practice, sponsored by IBM and IEEE.
- 4) Texas Tech University T-STEM⁴ — a Texas initiative to develop STEM curriculum resources with a focus on engineering projects to engage students in learning (the “FRAME” model copyrighted in 2009).
- 5) Massachusetts Science and Technology/Engineering Curriculum Framework⁵ — a 2006 document outlining the statewide guidelines for teaching science and engineering in the early grades and continuing through high school.
- 6) *Engineering and Technology* (Hacker, et al.)⁶ — a 2009 NSF-sponsored textbook using “informed design” activities to expose students to various technological areas.

Although identified by a common loop graphic, each of these six sources identified a different set of steps associated with the engineering design process. Table 1 outlines the individual steps. Note that the majority of the loop-based processes contain eight steps with very similar definitions of each step, with the primary variance being the ordering of ‘communicate’ and ‘redesign.’ Source #4 limits the process to five steps that spell out the acronym FRAME, thus allowing the students an easy way to remember the engineering design process.

STEP	Source #1 Loop	Source #2 Loop	Source #3 Loop	Source #4 Loop	Source #5 Loop	Source #6 Loop
1	Define the problem	Identify the need	Identify the problem or need	Frame the problem	Identify the need or problem	Describe the design problem clearly & fully
2	Research the problem	Research the problem	Research/consider requirements & constraints	Research the possibilities	Research the need or problem	Research and investigate the problem
3	Develop possible solutions	Develop possible solutions	Propose solutions / Identify tradeoffs	Analyze the data	Develop possible solution(s)	Generate alternative designs
4	Choose the best solution	Select the most promising solution	Select best solution	Model the design	Select the best possible solution(s)	Choose & justify your optimal design
5	Create a prototype	Construct a prototype	Construct prototype	Execute the design	Construct a prototype	Develop a prototype
6	Test and evaluate	Test and evaluate the prototype	Test and evaluate solutions		Test and evaluate the solution(s)	Test and evaluate design solution
7	Communicate the solution	Communicate the design	Communicate solutions		Communicate the solution(s)	Redesign the solution
8	Redesign	Redesign	Redesign		Redesign	Communicate your achievements

Table 1 — The individual design process steps for the six benchmarked processes designated by the loop model.

Following the loop approach, the second most common form for expressing the engineering design process was in terms of a list of steps. The list approach implies a series of steps for the engineering student to pursue in a specified order. The list approach does not explicitly signify the potential for iteration between steps; rather, if all the steps are conducted then the design is complete. The sources for the three list-defined processes are noted below:

- 7) *Engineering in K-12 Education*⁷ — National Academies Press 2009 publication that reviews the scope and impact of current engineering education and makes several recommendations to address curriculum.
- 8) Project Lead the Way⁸ — Curriculum providers for STEM education in middle and high school; Introduction to Engineering Design is a course provided for freshman (copyrighted in 2009).
- 9) *Engineering Your Future* (Gomez, et al.)⁹ — An introduction to engineering textbook for middle school and early high school grades (copyrighted in 2011).

From the dozen or so engineering design processes benchmarked, two processes used unique representations. The web-defined approach developed by source #10, the University of Colorado at Boulder for their freshman introductory engineering design course¹⁰, connects all the steps in an outer loop of arrows with an inner web of arrows. The message of the web approach is that every step of the design process is connected to all other steps, allowing for continuous reflection and iteration of previous work within the process. The final benchmarked source (#11) was that used by Design Squad¹¹, a PBS reality competition series that seeks to excite young people about engineering. According to the Design Squad website, “the design process helps people think creatively about a problem and produce a successful result.” The Design Squad process employs a linear flow of steps (‘identify problem’—‘brainstorm’—‘design’) feeding a loop of work (‘build’—‘test & evaluate’—‘redesign’) before exiting to the ‘share solution’ step. The imbedded loop allows for continuous improvement of the design solution before declaring it complete enough for sharing.

