AC 2009-663: ASSESSING DESIGN AND REFLECTIVE PRACTICE IN CAPSTONE ENGINEERING DESIGN COURSES

Denny Davis, Washington State University
Professor, Bioengineering, and Co-Director, Engineering Education Research Center, Washington State University

Steven Beyerlein, University of Idaho
Professor, Mechanical Engineering, University of Idaho

Phillip Thompson, Seattle University
Associate Professor and Chair, Civil and Environmental Engineering, Seattle University

Jay McCormack, University of Idaho
Assistant Professor, Mechanical Engineering, University of Idaho

Olakunle Harrison, Tuskegee University
Associate Professor, Mechanical Engineering, Tuskegee University

Michael Trevisan, Washington State University
Professor, Educational Leadership and Counseling Psychology, and Director, Assessment and Evaluation Center, Washington State University

Robert Gerlick, Washington State University
Graduate Research Assistant, Engineering Education, Washington State University

Susannah Howe, Smith College
Director, Design Clinic, Smith College

Assessing Design and Reflective Practice in Capstone Engineering Design Courses

Abstract

Engineering practitioners in the twenty-first century face complex challenges with social, political, environmental, ethical, and resource-limiting constraints. They work with diverse constituencies to solve rapidly-changing, complex problems. To be productive and responsive in this environment, engineering professionals must create innovative yet practical and responsible solutions that benefit society. As Schön (1983) argues, engineers will need to practice reflection-in-action (learning and adjusting as they perform) as well as reflection-on-action (intermittent analysis of conditions that leads to major advances). As agents of change, they continuously ask questions, make judgments, learn, and choose appropriate actions. Engineers must be competent, reflective practitioners if they are to contribute effectively in a dynamic global environment.

This paper describes a set of fifteen assessments for four areas of performance in capstone engineering design courses: professional development, teamwork, design processes, and solution assets. First, it presents the research foundation and structure for making the assessments useful for both guiding student achievement and measuring achievement in the context of team-based design projects. Next, the activities for each assessment are summarized along with factors for scoring performances. Finally, the paper describes how the assessments prompt students' reflection on design activities and how student reflections might be used to assess reflective practice occurring in design activities.

Assessment instruments are being tested for validity and reliability in a number of capstone design course environments. Additional research is needed to develop and test the measurement of reflective practice.

Introduction

Successful engineers of the twenty-first century will be markedly different from engineers of the past. Having sound understanding of engineering sciences, successful engineers will also need to be problem solvers and innovators who work effectively in times of rapid change. They will need to be global-minded, socially-responsible, systems-thinkers who adeptly address complex problems having significant human dimensions. [1-4] Engineers will need to perform a variety of roles in the context of their work: analyst, problem solver, designer, researcher, communicator, collaborator, leader, self-grower, achiever, and practitioner. [5] Important work in a "flat world" will require multidisciplinary teamwork, rapid prototyping, creativity, business savvy, entrepreneurship, and human-centered design. [6]

The social dimension of engineering will require excellent communication and social skills. Therefore, engineers will need to demonstrate strengths in listening, debate, and negotiation with people of different backgrounds and perspectives. [7] They will be challenged by working with others having different lifestyles, social values, and motivations. [8, 9]

The complexity and large-scale impact of problems will require engineers to work across traditional disciplinary boundaries and cultures. [2, 10, 11] At the same time, rapid societal changes and knowledge expansion will also force them to learn quickly from a variety of sources. Engineers of the twenty-first century must have adaptive expertise, the ability to transfer knowledge to new contexts and continue to develop new knowledge as needed. [12]

Schön and others contend that engineers need to demonstrate reflective practice, the way of competent practitioners who elevate both learning and performance as part of their practice. [13-15] These professionals are known for their reflection-in-action: They observe “real-time” the impacts of their professional knowledge-in-action, detect surprises in conditions or results, select a path to improve the situation, and learn from their experimentation how to improve in the future. They also practice reflection-on-action: They intermittently reflect on earlier actions to learn from their experiences and identify better ways to handle similar situations in the future. Reflection has been shown to enhance critical thinking [16], teamwork [17], professional skills [18], and professional practices [14]. Design teams need both reflection-in-action and reflection-on-action to effectively overcome barriers to success. [19]

