Assessment Structure and Methodology for Design Processes and Products in Engineering Capstone Courses

To enhance learning as well as satisfy requirements mandated by ABET, engineering programs and faculty are increasingly investigating ways to teach and assess the technical and non-technical outcomes set for students. Capstone courses provide an ideal place to assess these outcomes, as they typically address all or most of those listed in Criterion 3. With ongoing NSF support, the Transferable Integrated Design Engineering Education consortium (TIDEE) has been developing transferable assessment tools specifically for engineering capstone design courses. This work has produced a framework and cognitive model which outline the primary performance areas associated with capstones and provide an overarching structure of the assessment implementation strategy. The model represents the structure of a complete package of instruments that are valid for varied capstone courses, institutions, and faculty. Over the past few years, with this framework and model, TIDEE has designed, tested, and implemented several assessment instruments as part of this package. The work presented in this paper is a continuation of TIDEE’s effort, and describes the structure of the remaining assessment instruments to be developed – for design processes and resulting design products – along with a methodology for creation of these instruments.

BACKGROUND

The quality of engineering education in the US has received considerable attention recently, largely motivated by increased global competition. The National Research Council’s congressional report, *Rising Above the Gathering Storm*, underscores the need for education and policy leaders to embrace these changing dynamics and strive to better prepare future engineers for both known and unknown challenges. In the recently published book, *The Engineer of 2020: Visions of Engineering of the New Century*, along with its companion, *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*, the National Academy of Engineering gives a vision of these challenges, including social, political, cultural, and economic, as well as addresses many of the professional attributes needed for future graduates, such as strong analytical skills, creativity, ingenuity, professionalism, and leadership.

Additionally, and in support of this common vision, the engineering community has developed an extensive research agenda directed specifically at the transformation of engineering education to address these needs.

Engineering capstone design courses play an integral role in this effort. As a culminating experience for graduates, students apply their newly acquired knowledge and abilities to practical engineering problems. This experience allows them to make valuable connections between theory and practice, and serves as an excellent opportunity to develop critical professional skills. The value and significance of this course is highlighted by the inclusion of Criterion 4, the professional component in ABET’s accreditation requirements, which states that “students must be prepared for engineering practice through the curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier courses.”
A vital component to the success of capstone courses, and education in general, is the incorporation of a quality assessment program, at both the program and student level. At the program level, it provides the basis for institutional changes and improvements. At the student level, assessment allows faculty to gauge the quality of the student’s work and provides the communication link between faculty and students, leading to improved instruction and enhanced learning. The literature is rich with research highlighting the benefits of both formative and summative assessment as the key to effective teaching and learning\textsuperscript{10-12}. ABET also stresses the use of assessment in Criterion 1, requiring institutions to “evaluate, advise, and monitor students progress to foster their success in achieving program outcomes”\textsuperscript{9}. In addition, ABET’s criteria now place the ‘burden of proof’ on programs to demonstrate that outcomes are being met by students\textsuperscript{9}, which is largely accomplished through adequate assessment methods.

The engineering capstone course provides an ideal place for assessing these student learning outcomes. Many, if not all, of ABET’s eleven outcomes of Criterion 3 are encountered by students at some point throughout their design project\textsuperscript{12}. With the design nature of the course, several of these outcomes serve as the course’s primary focus; for example, Criterion 3c, “design of a system, component”\textsuperscript{9}. In a national study by McKenzie, he reports that 90\% of capstone faculty participating in the survey indicated that they engage in some form of assessment in their course\textsuperscript{12}. This percentage is likely to rise even further with the increased exposure and development of valid and reliable assessment instruments.

Research into the development of quality assessment instruments for capstones, as well as engineering in general, has been gaining momentum since ABET’s mandate of assessment in its 2000 Criteria. The literature now offers a considerable database of assessments for various aspects of engineering, and for capstones in particular. Many researchers report on the development, implementation, and tested results of instruments they have developed specifically for their course application\textsuperscript{13-17}. Although this rich repository of information is valuable and effective for individual uses and situations, missing is an organized system of assessments that are generalizable and yet focused enough to be valid for multiple programs, disciplines, and faculty needs. This need led participants of TIDEE to embark on an NSF supported project to develop a package of transferable assessments for capstone design courses\textsuperscript{18}.

TIDEE was formed for the purpose of developing, testing, and disseminating effective educational materials for engineering design education\textsuperscript{18}, and consists of participating institutions across the US. In 2004 it began development of assessment instruments specifically for capstone courses\textsuperscript{19}. Results from this work include a developmental framework and model based on current assessment foundations and principles, and a partial set of assessment instruments for capstone use. The framework provides an overall philosophy for the design of assessment instruments. This is based on the assessment triangle presented by the National Research Council, which advocates the alignment of three elements for quality assessment design: a cognitive model of learning, observation tasks, and interpretation\textsuperscript{20}. For the first of these elements, TIDEE has developed a model based on the outcomes addressed in typical capstone courses. The model organizes the outcomes by differentiating between those related to Learner Development and Solution Development. These have each been further divided into specific performance areas. The performance areas for Learner Development include Teamwork and Personal Capacity, and for Solution Development the areas are Design Process and Solution
Assets. Assessments have been designed and validated for the Learner Development outcomes. Current and future efforts, as presented in this paper, will focus on developing the remaining Solution Development instruments, which will complete TIDEE’s assessment package for capstone courses.