Table 2 outlines the individual design process steps for the three list approaches as well as the web and loop-plus-linear-flow representations. Note that the processes from sources #8, #9, and #10 contain ten steps with some unique steps not seen in the earlier loop processes, including step 7/source #8 (‘developing a design proposal’); step 9/source #9 (‘implement and commercialize’); and step 3/source #10 (‘plan and manage the project’). Two of the approaches from sources #7 and #10 abruptly end with the test and evaluate part of the design cycle. As noted earlier, the Design Squad approach uses a simple set of steps with a catchy graphic with the intent, similar to the FRAME model, to assist students with recall and application of the engineering design process.

STEP	Source #7 List	Source #8 List	Source #9 List	Source #10 Web	Source #11 Loop plus linear
1	Defining the problem	Defining a problem	Identify the problem	Recognize the need	Identify problem
2	Specifying requirements	Brainstorming	Define working criteria and goals	Define the problem	Brainstorm
3	Decomposing systems	Researching	Research and gather data	Plan and manage the project	Design
4	Generating solutions	Identifying requirements	Brainstorm and generate creative ideas	Gather information	Build
5	Drawing & creating representations	Exploring possibilities	Analyze potential solutions	Generate alternative concepts	Test & evaluate
6	Experimenting and testing	Selecting an approach	Develop and test models	Evaluate the alternatives: analysis	Redesign
7		Developing a design proposal	Make the decision	Select the most promising concept	Share solution
8		Making a model or prototype	Communicate and specify	Build the prototype	
9		Testing & refining	Implement and commercialize	Test	
10		Communicating results	Post-implementation review and assessment	Evaluate test results	

Table 2 — The individual design process steps for the three benchmarked processes designated by a list; the one designated by a web model; and the one designated by the loop plus linear flow model.

After consideration of these eleven engineering design processes plus the project’s own original waterfall approach (source #12), the UTeach*Engineering* team identified ten cross-cutting themes (steps) in these characterizations. They are as follows: identify the need; describe the need; characterize and analyze the system; generate concepts; select a concept; embody the concept; test and evaluate the concept; refine the concept; finalize and share the design; and evolve the design. The team subsequently mapped each representation from source #1 to source #12 onto this list of UTeach*Engineering* selected steps, as depicted in Table 3. Surveying the table one recognizes the commonality of most of the steps across the benchmarked processes. Key elements of note from the UTeach*Engineering* characterization are as follows:

- The UTeach*Engineering* characterization uses the term “need” rather than “problem.” Although the use of “problem” is more common and was initially used in the UTeach*Engineering* project’s own waterfall characterization, the team felt that the more positive connotation of “need” is better aligned with current research on effective messaging about

engineering.¹²

- The UTeach*Engineering* characterization includes a ‘characterize and analyze the system’ step. This is rarely addressed in the benchmarked processes, most of which jump from ‘describe the need’ (including research, requirements, and further definition) to generating concepts. Based on the team’s professional experience, they recognized the importance of teaching students to analyze the entire system prior to conceptualizing solutions. In this step, students translate the need into a system and learn to decompose that system into subsystems. The ‘characterize and analyze’ step also involves developing functional models of the system, recognizing operational constraints, deriving performance goals as well as understanding the relevant math and science for the particular design challenge. This level of work is critical to understanding the context of the problem prior to brainstorming solutions to that problem.
- The UTeach*Engineering* characterization also includes a ‘refine the concept’ step that is rarely addressed in the benchmarked processes.
- Most of the 12 benchmarked processes place the redesign of a solution *after* the design solution is communicated. Based on the UTeach*Engineering* team’s professional experience, they recognized the practice of resolving design issues after evaluating test results, with the intent of retesting the system prior to declaring it complete. Given this agreed-upon ‘refine’ then ‘finalize’ sequence, the UTeach*Engineering* design process approach includes a final step labeled ‘evolve the design’. This step reflects the redesign mentioned in many of the processes as the last possible step. The ‘evolve the design’ step represents the natural changes to a product’s design over its life cycle, taking into account that as time passes customer needs change and related technologies evolve.
- The UTeach*Engineering* characterization does not encompass three ideas that are each seen in one of the benchmarked processes. While the team agreed that ‘developing a design proposal’ (step 7/source #8) and ‘implement(ing) and commercializ(ing)’ (step 9/source #9) are interesting elements associated with design, these steps did not meet the threshold of essentialness for inclusion. Additionally, while developing the ability to ‘plan and manage the project’ (step 3/source #10) is important the team saw it not as a step in the process but as a set of skills used in completing the process.