Adams and colleagues explain how design activity is a context in which reflective practice occurs, and that reflective practice enhances the quality of design processes. [15] The designer, who is a creator and an experimenter, has a reflective conversation with a situation, seeking to grow understanding of the problem-and-solution match. The reflective process is triggered by a surprise that causes reflection and analysis, which leads to a revision of thinking and produces new ways of approaching the solution. Transformative change in design is often seen when an iteration (from reflection) causes one to cross boundaries between design steps (e.g., returning to revise an aspect of the problem definition). This is consistent with the way that Schön describes reflective practice contributing to a variety of professions. [13]

Assessments provide opportunities for learners to practice reflection and to develop skills important to a reflective practitioner. In reflective assessment, we seek to discover what we know, what we have learned, and what we might understand. [20] Portfolio assessments are effective for stimulating reflective thought and for revealing analysis occurring as part of reflection. [21] Peer assessment within teams can probe students’ reflections on member contributions and processes. [17, 22] Professional growth assessment can cause students to reflect on their own learning and professional development. [22] Assessment of design processes and design products can also provide opportunities to reflect on the processes, products, and relationships between the two. [23]

The Transferable Integrated Design Engineering Education (TIDEE) assessments cause students to reflectively assess performance for several different outcomes associated with capstone engineering design courses. This paper describes the research foundation for these assessments and the organizational structure that makes this set of assessments effective for assessing both engineering design outcomes and reflective practice.

Goal and Objectives

The goal of this paper is to present emerging tools and methods by which engineering faculty can assess design and reflective practice in capstone engineering design courses. To achieve this goal, this paper addresses the following objectives:

1. Establish design learning and solution development outcomes and performance criteria for capstone engineering design courses
2. Define an assessment structure that measures achievement of targeted outcomes in the context of capstone engineering design projects
3. Present assessment instruments and bases for scoring used in team-based design projects
4. Propose an approach for measuring reflective practice in team-based design projects

Outcomes and Performance Criteria

The Transferable Integrated Design Engineering Education (TIDEE) consortium recently reported four areas of performance for learning and solution development in capstone engineering design courses. [22-24] In this paper, the four areas have been revised to align closely with learner development and solution development needed in a rapidly changing global environment. The revised areas of performance for capstone design are:

Professional Development: Individual demonstration of improved knowledge, skills, and behaviors essential to engineering practice

Teamwork: Team member contributions and team processes employed to support team productivity in design

Design Processes: Practices implemented that effectively and efficiently facilitate the production of valuable design project assets

Solution Assets: Design results that meet needs and deliver satisfaction and value to key project stakeholders

Expectations for each area of performance are defined below by reviewing engineering education literature of the past ten years related to learner development and solution development. The following publication sources were used as starting points: *Journal of Engineering Education*, *Proceedings of the American Society for Engineering Education Annual Conference*, *International Journal of Engineering Education*, *Design Studies*, and numerous engineering design textbooks. Articles reviewed were those with key words or titles addressing professional attributes, teamwork, design, design communication, and educating engineers for the future. Additional articles were identified by branching from articles reviewed.

For each area of performance, articles were reviewed to identify factors that articulated important aspects of that area. Notes and quotations were recorded for each occurrence of a relevant factor. These factors were then grouped into categories and refined to represent a performance area by approximately ten performance factors in three or four categories. These provided the basis for performance criteria to be targeted for the respective performance area.

Professional Development. Performance factors for the Professional Development performance area were defined to span all of the ABET Criterion 3 outcomes [25], the roles defined in TIDEE's profile of an engineer [26], and the characteristics of the Engineer of 2020 [2]. Table A-1 shows the performance factors alongside ABET outcomes, TIDEE roles, and sources used to establish the content of the performance factor. This table structure reveals that ABET criteria do not explicitly address leading others, being a high achiever, or relating inclusively. Relating inclusively and adapting to change also were not explicitly addressed in the TIDEE roles. Numerous references for each performance factor testify to the importance of all twelve factors.

The twelve Professional Development performance factors are summarized in Table 1 with definitions derived from the respective references of Table A-1. Note that four performance factors are labeled technical, four are interpersonal, and four are individual. This balance makes a statement about the breadth of professional skills and abilities important to the engineering profession. Thus, capstone engineering design courses face broad challenges for teaching professional development needed in graduates of the twenty-first century.