**RESEARCH GOALS AND APPROACH**

The long term goals of this research are:

- To develop assessment instruments for assessing students’ knowledge of design processes (Design Process performance area assessments) used in engineering capstone projects.
- To develop assessment instruments for assessing the quality of students’ design products (Solution Assets performance area assessments) in capstones.
- To package these, together with those developed for Teamwork and Personal Capacity, into a complete set of assessments, scoring and interpretation rationale, and implementation guidance.
- To develop a web-based system, allowing for easy adoption and dissemination among capstone design course faculty.

The objectives of this paper are:

- To present a course structure for assessing design processes and products in engineering capstone design courses.
- To present a methodology for designing assessment instruments for design processes and products in capstones.

The research plan for this paper is to review literature on design processes, products, and current assessment practices in capstone design courses, and then use this as the basis for assessment development. A description and synthesis of common design processes and resulting products will be presented to identify those particular to capstone courses. Following, a brief review of current assessment practices for design processes and products in capstone courses will suggest appropriate assessments for capstones that will be valid and applicable for multiple uses and users.

**LITERATURE REVIEW**

**Design Processes and Products**

A first task in developing assessment instruments for design processes and products associated with student projects is to clearly define those which are commonly used or produced by students. Several design texts were consulted to survey design processes and products of importance, with some texts considered general purpose and others specific to one type of capstone design course. Nine sources were reviewed before new information gains from the last source suggested that a comprehensive listing of the design processes had been achieved\textsuperscript{21-29}. 
For design processes, each text reviewed lists similar but slightly varied versions of the typical progression of activities of a design project. Each gives similar discussions of the major phases and process activities, but with no clear boundaries between phases. Functional decomposition, for example, is presented in some texts as an activity performed during the problem definition phase to aid in defining customer requirements and engineering specification, while in other texts it is part of the concept generation phase. In reality, elements from this activity are required at multiple times throughout the project, highlighting the iterative nature of the design process.

It is therefore important to realize that the value of these design process philosophies is in the general sense, providing a semi-hierarchical snapshot of typical design activities, but not necessarily a prescriptive approach to all engineering projects. For the purposes of assessment development, a quite general categorization of the design process will be adequate, as the primary purpose of the assessment will be to broadly assess students’ approaches and uses of these activities, allowing for feedback and instruction to be given.

Table 1 gives a listing of the design phases with associated processes and products from the reviewed texts. Since each text divides the design process into different phases, a common basis for review is provided by synthesizing these into seven common phases. Common activities and products reported from the texts have been allocated to one of these seven phases.

Assessment in Capstone Design Courses

Approaches used to assess design processes in capstones

The following review highlights some of the different approaches taken to assess students’ application of design processes in engineering design. The review is not particular to capstone courses, but covers engineering design in general. The aim of this section is to show different methods of process-related practices in terms of both assessment and implementation. The next section will address assessment approaches taken for the products resulting from engineering design projects.

Atman and Bursic suggest the use of verbal protocol analysis to assess the design process abilities of students (in freshmen and senior engineering courses). With this method, students think aloud as they solve engineering problems or perform tasks. Their thought processes are recorded using audio, video, or both, and are then analyzed based on given criteria. Results indicate that the use of VPA is a powerful tool for understanding students’ knowledge of the design process. They report that comparison of the process knowledge with the quality of the final product allows for inferences to be made between good and poor processes and indicates which problems should be addressed by student teams.

