System Engineering Education for All Engineers - A Capstone Design Approach

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1.0 Overview

A hands-on educational approach for teaching undergraduate aircraft design students about Systems Engineering (SE) has been developed which we believe is applicable to other engineering disciplines. The impetus for the initiative is our conclusion that (1) fundamental understanding of the principles of SE and their practical application is important for all engineers and (2) SE can be taught as a principle of design without displacing other course content. Our educational concept has been tested for transition by Texas A&M University (TAMU) where aerospace colleagues substantially increased SE content in their well-established design course with minimum displacement of other course content. We believe, therefore, our course concept is ready for transition to other interested universities and engineering disciplines. However, we recognize there are other approaches as well as issues that should be researched. Included are SE knowledge requirements across engineering disciplines, learning effectiveness of various instructional techniques including capstone vs. other design courses, instructor knowledge requirements as well as traditional discipline SE education issues and methods. Therefore, we recommend a broader implementation strategy to include engineering discipline tailoring and educational research as discussed in our summary and conclusions.

2.0 Systems Engineering (SE) Design Course Concept

SE Design differs from the traditional engineering educational approach where, if SE is taught at all, it is taught as a separate subject. Our approach integrates SE fundamentals into the course as hands-on engineering principles and uses the structure of the course itself to apply SE to design. The approach is applicable to one and two semester course formats with either "paper" or hardware/software design projects although our experience suggests the most effective method involves hands-on projects that have to demonstrate a working capability.

By structure, we mean the underlying educational framework, not the specific project or its product development model. For example, our course is aerospace specific and follows a traditional Aerospace and Defense (A&D) development approach as shown in Figure 1. We start the 1st semester with release of a traditional A&D Request for Information (RFI) which describes the overall project goals and objectives including top-level customer defined requirements. Next we hold a traditional A&D Qualified Bidders Conference (QBC) where student teams present their understanding of the RFI and follow-on review expectations. We could have just as easily handed out a start-up investor market development opportunity notice along with a description of reviews required to support continuing investment. As long as we document project goals/objectives and/or top level product requirements, the name or format shouldn't matter.
Similarly we conduct our 2nd semester under a simulated A&D System Design and Development (SDD) type "contract". SDD defines required development phases and milestones including rules for a competitive fly-off demonstration whereas a commercial equivalent might be a start-up investment contract. Our "customer" documents, however, require rigorous SE design and development methods which are not typical in commercial contracts so some alternative would be needed. For example, a start-up investor might be described as an experienced product development engineer with a low tolerance for technical risk who insists on conducting rigorous technical reviews at investment decision milestones. Regardless of how it’s done, a requirement for a rigorous SE development approach is the key educational component of teaching SE Design. If expectations for how design is to be done are not defined, students will invent their own and it is likely to be ad hoc. In our experience ad hoc approaches to design do little to promote learning except perhaps to provide lessons learned on what not to do. In fact, one of the challenges we have in our course is getting students to unlearn some of the ad hoc approaches they picked up from less rigorous prior projects.

Educationally our first semester design course has an initial emphasis on individual student learning including model based design which, by definition, is engineering discipline specific. Therefore, our aerospace students develop conceptual aircraft design and analysis models through a series of homework assignments that are integrated into an overall air system design, analysis and trade study tool used for the remainder of the course. We also have a Leadership Lecture Series taught by Dr. Hans Mark. Former NASA Deputy Administrator and Secretary of the Air Force where he uses case studies from his NASA and DoD career to address not only project and program leadership skills but personal leadership as well. Non-aerospace course applications of our 1st semester concept would have different content and design/analysis methods and would use case studies applicable to another discipline. But conceptually the approach would be similar.

The beginning of the 1st semester has a secondary focus on team projects which we structure as a competition, i.e. all teams compete to win project. A single project ensures learning objectives are consistent across teams and simplifies course administration and grading. Our current 1st semester project is to conceptually develop and propose a long-endurance, semi-autonomous first responder search and rescue support drone which students design to meet (1) top-level customer mission capability requirements and (2) detailed SE requirements expressed in the form of

![Diagram](image-url)
SE milestone review entry and exit criteria. There are only two (2) SE-specific lectures during the course and, even then, SE principles are described in design engineering terms to reinforce our objective of teaching SE as a fundamental principle of design. There are, however, SE specific team assignments including requirement management, tracking and compliance planning and design decision documentation, all of which are SE Design submittals.