The performance criterion for Professional Development is synthesized from the performance factors identified for this area:

> *Individuals document professional development in technical, interpersonal, and individual attributes important to their personal and project needs, professional behaviors, and ways of a reflective practitioner.*

Table 1. Performance Factors for Professional Development Performance Area

	Performance Factor	Definition
Technical	**Analyzing information**	Applying methods/tools of analysis to understand and predict conditions
	Solving problems	Formulating, selecting, and implementing actions for optimal outcomes
	Designing products	Producing creative, practical products that bring value to varied stakeholders
	Researching questions	Investigating, processing and interpreting information to answer important questions
Interpersonal	**Communicating**	Receiving, processing, sharing information in many forms to achieve desired impact
	Collaborating	Working with a team to achieve collective and individual goals
	Relating inclusively	Valuing and sustaining a supportive environment for all knowledge and perspectives
	Leading others	Developing shared vision & plans; empowering to achieve individual & collective goals
Individual	**Practicing self-growth**	Planning, self-assessing, and achieving goals for personal development
	Being a high achiever	Delivering consistently high quality work and results on time
	Adapting to change	Being aware and responding proactively to social, global, and technological change
	Serving professionally	Serving with integrity, responsibility and sensitivity to individual and societal norms

Teamwork. Performance factors for the Teamwork performance area are determined from references that address the definition of teamwork skills, teaching teamwork to students, or assessing team effectiveness. Table A-2 summarizes teamwork attributes and behaviors identified from the references cited. The attributes/behaviors are grouped according to four categories— team relationships, joint work/achievements, member/individual contributions, and team information— and summarized in Table 2. These twelve performance factors include issues of concern to students (e.g., workload, work quality, communication, and team climate), those of concern to instructors (e.g., conflict resolution and project management), and those of concern to industry (e.g., work quality, stakeholder communication, and knowledge assets). These twelve paint a broad definition of issues teams need to address to be successful.

The performance criterion for Teamwork is established from the performance factors identified for this area. Desired performance is:

> *Team member behaviors and team processes contribute to constructive relationships, joint achievements, individual contributions, and information management that synergistically yield high productivity.*

Table 2. Performance Factors for Teamwork Performance Area

Category	Performance Factor
Team Relationships	**Inclusive Climate**: Building an inclusive supportive climate for all members
	Member Commitment: Gaining buy-in and interdependence of all members
	Conflict Resolution: Resolving conflicts to enhance teamwork
Joint Achievements	**Goal Establishment**: Establishing shared team goals
	Planning and Management: Managing tasks to achieve team goals
	Joint Work Products: Producing competent consensus outputs
Member Contributions	**Work Allocation**: Allocating responsibilities fairly to members
	Performance Quality: Achieving quality work from all members
	Member Growth: Facilitating team member growth
Team Information	**Internal Communication**: Achieving effective in-team communication
	Stakeholder Communication: Managing other stakeholder communication
	Knowledge Assets: Building shared knowledge assets

Design Processes. A foundation for Design Processes performance factors is established by reviewing a wide range of design texts as well as research articles addressing design processes and performance in design activity. Table A-3 summarizes types of design activities identified in a diverse subset of engineering design texts, with activities categorized into three major design phases: problem scoping, concept generation, and solution realization. [27-31] Table A-4 summarizes Design Processes performance factors identified from research articles. Research has shown that the design steps used, time spent in key steps (information gathering, problem definition, and problem solution), use of effective tools for each design step, and effective social processes (especially decision making) are important to the development of good design processes. [32-45] Reflection used in design activity guides transitions or iterations (of various types and value), produces learning in designers (important to a "flat world"), and advances the design from its previous state. [21, 32, 44, 46-54] Effective design processes use prior knowledge as well as many new information sources with broad perspectives to inform understanding of the problem and its impacts. [33, 45, 46, 55-59] Performance factors for Design Processes are summarized in Table 3.