Sims-Knight et al. have reported on a suite of assessments used to assess students’ declarative, procedural, and metacognitive knowledge of the design process in both capstone and general engineering courses. For declarative knowledge, they have developed a multiple-choice test, called the Design Process Knowledge Test, which “assesses the extent to which students understand the rules of best practices in design process.” For assessing design procedural
<table>
<thead>
<tr>
<th>Common Design Phases</th>
<th>Common Phase Processes/Activities</th>
<th>Common Phase Products</th>
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</thead>
<tbody>
<tr>
<td><strong>Product Opportunity</strong></td>
<td>• Develop a vision</td>
<td>• Mission statement</td>
</tr>
<tr>
<td><strong>Analysis</strong></td>
<td>• Analyze market opportunity and company situation</td>
<td>• Design proposal or business plan</td>
</tr>
<tr>
<td></td>
<td>• Evaluate and select product opportunity(ies)</td>
<td>• Project plan (task list, team roles, schedule, budget)</td>
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<tr>
<td></td>
<td>• Formulate product proposal</td>
<td></td>
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<tr>
<td></td>
<td>• Plan design project (identify and coordinate tasks and resources: schedule, budget, team)</td>
<td></td>
</tr>
<tr>
<td><strong>Problem Definition</strong></td>
<td>• Clarify objectives</td>
<td>• Problem statement</td>
</tr>
<tr>
<td></td>
<td>• Identify customers</td>
<td>• Objective trees</td>
</tr>
<tr>
<td></td>
<td>• Determine and evaluate needs and requirements</td>
<td>• House of quality matrix</td>
</tr>
<tr>
<td></td>
<td>• Identify constraints</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Identify essential functions/problems</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Evaluate competition</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Establish design specifications (metrics/parameters)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Set target specifications</td>
<td></td>
</tr>
<tr>
<td><strong>Concept Generation</strong></td>
<td>• Perform functional modeling/decomposition</td>
<td>• Function model structure/tree</td>
</tr>
<tr>
<td></td>
<td>• Define major subsystems and interfaces</td>
<td>• Concept (presented as a model: graphically, physically, and/or analytically; as a textual description; or other form that gives indication of the manner in which functions are achieved)</td>
</tr>
<tr>
<td></td>
<td>• Search for working principles</td>
<td>• Justification for concept selection: Pugh chart, evaluation matrix</td>
</tr>
<tr>
<td></td>
<td>• Generate alternatives</td>
<td>• Final specifications</td>
</tr>
<tr>
<td></td>
<td>• Model concepts</td>
<td></td>
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<tr>
<td></td>
<td>• Test concepts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Perform economic analysis</td>
<td></td>
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<tr>
<td></td>
<td>• Evaluate alternatives</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Select concept</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Set final specifications</td>
<td></td>
</tr>
<tr>
<td><strong>Preliminary Design</strong></td>
<td>• Generate alternative product architectures</td>
<td>• Layout drawing</td>
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<tr>
<td></td>
<td>• Select materials, components, etc.</td>
<td>• Preliminary detail drawing</td>
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<tr>
<td></td>
<td>• Perform preliminary design calculations</td>
<td>• Model (graphical, physical, and/or analytical)</td>
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<tr>
<td></td>
<td>• Select best preliminary layouts</td>
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<tr>
<td></td>
<td>• Select modeling/simulation process</td>
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<tr>
<td></td>
<td>• Model/simulate/analyze design</td>
<td></td>
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<tr>
<td></td>
<td>• Test, evaluate, refine, optimize design</td>
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</tr>
<tr>
<td></td>
<td>• Set final specifications</td>
<td></td>
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<tr>
<td><strong>Detail Design</strong></td>
<td>• Perform detailed modeling: physical and analytical</td>
<td>• Final model analysis</td>
</tr>
<tr>
<td></td>
<td>• Design for X (performance, robustness, etc.)</td>
<td>• Detailed design</td>
</tr>
<tr>
<td></td>
<td>• Test and evaluate design</td>
<td>• Test and validation results</td>
</tr>
<tr>
<td></td>
<td>• Refine, optimize, and validate design</td>
<td>• Prototype</td>
</tr>
<tr>
<td></td>
<td>• Develop prototype</td>
<td></td>
</tr>
<tr>
<td><strong>Documentation and</strong></td>
<td>• Develop required design documentation</td>
<td>• Final design communications (reports, presentations, drawings, support documentation, etc.)</td>
</tr>
<tr>
<td><strong>Communication</strong></td>
<td>• Communicate design</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Final product</td>
<td></td>
</tr>
<tr>
<td><strong>Implementation</strong></td>
<td>• Implement production</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Market and distribute</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Follow up</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Final product</td>
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</tbody>
</table>

knowledge, they discuss an assessment in which students engage in a design task (2-3 hour long task), followed by a postmortem questionnaire regarding the process activities used. Students are evaluated based on how well they address the processes used in the task. Other methods stated for collecting data on design procedural knowledge include: 1) verbal protocol analysis of students’ design notes from the task, 2) verbal protocol analysis of videotaped recordings of students performing the task (where the amount of time spent on each design activity was the criteria for assessment), and 3) the use of pre- and intermittent-tests throughout a design activity,
in which students give an ordered list of the design process activities used\textsuperscript{14}. Evaluation is based on the quality of the processes used.

As a further method for assessing procedural knowledge of the design process, Sims-Knight et al.\textsuperscript{32} have discussed the use of a computer-based simulation task, in which students watch a team engaged in design. At intermittent times throughout the task they are prompted to make recommendations on how the design team should proceed. Assessment questions probe, for example, what the team should do next and allow students to choose between alternative responses.

Additionally, Sims-Knight et al.\textsuperscript{33} have reported on the use of concept maps to assess students’ design process knowledge. The target is to assess understanding of how various aspects of the design process go together; a measure of structural knowledge of the design process, verses declarative knowledge\textsuperscript{33}. The purpose stated for the above mentioned assessments is continuous improvement of students in meeting the ABET criteria (formative use).