Upon conclusion of the design methodology portion of the course, the emphasis switches to competitive team proposal development for the 2nd semester which includes hands-on tasks such as structural build/test, sensor evaluation and team mission simulation. The semester ends with presentation of competitive team proposals at an Alternate System Concept Review (ASCR) and submittal of substantiating design and SE documentation. Down-select is based 50/50 on presentation and design documentation quality including SE related topics such as requirement compliance and decision documentation and implementation. Student grades are based on individual student exam and project grades combined with individual shares of team grades based on team peer evaluations of individual student contributions.

![Figure 2: ASCR reviewers include the instructional staff and local industry/former students who evaluate proposal briefings to defined exit criteria](image)

At the beginning of the 2nd semester down selected teams integrate into the selected team or teams. As a consequence the teams get larger which requires that student team leadership develop good task planning and management skills. A fall-out of the approach is to simplify class administration and grading. Second semester lectures focus on more advanced design and analysis topics required to support over twenty (20) technically rigorous milestone reviews. Student teams are responsible for task planning required to prepare for and satisfy milestone review entry criteria. The instructional staff role is to evaluate whether entry criteria are compliant and exit criteria satisfied (a minimum grade of 7 for every criterion on a 0-10 rating scale).

Our 2nd semester A&D development model starts with a planning and organizational review followed by design focused system requirements, preliminary and critical design reviews (SRR, PDR and CDR). Other early reviews include material and structural test readiness and test result reviews (TRR). SE Design applications in other disciplines might follow a different model but we anticipate the overall review process would have a similar logic flow.

Each 2nd semester team is required to develop two semi-autonomous air vehicles, one of which is a "baseline" and the other is a "variant" where the wing and tail design is optimized to meet demanding mission requirements the baseline can't satisfy. Both vehicles are developed, flown,
tested and verified against SE model based predictions. Flight testing occurs in phases starting with a first flight readiness review (FRR) and continues through engineering flight testing (EFT) and operational test and evaluation (OTE). Test and evaluation (T&E) concludes with a fly-off demonstration where the student teams demonstrate end-to-end mission capabilities as shown in Figure 3. And consistent with our emphasis on system capabilities, the product evaluated is not the vehicle but the map it produces for "customer" use which in our course is the Search and Rescue Team of the Austin Fire Department.

Figure 3: Fly-off demonstration of student system mission capabilities

The 2nd semester ends with student team System Design Review (SDR) presentations which are critically evaluated to defined review exit criteria, followed by evaluation of substantiating SE design documentation. Half of the SDR grade is determined by completeness and quality of the SDR presentations and substantiating documentation. The other half comes from deliverable SE Design products including documentation showing requirement compliance and design decision rationale. Early reviews are not graded to allow students to learn from mistakes and shortfalls. Whether graded or not, however, milestone reviews are repeated until exit criteria are satisfied. Individual student grades are based on their share of team review and fly-off grades as determined by peer evaluations.

3.0 SE Design Education Rationale and Background

The principles of Systems Engineering have been acknowledged enablers for design, development and validation of advanced technology products for over half a century\(^1\). In today's marketplace, it is essentially impossible to cost-effectively design, deliver and support a technology-based product without application of some principles of SE. In fact many, if not most, development program failures and embarrassments trace to improper understanding or application of SE, particularly in early program phases as addressed in Figure 4. Yet, we observe (admittedly anecdotally) that most traditional discipline engineers including aerospace graduate with little understanding of even the most basic SE concepts much less their application. We believe this shortfall results from the absence of SE content in undergraduate engineering curricula where the fundamentals of SE should be learned along with other engineering fundamentals, but generally aren't, because they aren't taught.
The initiative to integrate the fundamentals of SE into undergraduate aircraft design started in 2008 when this author retired from industry and went to academia. The initiative was supported by my faculty colleague Dr. Hans Mark, former Air Force Secretary and DoD Director of Research and Engineering. Some of my motivations were based on positive experiences but others were not as indicated in Figure 5.

The positive experiences came from programs such as the F-16 where a traditional Engineering Department form of SE was applied to technical planning, design, analysis and quality across disciplines. In those programs Systems Engineering was the responsibility of project and lead engineers who were technically capable of resolving complex interdisciplinary issues as a part of their engineering management and leadership responsibilities. Later, however, people called Systems Engineers started appearing on projects and they didn't have the same level of technical depth as project engineers. However, they had other skills including a focus on customer required processes, reviews and decision/design documentation as well as system
specialties such as security and architectures. When integrated into the overall engineering effort, the new skills improved engineering product quality. But when not integrated, bureaucratic walls went up and efficiency went down. One reason was that a number of SE responsibilities such as requirements and risk were already being performed by design engineers, analysts and/or team leads. The most efficient programs, therefore, integrated both efforts with SEs assuming responsibility for customer-level SE interfaces including specialized SE tools and methods while the other engineers focused on discipline specific applications. As a result of these and other experiences I concluded the fundamentals of SE should be learned by all engineers as a part of their undergraduate education. A similar conclusion had been reached by my spacecraft design education colleagues who had, with NASA support, already introduced SE into their capstone program\(^4\). So our aircraft design course followed suit but with an objective of integrating SE into the syllabus as a hands-on principle of design, not as separate subject.