Table 3. Performance Factors for the Design Processes Area

Performance Factor	Definition
Process Mechanics	Overall management of design steps, selection of design steps (information gathering, problem definition, idea generation, etc.), selection and use of tools/techniques for the step, time spent in each step, social processes employed in design activities
Reflection in Design	Recognition of surprises, decisions to transition (iterate) to readdress previous actions (possible in earlier design phases), gaining new knowledge or insight through reflection, developing ability to improve actions in the future, using insights to advance the design solution
Informing Design	Gathering information from old and new sources for broad and deep understanding, specifying the problem to address all key stakeholders, using information effectively in design activities, articulating the problem and solution impacts to others

The following performance criterion for Design Processes is synthesized from performance factors and major phases of the engineering design process:

> *Designers reflectively use design tools and information throughout problem scoping, concept generation, and solution realization activities to co-develop problem understanding and a responsive design solution.*

Solution Assets. A foundation for Solution Assets performance factors is established by review of design texts and research articles related to assessment of design solutions. These sources cite a wide range of factors that should be addressed in design solutions or design requirements to yield good design solutions. Table A-5 summarizes the performance factors identified along with references associated with factors in each grouping. A solution must meet the needs of the user with regard to its intended functionality, appearance, operability, and dependability. [25, 29, 31, 32, 46, 60-67] The desired solution must also provide value to investors, as seen in an attractive return for the investment, desirable image relative to other available solutions, and potential for broad use. [25, 29, 31, 32, 46, 60-68] The solution must be feasible to produce, test, maintain, and distribute. [25, 29, 31, 46, 56, 60-64, 66, 67] It must also reflect human-centered design that addresses issues of human and environmental well-being in its production, implementation, and retirement. [25, 29, 31, 32, 46, 56, 59-70] These performance factors for Solution Assets are summarized in Table 4 below.

Table 4. Performance Factors for Solution Assets Area

Performance Factor	Definition
Functionality	Delivers desirable features, ease of use, reliability, and simplicity to meet functional needs of potential users
Profitability	Offers attractive value relative to cost, desirable advantages over alternatives, and sizable customer base to justify investment
Feasibility	Requires means for production, testing, distribution, maintenance, and repair that are practical and reasonably efficient
Social Impact	Meets ethical and professional norms for human well-being and environmental sustainability on local and global scales

The following performance criterion for Solution Assets is synthesized from performance factors relevant to assets generated at various stages in the design process:

> *Designers deliver and effectively defend solutions that satisfy stakeholder needs for functionality, financial benefit, implementation feasibility, and impacts on society.*

Assessment Structure

The TIDEE assessments measure achievement in each of the four performance areas: Professional Development, Teamwork, Design Processes, and Solution Assets. This section describes the organizational structure used for assessments in each performance area and the rationale for this structure.

Professional Development. Four Professional Development assessments (described in Table 5) are defined to both facilitate and measure students' abilities to "*document professional development in technical, interpersonal, and individual attributes important to their personal and project needs, professional behaviors, and ways of a reflective practitioner.*" The first three assessments are primarily formative in nature (used as learning tools). The Growth Planning assessment guides students to set professional development goals to be achieved during a design project. The Growth Progress and Professional Practices assessments prompt reflection on current conditions at intermediate stages of the design activity. The Growth Achieved assessment is summative. It documents individual students' abilities to explain their professional growth achievements.

Table 5. Professional Development Assessments and Scoring

Name	Purpose	Activities	Scoring Factors
Growth Planning	Prompt and give feedback on (individual) abilities to plan important professional development	Rate importance and own current level in professional attributes. Describe: (a) impacts of shortcomings, (b) growth plans, and (c) criteria for success.	o Understanding of impacts o Quality of plan o Quality of achievement criteria
Growth Progress	Prompt and give feedback on (individual) progress and revised plans for professional development	Describe: (a) steps taken, (b) evidence of impacts achieved, (c) next steps for achieving professional development.	o Progress to-date o Quality of evidence o Quality of new steps planned
Professional Practices	Prompt and give feedback on (individual) performance of and revised plans for relevant professional practices	Rate importance and own performance in areas of ethical and professional responsibility. Describe: (a) understanding and impact, (b) opportunity for improvement, and (c) plan to improve performance.	o Evidence of understanding of a strong performance o Understanding of an opportunity and plan to improve performance
Growth Achieved	Measure achieved level of (individual) performance with regard to important ethical and professional attributes	Rate current importance and own level in professional attributes. Identify areas of greatest growth. Describe (a) gains, (b) impacts and (c) broader applicability of achieved professional development.	o Scope of professional development gains o Quality of impacts o Understanding of broader application

Teamwork. Four Teamwork assessments (Table 6) both facilitate and measure how "*team member behaviors and team processes contribute to constructive relationships, joint achievements, individual contributions, and information management that synergistically yield high productivity.*" The first three assessments are primarily formative in nature. The Team Contract assessment guides students to collectively develop an agreement among members regarding team relationships, achievements from working together, individual member responsibilities, team communication, and leadership responsibilities. The Team Member Citizenship assessment provides students opportunities to offer and receive peer feedback on their contributions, as well as receiving instructor feedback. The Team Processes assessment prompts students to reflect on the processes in-place for team functioning, and to suggest ways to improve their effectiveness. Both Team Member Citizenship and Team Processes assessments lay the groundwork for productive team discussions that build teamwork. The Teamwork Achieved assessment documents individual students' abilities to explain achievements in both team member contributions and team processes, collectively representing teamwork achievements.