Bailey and Szabo\textsuperscript{34} have reported on an assessment tool to assess design process knowledge in first year and senior capstone courses in which students analyze and critique a proposed process. After the process is presented to the students outlining the various steps, they are asked to identify the strengths and weaknesses of the proposed process. Students are given pre- and post-tests and an analytic rubric is used to evaluate the design knowledge evident in their responses. This process can be used to measure the amount of design process knowledge gained over time.

Newstetter and Kahn\textsuperscript{35} have reported on the use of portfolios and cognitive maps as effective tools for assessing student design process skills and knowledge. For the portfolios, targets for assessment include: 1) design of the portfolio as an artifact of communication and persuasion 2) evidence of problem-structuring, 3) evidence of problem decomposition 4) evidence of incremental development of the design solution 5) evidence of constraint setting, and 6) evidence of different levels of abstraction and various types of modeling/representation of the problem space. The cognitive maps are used to assess knowledge of the structure and relationships of design. Targets for assessment include propositions, hierarchy, cross-links, and examples.

As a method for course planning and assessment, Safoutin et al.\textsuperscript{36} have developed a design attribute framework of the design process activities based on Bloom’s taxonomy. ABET outcome 3c, “design of a component...” for example, is broken into various components (need recognition, problem definition, planning, etc.), and each component is defined for the seven cognitive levels – Bloom’s six cognitive levels and one additional level of “valuation.” This framework is a means of refining the broadly defined ABET outcome, and provides a way of organizing these outcomes based on an established and accepted cognitive hierarchy. For assessment purposes this framework can be used by selecting an appropriate combination of the design component and desired cognitive level for assessment. Based on this framework, Safoutin et al. have developed an assessment instrument for a general engineering design course. The instrument is a student survey which includes multiple components of the design process, each at various cognitive levels. For each survey item, students rate their confidence level on a five point scale. The emphasis of the assessment is on how students approach design problem solving, verses simply recall of information.
The examples above highlight some common methods for assessing student design process knowledge. In addition to this, faculty have used design products as opportunities to assess process activities. For instance, common capstone products include design reviews (peer, client, and faculty), oral presentations, and written reports. In the assessment and evaluation of these products, performance criteria may also be included to address various elements of the design process. This is commonly done by addressing a particular activity – identification of customer needs, for example – through a single scoring metric in a rubric. In this case, the nature of the assessment is more holistic with little depth, mainly used as a checklist for activity completion verses assessment of deep understanding.

*Approaches used to assess design products in capstones*

Products, as mentioned, are the results of tasks, phase activities, and overall project efforts. The purpose for product assessment is typically to provide evaluation data, where scores are based on the quality of the product as defined by selected performance criteria. Table 1 gave a list of the products associated with engineering design courses. A few of the most common products used for assessment, as seen in the literature, include progress reports, design reviews, final oral presentations, and final written reports. The following provides an overview of typical product assessments.

Brackin and Gibson\(^4^1\) demonstrate the use of multiple methods for assessing student performance in typical capstone courses. These include: company evaluations, status reports, student self-assessments, peer reviews, oral reports, and design reports. Performance criteria are given for the assessments as well as discussions of how the results can be used to improve student performance. Purposes include both formative and summative uses.

Sobek and Jain\(^1^5\) present two instruments for assessing and measuring the quality of design outcomes of capstone projects: the Client Satisfaction Questionnaire and the Design Quality Rubric. For the Client Satisfaction Questionnaire, clients or sponsors assess the quality of the final design project based on six metrics: quality, cost-benefit, involvement (between client and student team), complexity, deliverables (final report, final presentation, drawings, prototype), and an ‘overall’ metric (feasibility, satisfaction, thoroughness). To weight the metrics, they used the analytic hierarchy process, which is a systematic method for evaluating alternatives along multiple criteria. The Design Quality Rubric was developed to more objectively measure design quality. Metrics include: requirements (functionality), feasibility (manufacturability, marketability, application), creativity (originality, novelty, innovation), simplicity (reliability, serviceability, practicality, ergonomics, safety), and overall (aesthetics, professionalism). These instruments are given as a final assessment and evaluation of the students’ project. Therefore, emphasis is on summative use.

Estell and Hurtig\(^4^0\) discuss the use of rubrics for assessing capstone design projects. Included are detailed rubrics for written reports, design reviews, constraints analyses, oral presentations, poster evaluations, and project web sites. Assessment targets and corresponding performance criteria are given for each instrument. Targets of assessment for four of these instruments are as follows:
• for the technical written report, targets include: format and organization, mechanics, illustrations, references, use of appendices,
• for the technical design review, targets include: identification of the problem, information gathering, definition of the problem, development plan, execution plan, design verification, scheduling, and technical level,
• for constraints analysis, targets includes the consideration of the following constraints: economic, environmental, sustainability, manufacturability, ethical, health and safety, social, and political,
• for the oral presentation, targets include: content, visuals, presentation skills, organization, and handling of questions.