Steps in the UTeachEngineering Engineering Design Process	Related step from Source #1	Related step from Source #2	Related step from Source #3	Related step from Source #4	Related step from Source #5	Related step from Source #6	Related step from Source #7	Related step from Source #8	Related step from Source #9	Related step from Source #10	Related step from Source #11	Related step from Source #12
Identify the need	1	1	1	1	1		1	1	1	1	1	
Describe the need	2	2	2	2	2	1/2	2	3/4	2/3	2/4		1
Characterize & analyze the system							3		5	6		2
Generate concepts	3	3	3		3	3	4	2/5	4	5	2/3	3
Select a concept	4	4	4	3	4	4		6	7	7		3
Embody the concept	5	5	5	4	5	5	5	8	6	8	4	4/5
Test & evaluate the concept	6	6	6		6	6	6	9	6	9/10	5	5
Refine the concept						7		9			6	
Finalize & share the design	7	7	7	5	7	8		10	8		7	6
Evolve the design	8	8	8	6	8				10			

Table 3 — A comparison of the selected steps in the UTeachEngineering engineering design process (column 1) and the corresponding steps from the eleven individual processes analyzed in the benchmarking study, plus the original waterfall model (column 13/source #12).

Results

When the names of the 10 steps had been finalized, the UTeachEngineering team began the process of identifying the relationships between steps. The resultant topography was complex, with many loops and arrows. To make this representation more accessible to novices, closely related steps were grouped into five super-steps that describe the engineering design process at the highest level (identify, describe, generate, embody, finalize). Once the process had been distilled to its simplest form, the project team reintroduced the complexity by drawing looping steps within super-steps. The result is a unique, multi-level representation of the engineering design process that is sufficiently simple at its highest level so as to be accessible to students in a high school engineering course, yet sufficiently complex at its most detailed level so as to be of use in solving a wide range of engineering design challenges. Figure 3 depicts the resulting engineering design process.