Table 6. Teamwork Assessments and Scoring

Name	Purpose	Activities	Scoring Factors
Team Contract	Prompt and give feedback on (team) abilities to specify and plan important team behaviors and processes	Define a consensus contract: team relationships, collective achievements, individual responsibilities, team communication, and leadership.	o Contract clarity, comprehensiveness, specificity o Potential for team effectiveness and development
Team Member Citizenship	Prompt and give feedback (individually) on members' rating contributions and coaching performance	For each member (incl. self): (a) rate contributions & effectiveness, (b) identify a strength and its benefit to team, (c) identify desired improvement and steps to achieve it.	o Understanding of strength; evidence of effective use o Understanding of opportunity; quality of suggestions
Team Processes	Prompt and give (individual) feedback on team processes in place and proposed development	Rate importance & effectiveness of processes for managing: relationships, achievements, responsibilities, and information. Describe an effective process, with evidence. Describe an opportunity and plan to improve.	o Understanding of effectiveness; evidence of success o Understanding of opportunity; quality of plan
Teamwork Achieved	Measure achieved (individual) level of performance for team member contributions and team processes	Rate: (a) team performance, (b) importance & level of member contributions, and (c) relative contributions of each member. Describe greatest teamwork strengths, impacts, and broader applicability.	o Relative contributions of members o Teamwork achievements o Significance of impacts o Insight in applicability

Design Processes. Four Design Processes assessments (Table 7) both facilitate improvements and measure how the team's "*designers reflectively use design tools and information throughout problem scoping, concept generation, and solution realization activities to co-develop problem understanding and a responsive design solution.*" The first three assessments are associated with corresponding phases of the overall solution development process. They are formative in nature. The Problem Scoping Processes assessment guides students to collectively reflect upon their processes for that phase of design activity and to plan improvements to the process. The Concept Generation Processes assessment provides a similar opportunity to review and improve concept generation processes. The Solution Realization Processes assessment prompts reflection and improvement a third time. This repetition of reflective review should lead to higher quality reflection and improvements to students' design activity. The Design Reflection assessment is used to help students relate design processes with the resulting design products and to elevate their understanding of co-evolving the problem definition with the design solution. [71, 72]

Table 7. Design Processes Assessments and Scoring

Name	Purpose	Activities	Scoring Factors
Problem Scoping Processes	Prompt and give feedback on (team) abilities to reflect on and improve problem scoping processes	In middle of the problem scoping phase: (a) define process steps planned or used, (b) assess process status, (c) explain process strengths, (d) propose process improvement	o Evidence of process attributes that produce a quality defined problem o Ability to improve process for enhanced results
Concept Generation Processes	Prompt and give feedback on (team) abilities to reflect on and improve concept generation processes	In middle of the concept generation phase: (a) define process steps planned or used, (b) assess process status, (c) explain process strengths, (d) propose process improvement	o Evidence of process attributes that produce a quality selected concept o Ability to improve process for enhanced results
Solution Realization Processes	Prompt and give feedback on (team) abilities to reflect on and improve solution realization processes	In middle of the solution realization phase: (a) define process steps planned or used, (b) assess process status, (c) explain process strengths, (d) propose process improvement	o Evidence of process attributes that produce a quality proposed solution o Ability to improve process for enhanced results
Design Reflection	Measure achieved (individual) level of performance on design process understanding	At end of each design phase, rate own confidence in design work to-date. Explain a strength of the process. Propose an iteration to improve the design process.	o Substance and impact of identified strengths o Planned improvement and learning from reflection