Cooney and Reid\textsuperscript{13} present similar rubrics for assessing student outcomes. Rubrics are given for written reports, oral presentations, design project (design review), and teamwork. For oral presentations, two sources which give detailed discussions of developing sound assessments are that of Rice \textit{et al.}\textsuperscript{16} and Sharp\textsuperscript{43}. Assessment elements and performance criteria are discussed as well as evaluation and feedback methods.

The types of products assessed along with the performance targets and criteria stated above are typical of most engineering design projects, as seen in the literature. Most common are the end-of-term products, such as written reports and design presentations. Design reviews provide a means for checking the progress of the team at various milestones throughout the project, where the content for review and assessment could include any aspect of the design, from the initial planning phase to the final development phase. For instance, the House of Quality or similar matrix tool could be assessed to determine how well technical specifications meet the user needs\textsuperscript{15}. The brief literature review above provides an understanding of the methods used and types of targets faculty are interested in assessing. This will help to define targets, performance criteria, and methods for assessment and interpretation for the current set of instruments presented in this paper.

\textbf{CURRENT CAPSTONE COURSE ASSESSMENT FRAMEWORK AND MODEL}

TIDEE’s general framework for developing valid assessment instruments, as previously mentioned, is based on the assessment triangle presented by the National Research Council\textsuperscript{20}, adapted and detailed further for specific engineering capstone courses by Beyerlein \textit{et al.}\textsuperscript{19} The goal of this framework is the alignment of the elements of development model, observation tasks in the assessment instrument, and interpretation of assessment responses. Diagrams of this framework and the development model are given in Appendix A and B, respectively.

The model represents the first leg of the assessment triangle and has been broadly defined based on typical capstone course outcomes\textsuperscript{44}. Outcomes are divided into two distinguishable areas of student learning objectives: Learner Development and Solution Development. Learner Development includes outcomes relating to the professional attributes important to students in a design project, such as ethics, reflection, personal growth, professional development, and teaming skill. These are broadly classified into two student performance areas: Personal Capacity and Teamwork. Solution Development includes outcomes associated with the technical aspects of a project, including the processes students utilize throughout a project and their
corresponding products (the assets). Solution Development is therefore classified into two student performance areas: Design Process and Solution Assets.

Figure 1 gives an outline of TIDEE’s model, showing the breakdown of learning outcomes into the four performance areas for assessment. These are briefly defined in Table 2 and discussed further below. Table 3, identifying the ABET outcomes relating to each performance area, illustrates that all ABET Engineering Criterion 3 outcomes can be encompassed in the four performance areas for capstone engineering design courses. Together, the framework and model discussed provide a solid foundation for building assessment instruments for ABET outcomes demonstrated in a capstone design course.

**Figure 1. Outline of engineering capstone design course assessment performance areas**

<table>
<thead>
<tr>
<th>Personal Capacity</th>
<th>Individuals performing and improving individual skills essential to engineering design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teamwork</td>
<td>Teams developing and implementing collective processes that support team productivity in design</td>
</tr>
<tr>
<td>Design Process</td>
<td>Teams selecting and implementing design processes that effectively and efficiently facilitate the production of valuable project assets</td>
</tr>
<tr>
<td>Solution Assets</td>
<td>Results throughout a design project that meet needs and deliver satisfaction and value to key project stakeholders</td>
</tr>
</tbody>
</table>

**Design Process performance area**

The term process refers to a set of actions employed to accomplish a particular goal. More specifically, the engineering design process is the transformation of customer needs into valuable products (assets) through a planned sequence of activities, or sub-processes. A myriad of standard processes and formal tools for use in carrying out particular processes are taught throughout the engineering curriculum.

A critical aspect of the capstone course is its ability to solidify students’ technical and procedural knowledge of these processes with hands-on opportunities. Unlike most technical content of
engineering education, which has solid mathematical roots, design methodology encompasses creativity, ingenuity, and subjectivity, and therefore skill is most readily gained through experience. The authentic nature of a capstone project, with real constraints such as time and resources, forces students to analyze potential methods and select those which will best serve their purposes under the given conditions.

**Solution Assets performance area**

Typical results from a design project include a physical product, a final design communicated in some form (drawings, models, software, oral or written reports, etc.), or other required deliverables. Solution Assets refer to results from intermediate processes and phases, in addition to those of the overall project. The Solution Assets performance area focuses on assessing the quality of these resulting assets. This provides an opportunity to give feedback to students at various times prior to the project’s completion.