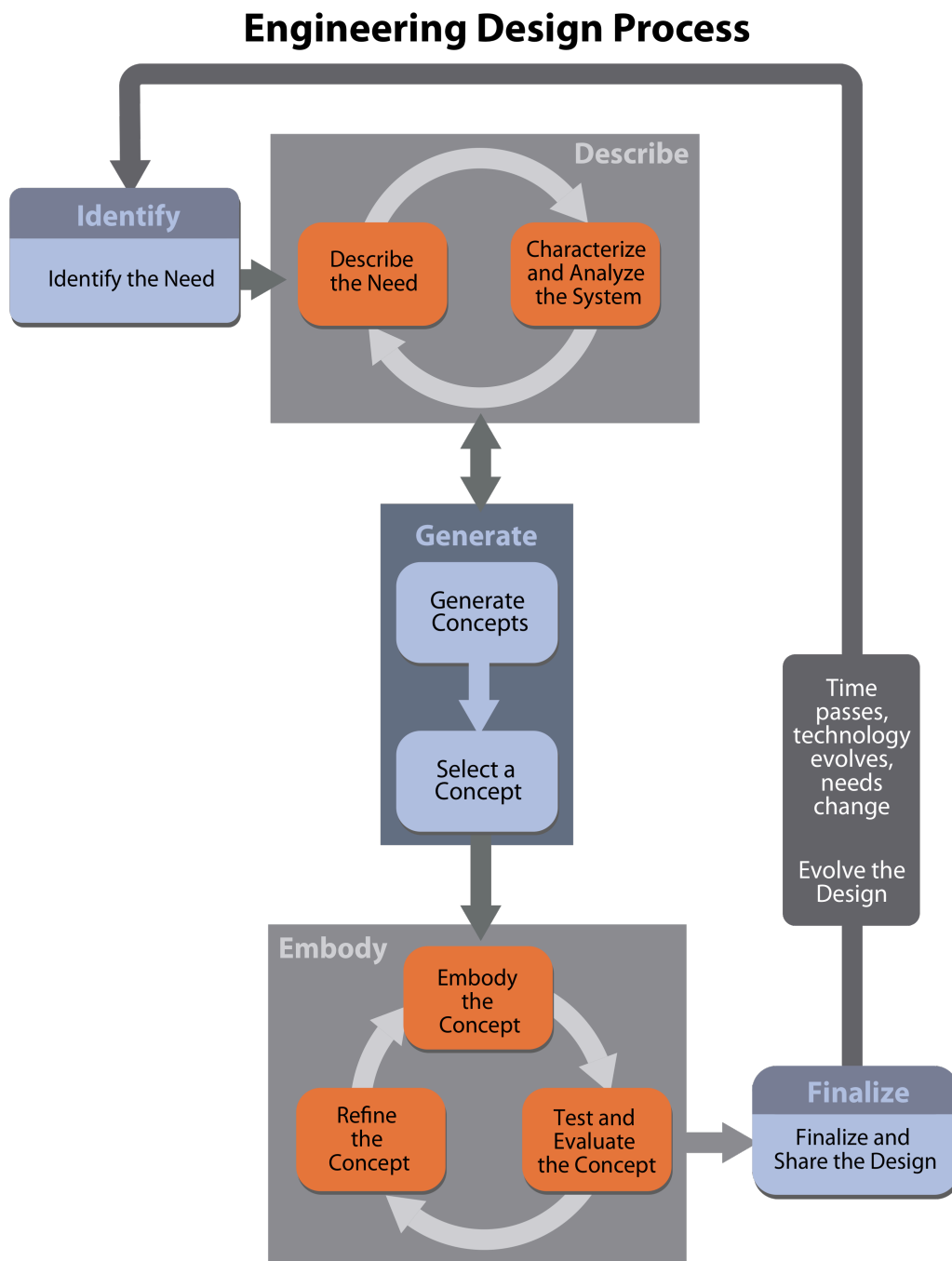


Figure 3 — The Resulting UTeachEngineering Engineering Design Process.

An annotated version of the process includes examples of the activities undertaken in each step. These annotations are listed below and tagged to each step in the design process.

Describe the need

- Analyze customer needs
- Research existing approaches
- Identify constraints and requirements

Characterize and analyze the system

- Understand the relevant science and math
- Decompose system and identify critical subsystems
- Develop performance targets
- Develop functional models

Generate concepts

- Define form factor and materials
- Generate ideas (brainstorming, mind-mapping, etc.)

Select a concept

- Analyze and consider tradeoffs
- Evaluate concept alternatives
- Choose “best” design concept

Embody the concept

- Perform modeling
- Create a prototype

Test and evaluate the concept

- Test
- Evaluate test results

Refine the concept

- Make appropriate changes to the design to assure compliance with requirements and performance targets
- Prepare model/prototype for re-testing

Finalize and share the design

- Produce/reproduce the design
- Communicate the design solution

At the time of this writing, the second version of the UTeach*Engineering* high school course, known as *Engineer Your World*, is being piloted by eight teachers with more than 230 students in seven Texas high schools. The framework for *Engineer Your World*, which is described fully by the authors in a related paper¹³, allows the students to *discover* the engineering design process early in the course. Each subsequent design challenge applies and reinforces the UTeach*Engineering* articulated process, such that, by the completion of *Engineer Your World*, the students will have used the process at least five times in varying contexts. Formal research and evaluation of this second course pilot includes a focus on the engineering design process. Given this new construct, researchers intend to determine the level of student understanding and application of this process as described. Specifically, do students intuitively understand the process; do they internalize the process; and do they apply the process appropriately? The results of this

research will follow from the completion of the current 2011-2012 academic year.

Conclusion

For a high school student, design challenges can mean hands-on construction of something that will satisfy what the teacher prescribed. Without appropriate discipline in their efforts, the students may or may not produce a viable design solution. The engineering design process provides the appropriate discipline, from understanding the proposed challenge to determining the best solution. The intent of introducing the process to a pre-engineer audience is to ensure thinking before tinkering.