Solution Assets. Three Solution Assets assessments (Table 8) prompt reflection and measure how the team's "*designers deliver and effectively defend solutions that satisfy stakeholder needs for functionality, financial benefit, implementation feasibility, and impacts on society.*" These assessments correspond to design products delivered at the end of the corresponding phases of the overall solution development process. The assessments are summative in the sense that they represent the results of a design phase, but the first two are formative in the sense that they are preliminary to the final proposed solution. The Defined Problem assessment provides a review of the team's understanding of the problem after substantive information gathering has been completed. The Selected Concept assessment reviews the team's definition and defense of their chosen design concept and revisions to their understanding of the problem. The Proposed Solution assessment reviews the team's design solution representing their most recent (and complete) understanding of the problem being addressed and the corresponding detailed design solution. At each of these three reviews, the corresponding solution asset is examined with regard to the team's ability to defend both problem understanding and solution quality in four dimensions: functionality as seen by users, financial benefits to investors, technical feasibility of implementation, and social impact. The team's level of understanding and solution development should become more sophisticated with each successive assessment. Therefore, the Proposed Solution assessment gives a summative demonstration of the team's ability to produce and defend a design solution for a broad set of stakeholders with diverse expectations and constraints. [25]

Table 8. Solution Assets Assessments and Scoring

Name	Purpose	Activities	Scoring Factors
Defined Problem	Prompt and give feedback on (team) abilities to produce and defend a comprehensive problem definition	Prepare a formal problem definition proposal submitted to stakeholders including: (a) executive summary, (b) stakeholder needs, and (c) solution specifications	o Quality of executive summary, stakeholder needs, and solution specifications for functionality, profitability, feasibility, and social impact o Quality of communication of the defined problem
Selected Concept	Prompt and give feedback on (team) abilities to produce and defend a selected solution concept	Prepare a formal concept proposal submitted to project stakeholders including: (a) revised executive summary, (b) revised solution specifications, (c) summary of concepts considered, and (d) description of selected concept	o Quality of executive summary and solution specs o Concept potential for solution functionality, profitability, feasibility, and social impact o Quality of communication of the selected concept
Proposed Solution	Prompt and give feedback on (team) abilities to produce and defend a tested design solution	Prepare a formal design report submitted to project stakeholders including: (a) revised executive summary, (b) revised solution specifications, (c) description of design solution, and (d) evidence of solution meeting specifications	o Quality of executive summary and solution specs o Proof of solution functionality, profitability, feasibility, and social impact o Quality of communication of the proposed solution

Structure for Assessing Reflective Practice

Schön identifies design as one of the professions in which reflection is an integral part. [13, 73] He emphasizes a need for the doing of engineering to learn engineering: ". . . a student cannot at first understand what he needs to learn, can learn it only by educating himself, and can educate himself only by beginning to do what he does not yet understand." (p. 93)[73] He states that design is not teachable, but it is learnable through reflective practice in the context of a design project. Design demonstrates knowing-in-action punctuated by surprises that trigger reflection-in-action: experiments to find improved actions. Implementing proposed actions provides feedback that enhances the designer's learning and finding better solutions.

The role of reflection in design is further explained by Stumpf: (p. 2) [19]
"Reflection-in-action proceeds by a construction cycle of framing, naming, moving and reflecting. Framing and naming concern the problem-setting in that the designer constructs a problem out of a situation by naming the things to which she will pay attention whilst at the same time framing the way that the problem is viewed. Framing in this sense imposes an order onto the problem; moves are made toward a solution in relation to how the situation is framed.

However, the situation 'talks back'; surprise at the outcomes of moves leads to reflecting. Reflecting on outcomes may trigger either further moves or a new framing. Reflection-in-action is not an interruption to fluid action; it is always embedded within action. Reflection-on-action, on the other hand, draws on the experience of an action as a whole; it is a conscious 'stepping aside' to assess a situation. Yet, reflection-on-action may still make a difference to further acts of designing. Schön (1987) describes this as a 'ladder of reflection', where the designer climbs up from an activity to reflect on that activity and climbs down from reflection-on-action to an activity that enacts what is learned through reflection."

Valkenburg summarizes the four design activities of reflective practice: [74]

1. **Naming**: In setting a design problem, the designer names the problem, a means of sharing the issue with team members
2. **Framing**: Defining sense-making devices that establish parameters of a problem, for common understanding of how to approach the problem
3. **Moving**: Making a local experiment (generating ideas, exploring problems, considering consequences) that contributes to the global experiment to find a solution
4. **Reflecting**: Reflecting on the activity with respect to the goals of the design exercise; learning from the experiments

Reflective practice can, therefore, be observed through documentation of students' design actions and design thinking. Reflection-in-action is seen in the ways that students respond to problems, navigate development of solutions, and gain new understanding. Four types of reflective actions are evident, as described below and summarized in Table 9.