Table 3. Alignment of TIDEE’s assessment model with ABET criteria (from Davis *et al.*45)

<table>
<thead>
<tr>
<th>Performance Areas</th>
<th>ABET Criteria 3 Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personal Capacity</td>
<td>X</td>
</tr>
<tr>
<td>Teamwork</td>
<td>X</td>
</tr>
<tr>
<td>Design Process</td>
<td>X</td>
</tr>
<tr>
<td>Solution Assets</td>
<td>X</td>
</tr>
</tbody>
</table>

6. **CAPSTONE COURSE ASSESSMENT STRUCTURE FOR SOLUTION DEVELOPMENT**

The four performance areas provide an overarching structure from which to base assessment development. For Learner Development, previous work has encompassed the development, testing, and validation of four assessment instruments: two for Personal Capacity and two for Teamwork46. This section will present the structure of assessments for the Solution Development performance areas. A general methodology for designing these assessments will be given in the next section.

The approach taken for defining assessments for the two Solution Development performance areas includes:
- first, identifying design activities and products most commonly associated with a wide variety of capstone design projects,
second, organizing these processes and resulting products into an appropriate assessment structure and defining assessments for the Design Process and Solution Assets performance areas,

third, defining an implementation sequence for each assessment.

**Design Process**

Table 1 listed and described important activities and products of the design process, as reported in various student design textbooks. Table 4 presents a synthesis of these processes and products most common to capstone design projects. This synthesis of the seven phases from Table 1 produces three generalized design phases – Problem Scoping, Concept Generation, and Solution Realization.

The processes and products listed in Table 4 are applicable for many engineering fields, but do not necessarily constitute a comprehensive or exclusive list. As mentioned, the table is a synthesis of several texts common to engineering design courses. The discipline specific expertise of each author will undoubtedly contribute some bias. Accordingly, while generating Table 4, effort was made to maintain generality across disciplines while still providing sufficient detail.

**Assessment Structure**

The three design phases from Table 4 are central to the development of assessments for capstone design. They give an appropriate level of depth and breadth for the purpose of providing a general and transferable assessment system for engineering capstone courses based on the commonality among various disciplines. That is, most engineering projects, regardless of field, entail a period of scoping, where information gathering and refinement processes are the focus, followed by a phase of transforming this information into a useful solution concept, and then an implementation phase where the information is used to construct a product to satisfy a need.

The common nature of these phases among disciplines provides justification for framing assessment opportunities around these three project phases. Therefore, Design Process assessments will look at common processes associated with each phase, assessing the appropriateness and effectiveness of the processes selected and implemented by students. For Solution Assets, assessments will look at the quality of the resulting products for each design phase. Table 5 describes the assessments for the Design Process and Solution Assets performance areas.

The Design Process area comprises three assessments: Problem Scoping Processes, Concept Generation Processes, and Solution Realization Processes. The focus of each is stated in Table 5, which closely follows the major design process categories given in Table 4.

Three companion Solution Assets assessments include Problem Definition, Selected Concept, and Proposed Solution. This set of assessments provides generality and transferability for multiple users. The focus for assessment includes the quality of the asset as well as the quality of the communication itself. The communication is the form of the presentation, which can be
written, oral, physical, or other. For a final design solution of a project, for example, the asset is the design, which is assessed based on appropriate engineering design criteria, while the communication could be a written report, which is assessed based on a different set of criteria.

Table 4. Common design phases, processes, and products for capstone projects

<table>
<thead>
<tr>
<th>Design Phases</th>
<th>Design Processes/Activities</th>
<th>Design Products</th>
</tr>
</thead>
</table>
| **Problem Scoping** | **Analyse product opportunity:**  
  - Analyse, evaluate, and select product opportunity(ies)  
  - Formulate product proposal  
  - Plan design project (identify and plan tasks and resources: schedule, budget, team)  
  **Clearly define the problem:**  
  - Identify customers  
  - Identify and evaluate requirements and constraints  
  - Identify essential functions  
  - Evaluate competition/similar products  
  - Establish specifications (metrics/parameters)  
  - Set target specifications  
|                     | **Selected product opportunity:**  
  - Mission statement  
  - Design proposal and/or business plan  
  - Project plan (task list, schedule, budget, responsibilities)  
|                     | **Problem definition:**  
  - Preliminary design specifications or similar |
| **Concept Generation** | **Generate alternative concepts:**  
  - Perform functional decomposition  
  - Define major subsystems and interfaces  
  - Search for working principles and working structures  
  - Generate concepts  
  **Select concept:**  
  - Evaluate concepts  
  - Select concept  
  - Set final specifications  
|                     | **Concept variants:**  
  - Functional analysis communication  
  - Morphological chart  
  - Concept variants  
|                     | **Concept selection:**  
  - Justification of selected concept  
  - Concept communication (sketch, model, artifact, report, etc.)  
  - Final solution specifications |
| **Solution Realization** | **Design product:**  
  - Generate product embodiment (architecture/layout)  
  - Model/simulate/analyze design  
  - Design for X (performance, robustness, reliability, etc.)  
  - Test, evaluate, refine, optimize, validate design  
  **Communicate design:**  
  - Develop detail drawings and support documentation  
  - Document and communicate design  
  - Implement production  
|                     | **Final design:**  
  - Layout drawings, models, etc.  
  - Detailed design  
  - Test and validation results  
|                     | **Final design communications:**  
  - Final design communications (reports, presentations, drawings, support documentation, etc.)  
  - Final product |
### Table 5. Design Process and Solution Assets assessment instruments