Since the early 1960's, many versions of the engineering design process have been prescribed by authors¹⁴. Some representations of the process are very brief whereas others are decomposed into numerous tasks that are to be performed by the design engineer. This paper addresses the variations in the engineering design process through a benchmarking effort to better understand the commonality of steps across processes. The exercise allowed the UTeachEngineering team to derive a unique engineering design process to be used as a cornerstone of learning in a high school engineering course. The resulting process reflects the progression of work as well as the need for iteration within the overall process. In addition, by including the 'evolve the design' step, the engineering design process emphasizes that there is no optimal solution at the end. Rather there may exist Nth generations of design solutions — once a product is marketed, feedback about the design is collected from users, and the product then undergoes redesign to better meet the users' needs. Ideally, the high school students would experience this larger looping back through the design cycle by revisiting one of their design challenges during the year-long course. By doing so, they would gain a valuable engineering skill: to reflect on one's work and apply lessons learned to future design endeavors.

Acknowledgement

The work described in this paper was made possible by support from the National Science Foundation (Award DUE-0831811).

Bibliography

1. Engineering the Future: Science, Technology and the Engineering Design Process. (2008). Boston, MA: Museum of Science. Accessed at www.mos.org/etf/
2. TeachEngineering.org. (2009). *Curricular Unit: Creative Engineering Design*. Accessed at: http://www.teachengineering.org/view_curricularunit.php?url=http://www.teachengineering.org/collection/cub/_curricular_units/cub_creative/cub_creative_curricularunit.xml
3. TryEngineering.org. (2010). *Engineer Your Classroom: A Pre-University Teacher Training Module*. Accessed at <http://www.tryengineering.org/lesson.php>
4. T-STEM Center. (2009). *Design FRAME, problem solving with the engineering design process*. Lubbock, TX: Texas Tech University. Accessed at

- www.depts.ttu.edu/tstem/curriculum/docs/FRAME_Model.pdf
5. Massachusetts Department of Education. (2006). Massachusetts Science and Technology/Engineering Curriculum Framework. Malden, MA: Massachusetts Department of Education.
 6. Hacker, M., Gordon, A., Peruzzi, W., Burghardt, D., and Fletcher, L. (2009). *Engineering and Technology*. Florence, KY: Cengage Learning.
 7. Committee on K-12 Engineering Education. (2009). *Engineering in K-12 Education: Understanding the Status and Improving the Prospects*. Washington, DC: National Academy of Engineering and National Research Council.
 8. Project Lead the Way. (2009). *Project Lead the Way: Engineering Curriculum: High School: Introduction to Engineering Design*. Accessed at <http://www.pltw.org/engineering/Curriculum/Curriculum-high-school.cfm>
 9. Gomez, A., Oakes, W., and Leone, L. (2011). *Engineering Your Future: A Project-Based Introduction to Engineering*. Cottleville, MO: Great Lakes Press.
 10. Integrated Teaching and Learning Laboratory, College of Engineering and Applied Sciences. (2000). *Introductory Engineering Design: A Project-Based Approach*. Boulder, CO: University of Colorado at Boulder. Accessed at http://itll.colorado.edu/index.php/courses_workshops/geen_1400/resources/textbook/
 11. Design Squad: Teacher's Guide. (2010) Public Broadcasting Service. Accessed at: http://pbskids.org/designsquad/parentseducators/guides/teachers_guide.html
 12. Committee on Public Understanding of Engineering Messages. (2008). *Changing the Conversation: Messages for Improving Public Understanding of Engineering*. Washington, DC: National Academy of Engineering.
 13. Farmer, C., Allen, D., Berland, L., Crawford, R., and Guerra, L. *Engineer Your World: An Innovative Approach to Developing a High School Engineering Design Course*. American Society for Engineering Education: accepted for publication in AC 2012 proceedings.
 14. Voland, G. (2004). *Engineering by Design*. Upper Saddle River, NJ: Pearson Prentice Hall.