Our capstone course concept was unique so no texts or course materials were available. So the author and Dr. Mark approached the Office of the Assistant Secretary of Defense, Research and Engineering (ASD/RE) seeking support for development of the two-semester SE Design capstone course concept. We proposed to develop and test the concept for aircraft design students and then offer the concept to interested universities and engineering disciplines. My rationale for why ASD/RE should support the effort was cost avoidance. I analyzed 25 years of DoD Systems Acquisition Reports (SAR) and calculated that the annual average cost per U.S. tax payer for SAR cost overruns at $2000 as shown in Figure 6\(^1\). Of that amount at least one-half could be traced to issues that were described as SE related but in fact were driven by traditional engineering disciplines.

![Causal Factors - US DoD SAR Cost Growth](image)

**Figure 6 - Engineering and Cost Estimating Errors Drive SAR Cost Overruns\(^1\)**

Our ASD/SE proposal speculated that the potential for cost avoidance alone "might just cause instructors to think just a little bit differently about what we teach students about how to deal
with design requirements that push credibility, why it is important to check work carefully and why engineers should speak up when shoddy engineering "visions" including those that violate the laws of physics are proposed". We described our approach as, "teaching SE as a fundamental principle of design," or simply "SE Design" with the characteristics shown in Figure 7.

<table>
<thead>
<tr>
<th>Integrate systems engineering education (rigor and discipline) with design education (math, physics and technical integration)</th>
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</thead>
<tbody>
<tr>
<td>- Systems Engineering introduced simply as “how we do engineering design”, not something separate</td>
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<tr>
<td>Demonstrate why process, rigor and discipline is important</td>
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<td>- Make student design projects complex, can’t work without SE</td>
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<tr>
<td>- <em>E.g.</em> chaos develops when requirements/configurations float</td>
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<tr>
<td>Introduce risk reduction and risk planning as straightforward engineering approaches</td>
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<tr>
<td>- Generate data needed to support design decisions</td>
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<tr>
<td>Require students to think and design across disciplines</td>
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<tr>
<td>- Include communications, sensors and CONOPS in projects</td>
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<tr>
<td>Achieve SE objectives through combination of design, build, experimentation and flight test focused projects</td>
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**Figure 7: 2010 UT Proposal on Systems Engineering Design Education**

ASD/RE accepted our proposal and funded our SE Design course development effort for the period 2010-2012. The task was challenging and the road was bumpy. Nonetheless, by the end of FY2012, our first two student teams successfully demonstrated the capabilities of their system designs to conduct a defined search, surveillance and payload delivery mission as shown in Figure 8. They also successfully defended their system design and development (SDD) approach and verified compliance with overall mission performance requirements.

**Figure 8: Mission Search, Surveillance and Payload Delivery Demonstration, April 2012**

Despite the visible success of the effort there were still issues with the course concept and we concluded it was not ready for transition. Some of the issues were administrative, others were not. The most significant were course maturity and student readiness for an open-ended, multi-discipline system design project. The maturity issue was partially resolved by improving course structure and content but one issue was lack of a text book. Fixing that issue required
development of lecture notes and assignments equivalent to a text book. The student readiness issue required restructure of the first semester to start off more like a traditional engineering course with homework assignments and methodology exams before transitioning into a more open-ended system design environment.

Therefore, we submitted a follow-on proposal to ASD/RE to refine the SE Design course concept and conduct transition testing during the period 2013-15. Our transition partner was the Department of Aerospace Engineering at TAMU. The transition plan focused on specific SE learning objectives which we defined as fundamental principles of SE as discussed next. The focus on specific SE principles and learning objectives was important. TAMU already had a well-developed two semester aircraft design course that included some SE content and it was important to identify what SE was added. TAMU also applied the concept to a control station design course where the student project was to design, develop and demonstrate control of a UT drone in flight.