Table 9. Performance Factors and Scoring Factors for Reflective Practice

Factor	**Description**	**Scoring Factors**
Naming/ Owning	Identifying a problem, bounding its scope, claiming responsibility for finding a solution; identifying what will be attended	○ Specificity in problem identification; relevance of name given to problem
Framing/ Defining	Associating with familiar exemplars, defining models and assumptions, proposing hypotheses, proposing basis for a solution	○ Appropriateness of selected models; suitability of assumptions
Moving/ Experimenting	Exploring virtual solutions and implications, challenging assumptions and theories, testing knowledge	○ Extent and validity to probing of assumptions and methods
Reflecting/ Realization	Confirming or redefining knowledge, finalizing or reframing solution, contributing to profession	○ Soundness in decisions made; insightfulness of discoveries and solutions

Naming/Owning. When designers encounter a problem, they take ownership of the problem by naming it. For example, they may name it a "minimization of manufacturing cost" problem. They recognize that it is a problem to be solved, set boundaries that identify what they will and will not address, and they articulate this to others to establish focus for problem solving. In their naming, they articulate their role in solving this problem and values important to a solution.

Framing/Defining. In addressing the problem, designers attempt to formulate a model or approach that links possible actions to expected impacts. Based on their knowledge and experience, they draw on mathematical models, standard procedures, plausible theories, and assumptions to formulate a way of exploring solution paths. For example, they may assume that Newtonian physics describes the ways in which objects will interact on a conveyer system.

Moving/Experimenting. The designers explore impacts of possible solution ideas by implementing their framing of the problem. They use virtual constructions of solution ideas to see what impacts these "solutions" bring to the situation. They identify information that confirms or conflicts with their desired outcomes. They analyze and observe carefully to identify all recognizable impacts.

Reflecting/Realization. Designers reflect on findings to make sense of them. In this activity, they may confirm or reject theories or understandings; rejection will lead to new hypotheses to be explored. They may confirm a good solution that meets their expectations and aligns with their values. A 'bad' result will lead to reframing the problem to find a better solution. Reflection on what is observed produces deeper understanding of professional practice and refines solutions to better achieve desired impacts.

Reflection-on-action is also observable from intermittent 'stepping aside' [19] from design activity to ponder and better understand the processes involved. In this case, the designers may have occasion to name a problem detected and frame it, then perform the moving and reflecting over a period of continued design activity, possibly culminating at the next intermittent reflection. This type of reflection (reflection-on-action) likely will address global process changes rather than the details of a design solution that are addressed by reflection-in-action.

The TIDEE assessments are tools for prompting and revealing reflective practice in the context of capstone design courses. As summarized in Table 10, reflective activity is prompted throughout the design project as students are asked to self-assess and improve the quality of professional development, teamwork, design processes, and solution assets. Each exercise included in this table serves as a reflection-on-action, a distinct pause in activity to reflect on success and learn from this experience. [13] These reflections should also reveal evidence of students' naming problems, framing problems, moving toward solutions, and reflecting to learn and improve—all of which evidence students' reflection-in-action. These tools, therefore, provide instructors data from which to evaluate the extent and quality of reflective practice occurring in design projects.

Table 10. Reflection Experiences in TIDEE Assessment System

Assessment Name	Reflection Experiences
Growth Progress	Reflection on personal growth development process after time-in-process and defining steps to improve growth
Professional Practices	Reflection on own professional practices employed in design activities and actions to make appropriate improvements
Growth Achieved	Reflection on own professional development achievements, impacts, and associated learning
Team Member Citizenship	Reflection on own contributions to the team relative to their importance, how to give effective coaching to others, and ways to improve own contributions
Team Processes	Reflection on status and importance of team processes and on ways to improve them to benefit team effectiveness
Teamwork Achieved	Reflection on achievements from team development activities, their impacts on team overall performance, and ways to apply related learning
Problem Scoping Processes	Reflection on problem scoping activities and changes needed to develop a useful problem definition
Concept Generation Processes	Reflection on concept generation activities and changes needed to select a preferred solution concept
Solution Realization Processes	Reflection on solution realization processes and changes needed to produce a defensible design solution
Design Reflection	Reflection on the impact of design process activity on the quality of a problem definition, concept selection, or design solution; learning that can be applied elsewhere