<table>
<thead>
<tr>
<th>Design Phases</th>
<th>Design Process Assessments</th>
<th>Solution Assets Assessments</th>
</tr>
</thead>
</table>
| **Problem Scoping**| *Problem Scoping Processes* assessment addresses the selection and use of processes/activities related to:  
  - analyzing product opportunity(ies)  
  - defining the design problem                      | *Problem Definition* assessment addresses:  
  - communication of the problem definition  
  - quality of the problem definition (quality of the given evidence that the problem definition properly addresses the voice of the customer, business, technology, and society) |
| **Concept Generation**| *Concept Generation Processes* assessment addresses the selection and use of processes/activities related to:  
  - generating alternative concepts  
  - selecting a concept | *Selected Concept* assessment addresses:  
  - communication of the selected concept  
  - quality of the concept (quality of the given evidence that the concept offers potential for targeted performance, profitability, feasibility, and impact) |
| **Solution Realization** | *Solution Realization Processes* assessment addresses the selection and use of processes/activities related to:  
  - designing the product solution  
  - validating the product solution | *Proposed Solution* assessment addresses:  
  - communication of the design solution  
  - quality of the solution (quality of the given evidence that the solution delivers value through performance, profitability, feasibility, and impact) |

### Assessment Implementation

The implementation sequence and timing for Solution Development assessments is given in Figure 3. The three general phases are shown, illustrating typical progression in capstone courses. Design Process assessments are administered midway throughout each phase while the resulting Solution Assets assessments are administered toward the end of each phase. The mid-phase administration of the process assessments allows for critical feedback to be given to students with sufficient time to make corrections or improvements (formative use). End-of-phase product assessments provide an opportunity to evaluate the quality of solution assets resulting from each phase, versus a single end-of-project assessment and evaluation (summative use).

The underlying organization of this structure is the use of formative assessments for phase processes and summative assessments to evaluate phase products. This formative/summative sequence requires students to engage in self reflection at critical project milestones, and allows adequate time for them to readdress any problematic aspects. The motivation for this assessment philosophy is to instill in students the value of reflective practice and iteration in design.
The following sections will present the methodology and principles for assessment design as they pertain to both design processes and products. One of the Solution Development assessments – the Problem Scoping Processes assessment – is referenced throughout this section to illustrate each principle.

**Purposes for Assessing**

Assessment is simply the process of gathering the data indicative of the desired qualities or performances\(^{47}\). Use of this data depends upon the assessment’s purpose. The evaluation and interpretation of valid assessment data form the basis for which subsequent decisions are made and corresponding actions taken\(^{47}\). Therefore, accurate assessment is a prerequisite for well-informed decisions.

Clearly defining the purpose for assessment represents one of the most important aspects of the assessment design process. There are multiple purposes for assessment, all of which can be categorized into either *assessment of learning* or *assessment for learning*. Examples of these, relevant to capstones, are indicated in the following list (adapted from Stiggins\(^{48}\)):

- purposes for students: to track own success, to identify own needs, to plan educational needs (study plan),
- purposes for faculty: to identify needs of individual, to identify needs of groups or class, for grading, to evaluate instruction, to evaluate self, and
- purposes for policy makers: to document, evaluate, and base program-level improvement decisions on.
These purposes can similarly be stated as: 1) to assist learning (formative), 2) to assess individual achievement (summative), and 3) to evaluate programs. The purpose for an assessment has implications for its construction, use, and interpretation.

<table>
<thead>
<tr>
<th>Purpose of the Problem Scoping Processes assessment:</th>
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<tbody>
<tr>
<td>The purpose of this assessment is primarily for formative use; to assist students by helping them to identify areas for improvement. Assessment data will allow faculty to address issues at the individual, team, and class level. The data can also be used for assigning scores and documenting achievement for ABET requirements. Mid-phase implementation allows adequate time for feedback and improvements to be made prior to moving on to the next phase.</td>
</tr>
</tbody>
</table>

**Targets for Assessment**

Targets represent the specific achievement students strive towards in a learning experience. That is, targets are defined by first specifying what is to be assessed, followed by defining the quality level expected. Examples could include: mastery of content knowledge, achieving a certain level of proficiency in giving oral presentations, or acquiring a certain level of understanding on a topic. Therefore, targets are defined in terms of specifically stated performance criteria.

Stiggins defines five kinds of achievement targets – knowledge, reasoning, skill, product, and disposition – and suggests the following guidance for determining these for assessment design:

- Define the important knowledge students should understand: declarative and procedural.
- Reflect on the patterns of reasoning you might expect they will need to acquire. For example, analytic, synthesis, comparative, classification, inferential, evaluation.
- Identify any skill or product development targets: skills they are to master, things they should be able to do, products you want them to create.
- Identify the disposition (attitudes, values, interests) you hope for them to acquire.