After testing the SE Design concept TAMU concluded their aircraft design students learned more about SE than before. There were some issues, however, about application of SE Design principles to RFP development. At UT students are given a RFP as a source document for mission design and required design process. TAMU, however, had their students develop an RFP based on interviews with project customers. The experience was valuable for the students and was favorably reviewed during student course feedback. The project, however, took 1-2 weeks of effort and resulted in some loss of 1st semester course content. The 2nd semester design instructor reported no loss of content and was pleased with the overall result.

TAMU's test of the SE Design concept on their control station design course produced unexpected benefits. About half the students in the course were aerospace students, most of which had taken or would take aircraft design. The other half was computer science students who provided an opportunity for feedback on the concept from non-aerospace students. The feedback was quite favorable and the instructor rated achievement of SE learning objectives as higher than previous years. The transition test was also beneficial for UT students who learned about design interface control and the importance of clear and unambiguous communication for achieving success as shown at their joint mission fly off demonstration in Figure 9.

![Figure 9: SE Design students celebrate success at their joint-fly off demonstration](image)

4. Fundamental Principles of Systems Engineering
Regardless of how SE is depicted, the generic nature of the processes and the level of abstraction applied often results in less than complete students understanding of what SE really involves and how it is applied. Generic processes can be useful but they need to be translated into principles that can be understood and internalized. And in university education, principles must be reduced to fundamental concepts that once learned, can be applied elsewhere.

Out of hundreds of pages of processes and practices documented in SE manuals, Figure 10 lists sixteen (16) fundamental SE principles we believe are most important for aeronautical system design and development. That does not mean other SE principles are unimportant. What it does mean is that in aeronautics, these are what we think undergraduate engineers need to learn and know how to apply. The order of the principles does not imply order of importance; it is based on technical logic flow starting with requirements.

<table>
<thead>
<tr>
<th></th>
<th>Requirement Types and Analysis – Defined, derived, rational flow-down</th>
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<tbody>
<tr>
<td>2</td>
<td>Requirements Management – Track and demonstrate compliance</td>
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<tr>
<td>3</td>
<td>Margins – Design and operational, allocation and management</td>
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<td>4</td>
<td>Concepts of Operation – Design, develop and test</td>
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<td>5</td>
<td>Measures of Effectiveness (MoE) – Definition, application and tracking</td>
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<td>6</td>
<td>Trade Studies/Analysis of Alternatives – Including physics-based trades</td>
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<tr>
<td>7</td>
<td>Model Based Design – Development, verification and validation</td>
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<td>8</td>
<td>Technical Decision Making – Decision approach and documentation</td>
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<td>9</td>
<td>Risk – Identification, planning and management</td>
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<tr>
<td>10</td>
<td>Review – Entry and exit criteria, external (formal) and internal (informal)</td>
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<tr>
<td>11</td>
<td>Configuration Management – Baseline and interface definition/control</td>
</tr>
<tr>
<td>12</td>
<td>Test and Evaluation – Plans, reviews, execution, analysis and reports</td>
</tr>
<tr>
<td>13</td>
<td>Leadership – Personal / Team</td>
</tr>
<tr>
<td>14</td>
<td>Project Planning – Long and short term planning and tracking</td>
</tr>
<tr>
<td>15</td>
<td>Product Cost – Analysis, prediction and tracking</td>
</tr>
<tr>
<td>16</td>
<td>Project Management – Task, schedule and cost (status and forecast)</td>
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</table>

Figure 10: UT SE Learning Objectives for Air System Design

We take a somewhat unconventional approach to the term "requirement" and define it very broadly to capture everything a product is expected to accomplish. Included are goals, objectives, specifications and even elements of mission statements. In essence, we have our students take a designer's view of requirements. If a design is expected to do something, a good designer will write it down, assess the impact and feasibility and prepare to push back as appropriate. And with a few exceptions, we teach our students that requirements should be considered negotiable. The exceptions are issues associated with safety and/or hard, non-negotiable regulatory issues. Since requirements evolve during product development we move next to the product development cycle and associated phases. Development phases start and end with reviews so we discuss them next. Included in the discussion of phases is Test and Evaluation (T&E). Then we go back to requirements and discuss (1) requirement analysis and development, (2) how to design products to meet requirements, (3) how to verify/validation that products meet requirements and (4) how to document requirement compliance. Then we work our way down the rest of the list of sixteen but skip over Reviews and T&E since they have already been addressed.
Other engineering disciplines have their own views on what undergraduate engineering students should learn about SE in their areas as shown in Figure 11. In 2015 the author participated in a workshop cosponsored by the Systems Engineering Research Center (SERC) and the International Council of Systems Engineering (INCOSE) that specifically addressed SE learning objectives across engineering disciplines. Although the findings had not yet been finalized, the first round of discussions resulted in what I summarized from notes as shown in Figure 11. The lists in Figures 10 and 11 are different but there is commonality which supports the thesis that all engineers need to understand some fundamentals of SE while others that may be important only for their or related disciplines.

![Figure 11: SE learning objectives for Engineering - A preliminary consensus](image)

Although SE documentation is not included in either list of learning objectives, it is inherent in all engineering and is included by definition. The message to our students is that engineering of any kind without documentation is useless. Aerospace product development, in particular, is a high-risk, high-cost undertaking and customers insist that the engineering behind those products be disciplined, thorough, well-documented and independently verified. Most aerospace products also have to be certified which, by its nature, is documentation intensive. The issue for engineering design students, therefore, is not whether to document but what to document and how as discussed in Section 5.

5. Instructor Guide to SE Design Application to Capstone Courses

This section generalizes our aerospace-focused SE Design approach for other engineering disciplines interested in SE Design application to capstone and other design related courses. The generalized approach was developed with SERC sponsorship through the Capstone Marketplace Project. As shown in Figure 12, capstone courses have multiple implementation options. The options include project deliverable type which we categorize as (1) Products (hardware or software including reports) and (2) Reports. Product focused projects increase workload for both students and instructional teams and competitive (single projects) reduce workload for the instructional team but not the students. Another observation is existing projects have wide variation in SE content ranging from projects that claim SE content and actually have little to those that claim none and have some. Therefore, unless a project is defined specifically to meet SE Design education objectives, we assess them as neutral on SE Design content.
Projects can be sponsored by government, industry and/or professional organizations (or not which provides yet another implementation option). Projects can also be competitive where student teams from multiple schools compete or, as in our course, teams compete within the class. Other options include projects that are assigned or selected by one team only which we categorize as Team Unique. Although we have no hard data to support our assessments, we have experience across many of the options so we anecdotally rate them all for student, instructional team and sponsor workload. Our workload standard is a report-only capstone course defined only by a request for proposal (RFP). No external support is assumed. The RFP standard is minimally documented and reports are assumed to be reviewed by sponsors but not graded. Unsponsored projects, therefore, are assumed to increase the workload on the instructional team.

**Figure 12: SE Design Capstone Course Considerations**

This section assumes the reader has experience teaching traditional capstone courses and is interested in integrating SE Design into their course. Therefore, our 1st recommendation is to start off with a singular focus on engineering discipline capstone learning objectives including levels of SE knowledge required for today's projects, most of which are multi-disciplinary. When you are satisfied with the learning objectives, superimpose curriculum and facility/faculty constraints that limit course content and structure. Then within the constraints including credit hours and semester schedule, functionally define what you think would be one or more ideal projects that satisfy your SE Design learning objectives. Generalize the results in the form of project selection criteria and then and only then start looking for company or organization sponsored projects that meet the criteria. In addition to your Department's project lists, another place to look for funded projects is the SERC Capstone Marketplace. Hopefully you will find a number of candidate projects that satisfy your SE learning objectives. Some may require tailoring and sponsor negotiation to align with your new course objectives and/or selection
criteria. However, we suggest you stick to your guns and decline any project that lacks required SE content and/or doesn't meet learning criteria, regardless of the funding and/or sponsor influence.

If you can't find a suitable project, then think about creating your own. In our experience, the simplest and most efficient option is to select a single project and have all teams compete to develop the "best" solution to meet requirements. The approach will reduce the course administrative burden and leave more time to interact substantively with the students. Our preferred interaction is through in-depth, technical design reviews where, in our experience, real design learning starts to occur.

If the project deliverable is a paper design, you'll probably have to come up with a new project every semester. If, however, the deliverable is hardware and/or software that has to perform, the project can be repeated if follow-on classes are required to develop different and better performing solutions which is the approach we use. Since 2012 we have assigned only two projects, both of which were developed in-house. Yet every semester 20-40 very bright and capable kids struggle to meet even minimum demonstration requirements. And despite the fact we have excellent teaching assistant support, it still takes most of our available time to pull off just one competitive project. So we consider multiple hardware or software projects a challenge.