In developing performance criteria for targets, Stiggins gives a six step method:

1. Develop a list of factors associated with the performance addressed (the five kinds of achievement targets would be a starting point from which to expand),
2. Condense the list into major categories,
3. Define each major category (considering elements from original list),
4. Contrast levels of proficiency for each major category by qualitatively describing a range of performances (establishing a continuum of performance in levels),
5. Add detail by assigning scoring values to each performance level,
6. Test and refine the set of performance criteria.

<table>
<thead>
<tr>
<th>Targets for the Problem Scoping Processes assessment:</th>
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</thead>
<tbody>
<tr>
<td>The broad, generalized, targets for assessment of Problem Scoping Processes are:</td>
</tr>
<tr>
<td>• Appropriate selection of design processes based on given project needs, resources, constraints, etc.</td>
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<tr>
<td>• Effective and efficient implementation of design processes</td>
</tr>
<tr>
<td>• Constructive self-assessment regarding the selection and use of design processes throughout project</td>
</tr>
</tbody>
</table>

**Methods for Assessing**

Assessment tasks for students can be designed when the targets for assessment and performance criteria have been clearly defined. Methods commonly used include: selected response
questions, essays, authentic performance, as well as personal observation and communication. For effective assessment, the method selected must be appropriate for the types of inferences desired. For example, to assess analytical reasoning, an essay type of assessment would be preferred over selected response. The selection of a method is also influenced by other factors such as the level of detail desired, implementation constraints, and time considerations for reviewing and evaluation. A variety of methods are used for the multiple assessments included in TIDEE’s assessment system, including selected response, reflective essays, and authentic performance. Selected response requires less time for reviewing but is limited in the level of depth assessable, while essays give richer insights to the level of understanding students have, but require significantly more time investment. Methods for the current assessments are selected to minimize these limitations.

Methods for the Problem Scoping Processes assessment:
The assessment will consist of both selected response questions and short essays. Selected response will probe students’ declarative knowledge about appropriate design phase processes. Reflective essays will be used to query students’ procedural knowledge, reasoning, and skill regarding the processes applied; for example, procedural knowledge of particular processes involved in gathering customer needs, reasoning regarding the analysis, synthesis, and evaluation of customer needs, and skill in manipulating needs data into usable engineering specifications.

Interpreting Assessments

Interpreting and reporting assessment results are keys to student improvement. Defined targets and performance criteria provide guidance for designing a scoring methodology for an assessment. Inferences can then be made based on these scores as to the quality of the student’s work. Scores can be reported to students and should be coupled with constructive feedback critiquing their performance. Therefore, for formative assessment purposes, assessments should be designed such that feedback can be provided easily for: (1) allowing the student to know how they are performing relative to expectations, (2) what are areas of strength to build upon, and (3) what can be done to improve. In the broad sense, this philosophy follows that of the common SII method (Strength, Improvement, and Insight) for assessing and providing useful feedback. For summative assessment use, descriptive feedback can also be given to provide guidance for productive iteration of necessary activities.

Interpretation of the Problem Scoping Processes assessment:
A scoring rubric, based on detailed performance criteria, will be developed and used to evaluate student responses to the assessment. The rubric will be analytic – a three to five point descriptive scale – providing greater detail for constructive feedback. Additionally, comments will be offered stating deficiencies and suggesting possible improvements.

CONCLUSIONS

1. A structure was presented showing a plan for assessment of both design processes and products in engineering capstone courses.

2. Building on TIDEE’s previous work on Learner Development assessments, a methodology was developed and presented for use in designing assessments for design processes and products in capstones.
3. The generic nature of the design processes selected for this study makes the methodology transferable across faculty, institutions, and disciplines.

4. Elements of one assessment were used in illustrating the key principles of the methodology – purposes, targets, performance criteria, methods, interpretation, and alignment – providing for easy adaptation to other instruments.

5. The Problem Scoping assessment instrument was included in this paper.

FUTURE WORK AND RECOMMENDATIONS

Future work envisioned includes:
1. use this structure and methodology to design the remaining instruments for design processes and products,
2. test and refine instruments, individually, for construct validity and inter- and intra-rater reliability,
3. test instruments, collectively, for validity and reliability,
4. test in various contexts for transferability: different disciplines, capstones, project types, etc.,
5. incorporate assessments into a web-based implementation system,
6. with the validated capstone assessment package, this could open the path for additional research in effectiveness of instructional practices in achieving targeted student performance in capstone design courses.

ACKNOWLEDGEMENTS

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Bibliography

18. TIDEE - Transferable Integrated Design Engineering Education. from www.tidee.cea.wsu.edu
APPENDIX

A. Capstone course assessment framework diagram (from Beyerlein et al. 19)

B. Capstone course assessment model diagram (adapted from TIDEE 18)