During our first semester, we spend most of our time lecturing and a lesser amount of time conducting team reviews. During the second semester, the emphasis is reversed. During both courses we invite participation by industry and government colleagues but to enhance vs. define the student learning experience. We can operate this way because between Dr. Mark and the author, our design experience starts from before Apollo and continues through F-35 first flight. It may be somewhat unusual for professors to have more design experience than invited reviewers but that's not its important. It is important because design students need regular interaction with people who have first-hand design experience which is not restricted to government or industry mentors. And even if government or industry mentors have first-hand experience and strong technical credentials, student interaction is often less frequent and sometimes unreliable. We recommend, therefore, that SE Design, and for that matter capstone design, be taught by "design experienced" instructors. We use the term "design" experienced vs. industry or government experienced because having industry and/or government experience doesn't necessarily mean one has hands-on design experience and vice versa. Also design projects in academia can provide the requisite experience but only, in our opinion, if the project(s) involve strict engineering discipline and in-depth reviews. If design experienced instructors are not available, course objectives can still be met but the class will probably lack design room realism.

**How to start** - Figure 13 is a summary of our recommendations if you find yourself having to develop your own SE Design course of instruction.
1. Define contemporary design process through product acceptance  
2. Finalize capstone learning objectives.  
3. Search for established course of instruction and text.  
4. Structure course around SE milestone reviews with defined review entry and exit criteria  
5. Functionally define “ideal” capstone project involving objective design and analysis of alternatives.  
6. Functionally define required deliverable product demonstration  
7. Develop project agnostic requirements document with a top-level performance and detailed design and test requirements (see #4)  
8. Define required team size based on SE Design learning objectives  
9. Define product-focused team organizational interfaces  
10. Select project, avoid those limiting instructor review responsibility

**Figure 13: SE Design Capstone Course Design Approach**

1. If you don't have first-hand design experience, educate yourself on how it's done in government and/or industry starting from initial concept and continuing through design, development, operation and support including competitive, cost, safety, regulatory and public perception issues. Identify which phases or issues are most important for students to learn from a fundamental educational perspective. Don't get distracted by cool or trendy tools and methods which can and will be learned on the job. If design students leave your course with nothing more than how to work their way through design, build and test using first principles and back of the envelope calculations, they will leave with deeper and more enduring knowledge than students who spend their time running sophisticated codes they don't understand.

2. Clearly define your functional discipline and SE design learning objectives and discuss them with faculty colleagues and students. Solicit inputs from government and industry but be wary of assertions about what students don't need to know, especially if it involves SE. There are a companies and organizations that still use Stone Age or ad hoc engineering approaches and that's not what students need to learn.

   - Note on Model Based Design - If learning objectives include model based design, select a design textbook with student software that enables it. If none exists, is there is an established modeling language or modeling system available? If so, use the tool or method (e.g. SysML). If not, you'll have to define and develop a model structure to meet your engineering discipline model based design requirements and it will be time consuming. If you are not able to invest the time and effort required, select a commercially available product, learn it and teach to it. But insist that the students learn and understand the underlying methods and assumptions.

3. Try to find an established course of instruction and text that meets your SE educational objectives or requirements. For those that come close, you can develop modules to fill the gaps. If you can't find a course of instruction or text and you still want to teach SE Design, plan on spending a lot of time developing class handouts and homework. This statement comes from personal experience so do it only as a last resort.

4. If you are an experienced designer but don't have a Systems Engineering background, study the principles and identify which are most applicable in your area. Then write a systems
engineering design guide for your students. Stay away from jargon and process charts and state the principles in simple engineering terms. Finally structure your design course around those fundamental SE principles starting with concept development and continuing through modeling, test, validation and verification. Structure the course around milestone reviews where students have to demonstrate readiness (i.e. meet entry criteria) and pass defined exit criteria. Exit criteria should be expressed in go/no go terms where unsatisfactory performance means they have to come back and do it again until the results are satisfactory. Review entry and exit criterion from our Air System Engineering Design course are available upon request.

5. Design/define what you think will be an ideal project to meet your functional design and SE learning requirements. Try to make it generic and include both hardware and software elements. The project needs to involve more than analyzing or building a prescribed concept. Students need to learn how to identify and then convince independent reviewers that their proposed solution is the "best" among alternatives. Students who don't learn how to objectively evaluate alternatives don't learn the most fundamental principle of design. Drawing or analyzing somebody else's design may have some educational value but it is not real design unless it involves design feedback, tradeoffs and decision making.

6. Focus the student effort on a hands-on product that has to work and demonstrate a working capability. The laws of physics and Mother Nature do a much better job of teaching students the difference between cartoons and real design than any textbook or instructor could ever do.

7. Structure a generic customer-focused project description document. Use "shall" to define required student tasks or actions. Use "will" to define customer plans. Document the project and the required SE Design processes in the form of a Request for Information/Proposal and System Design and Development document or whatever definitions are used in your discipline area. An example from our course is available on request. Suggested project document structure is as follows:

   1. Overview of project with top level requirements and plans in terms of "shall"s and "wills"

   2. Define required development phases and associated tasks and entry/exit criteria, e.g.
      a. Requirements analysis
      b. Analysis of alternatives
      c. Conceptual design
      d. Conceptual Design Review (CoDR) and documentation

   3. Define demonstration requirements (as appropriate)
      - In our project, demonstration requirements are defined by fly off contest rules

   4. Define demonstration or competition scoring (if appropriate)

   5. Define project briefing and documentation evaluation criteria
Once documented, project descriptions can be adapted for other projects by tailoring the individual sections as appropriate. When we changed our design project in 2015, the changes required involved only the overview, demonstration and scoring sections.

8. Determine how many teams your course can or wants to handle. Our experience is the smaller the team, the easier it is for the students but the less the engineering depth. We also believe students learn more across functional areas and about Systems Engineering Design on larger teams. Larger teams make it easier for the instructional team to interact. These observations, however, are anecdotal and research is needed to sort out the assertions. Our approach is as follows:

- First semester conceptual design teams consist of 6-8 students organized by top-level product. Our 2nd semester teams consist of 15-25 students, also organized by task and product, e.g. Team Lead, Chief System Engineer, Mission Design, Baseline Vehicle, Variant Vehicle, System Control, Test and Evaluation. Most team members have multiple assignments that vary by development phase.

9. Encourage students to organize around deliverable products. Avoid using traditional discipline names on organization charts, i.e. mechanical, electrical or fluid. Instead use product deliverable focused descriptions. That way the students focus on the work to be done vs. the type of people that do the work. Sometimes students will resist organizing by product and it's OK if it doesn't go on very long. Teams quickly see why an engineering discipline focused organizational approach is inefficient except on very large projects, which student projects aren't. Organizing incorrectly is a valuable lesson for students to learn but it also can put them behind schedule and affect learning outcome.

10. Assess your department’s design course philosophy and the role of the instructional staff.

- If the philosophy is for students to pick and choose from a range of tasks provided by industry or government sponsors where the role of the instructor is to coordinate and/or facilitate a defined task, forget about SE Design. There will be too much variability in the projects and the educational content to meet SE Design objectives. Meeting SE Design objectives requires a focus on specific SE learning objectives. Tasks from sponsors looking for cheap student labor also often have little if any SE Design or other design education content.

- If, however, a sponsor defines design objectives in terms of desired product capabilities, SE Design objectives can be satisfied. But everybody involved (instructor, mentor, etc.) needs to be on the same page about technical quality requirements including tools, methods and required reviews.

6. SE Design projects and research

Although our approach to teaching SE across engineering as a fundamental principle of design works and is independently verified, there are other approaches and issues that should be researched. Included are SE knowledge requirements across engineering disciplines, learning effectiveness of various instructional techniques including capstone vs. other design courses,
instructor knowledge requirements as well as traditional discipline SE education issues and methods as summarized in Table 1 and expanded upon in the text that follows.

Table 1: Suggested SE Design Research Areas

| 1. SE knowledge survey by discipline |
| 2. Simple SE method depiction |
| 3. Comparison of SE Design delivery methods |
| 4. SE Design content displacement effects |
| 5. SE Design instructor experience requirements |
| 6. Student teams size effects on SE Design learning |
| 7. Student team competition effects of SE Design learning |
| 8. Traditional capstone vs. SE Design student quality perceptions |

1. SE Knowledge Survey - Conduct entry and exit and entry assessments of the current state of SE understanding across engineering disciplines. Correlate the results with government and industry expectations for SE knowledge. Identify educational options and initiatives to fill the gaps. An example of our knowledge survey for incoming aerospace students is available upon request.

2. Systems Engineering and the Scientific Method - The Scientific Method is a fundamental basis for scientific development. Like SE it is not a one-size-fits-all cookbook method and requires intelligent tailoring of fundamental principles to achieve desired outcomes. The Scientific Method is learned early in STEM education and applied across multiple courses that follow. Systems Engineering, however, is just as fundamental to engineering and most non-systems engineers, in our opinion, graduate with little or no understanding of even the most fundamental concepts. The proposed research task would develop a simple and easy way to teach the concept of SE based on the scientific method model that all STEM students can also learn and internalize with the same ubiquity as the Scientific Method. This task will require revising current internet sites that tout an "Engineering Method" that bears little resemblance to how engineering is practiced except on very simple projects.

3. SE Design course delivery concepts - Independently evaluate the effectiveness of various SE Design concepts. Examples of course "concepts" include:

   a. "Report" vs. "Product" design projects. We assume most if not all design courses require submittal of a design report that documents, provides rationale for and substantiates a design. Our and some other courses also involve hands-on product deliverables in the form of prototype hardware or software. Our experience is that student SE Design learning goes up significantly when the project is a hands-on product but we have no data to support the conclusion.

   b. "Separate" vs. "Integrated" SE content. SE is traditionally taught as a separate subject, typically using a lecture format. We, however, integrate SE into the course structure with one or two lectures. The approach fits our course concept but we have no data to confirm it is most effective approach although we believe it is.
c. "Instructor or mentor" vs. "student" project management. In some courses, instructors or mentors define design team deliverables and schedules. In others, the instructor or mentor plays a customer role and students are responsible for planning and scheduling. We use and believe the latter approach provides a better SE learning environment but again, no data.

4. SE Design educational methods for content and schedule constrained engineering curricula. There is a prevailing view among engineering educators that curricula are already packed full of functional discipline and university required learning objectives and requirements and there is no room to add SE content. The research task would independently validate our experience that the fundamentals of SE can be integrated into design courses without displacing other content. The research output would be a comparison of results across disciplines and recommendations for broader applications.

5. Design course instructor SE experience. Instructors without prior industry design or SE experience may feel unqualified to teach SE Design. Our view is the fundamentals of SE Design are not complicated, particularly when taught as hands-on principles of design. The research task would evaluate SE Design effectiveness as taught by capstone instructors with and without prior design and/or SE experience and correlate educational effectiveness with experience in both areas.

6. Student team size effects on SE Design learning. Our aircraft design experience is that small student design teams simplify student task planning, tracking and scheduling to the point that project management skills may go untested. We also find that small teams do not have time to address complex issues and fall back on simplistic assessments and/or assertions. These conclusions, however, are untested. The research task, therefore, would independently evaluate the effects of team size on SE learning effectiveness and depth of knowledge gained across a range of SE Design project types and disciplines.

7. Student competition as a factor in learning. Our aircraft design course experience is that design projects involving student team competition for the same project enhance student learning and increase instructor technical involvement by reducing administrative workload. However, the norm in academia is for student teams to have different projects and/or different sponsors. We propose the two design course concepts be independently evaluated for learning effectiveness and outcomes.

8. External perceptions of the quality of traditional discipline vs. SE Design course outcomes. Many traditional design course instructors probably feel their courses of instruction fully satisfy industry and government employers, ABET and student design expectations. Their views are probably reinforced by anecdotal feedback from advisory boards and student course evaluations. My conclusion, however, is that understanding SE fundamentals is a prerequisite for contemporary engineers. The proposed research task would be to survey engineering department advisory boards, employers and former students about their assessment of the value of including or not including SE content in university design education.
7. Summary and Recommendations

Starting 2010 this author, with support from the Department of Defense, the Systems Engineering Research Center (SERC) and faculty colleagues has focused on developing and demonstrating the benefits of teaching Systems Engineering (SE) as a hands-on principle of engineering through capstone design. The concept is called SE Design and the rationale is that in today's world of multi-discipline, integrated products, a fundamental understanding of SE is an educational imperative. The enabler for our concept is that design education requires structure and discipline and SE can provide it without displacing other educational content if applied hands-on. The concept is now well-developed and has been verified for transition by colleagues at Texas A&M University. Thus far, however, the application has been limited to aeronautics related design. Anecdotal evidence suggests that the concept will work across aerospace but it has not yet been demonstrated.

Questions about applicability of SE Design across engineering also exist. Aerospace Engineering is inherently multi-discipline and, as an industry, is steeped in a culture of SE. While we believe our lessons learned and feedback from graduates working in other industries, support our premise that an understanding of SE is an imperative across engineering, we have no data to substantiate it. We also have no data that says our educational concept works better than other educational concepts even though we believe it does. So our suggestion for other engineering discipline educators is to go back to where we started. Evaluate what your students need to learn to enable them to function effectively in today's multi-discipline design environment and develop your own approach as suggested in section 5. We also recommend educational research on how to best teach SE through design education. Research topics include discipline specific SE knowledge requirements, SE Design learning effectiveness of various instructional techniques including capstone vs. other design courses, instructor knowledge requirements as well as fundamental SE educational issues such as discipline acceptance and transition.

References


7 Draft Findings, Workshop on SE For All Engineering Worcester Polytechnic Institute, Worcester, MA, 18 May 2015