Summary and Conclusions

The goal of this article was to present emergent tools and methods by which engineering faculty can assess design and reflective practice in capstone engineering design courses. A set of assessment instruments was described— spanning performances in professional development, teamwork, design processes, and solution assets. Performance criteria for each area of performance have been defined from desired attributes and abilities reported in the literature. Within each area, separate but related formative assessments (design learning tools) prompt student definition of achievement targets, self-assessment of progress, and refinements to improve performance. The basis for scoring each assessment is derived from the corresponding performance criterion. Instructor feedback on each assessment guides student actions and learning. Summative assessments in each performance area document significant achievements in both learning and solution development.

TIDEE assessments contain distinct reflective components to stimulate reflective thinking and to document reflective practice. Individual assessments provide evidence of students' reflections, from which reflection-on-action can be assessed. Details of problem naming, framing, moving, and reflecting recorded in these assessments will provide evidence of reflection-in-action that has occurred during design activities addressed by the assessment. Factors for scoring these reflections are identified, but specific metrics for reflective practice are yet to be defined.

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Appendix A. Literature Sources Defining Design Performance Factors

Table A-1. Professional Development Performance Factors Mapped to Other Profiles

	ABET Outcome	TIDEE Role	Performance Factor	References
Technical	3a. Math/Sci/Engg 3k. Use tools	Analyst	Analyzing information	[75] [26] [76] [77] [2] [78] [3] [1]
	3e. Solve problems	Problem solver	Solving problems	[75] [26] [77] [2] [78] [3] [1]
	3c. Design	Designer	Designing products	[75] [6] [26] [77] [79] [2] [78] [4] [3] [1]
	3b. Experimentation	Researcher	Researching questions	[75] [26] [77] [2] [78] [1]
Interpersonal	3g. Communication	Communicator	Communicating	[51] [75] [26] [77] [79] [2] [78] [3] [1] [80]
	3d. Teamwork	Collaborator	Collaborating	[75] [6] [26] [77] [2] [78] [4] [3] [1]
			Relating inclusively	[76] [77] [2] [4] [3] [1] [81] [8] [80]
		Leader	Leading others	[26] [77] [79] [2] [78] [80]
Individual	3i. Lifelong learning	Self-grower	Practicing self-growth	[75] [26] [77] [82] [2] [78] [1] [83] [84]
		Achiever	Being a high achiever	[26] [77] [2] [78]
	3j. Contemporary issues		Adapting to change	[75] [85] [6] [77] [2] [78] [4] [1]
	3f. Profession/ethics 3h. Impact	Practitioner	Serving professionally	[75] [6] [26] [76] [77] [79] [2] [78] [3] [1]

Table A-2. Teamwork Attributes and Behaviors Derived from References

Attributes/Behaviors	References
Roles and responsibilities/workload balance	[86] [87] [88] [89] [90] [9] [91]
Member growth/leadership/initiative	[92] [93] [94] [91]
Performance expectations/accountability	[86] [87] [93] [91]
Peer/self review; constructive criticism	[95] [87] [88] [90]
Behavioral norms; respect; support others; climate	[86] [87] [92] [89] [93]
Buy-in to full participation/interdependence; spirit	[87] [96] [92] [89] [90] [91]
Team processing/using differences, abilities	[86] [87] [2] [90] [97] [93] [94] [9] [91]
Conflict resolution/team building	[86] [87] [98] [92] [89] [94]
Goal setting/goal driven/common focus	[86] [87] [96] [98] [89] [90] [93] [94] [91]
Developing structures/plans/project mgmt	[87] [88] [90]
Decision making, consensus	[87] [88] [98] [89] [94] [91]
Potency/productivity; timeliness, competency	[96] [92] [90] [93] [94] [9] [91]
Process monitoring, review, celebration	[95] [98] [92] [94] [91]
Meetings	[86] [87]
Communication; active listening; persuasion	[86] [87] [98] [2] [89] [93] [94] [91]
Shared understanding/learning	[95] [99] [87] [96]

Table A-3. Component Design Activities within Three Design Phases

Design Phase	Design Processes/Activities
Problem Scoping	**Analyze product opportunity:** Analyze, 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**; i**dentify and evaluate requirements and constraints**; i**dentify essential functions**; e**valuate competition/similar products**; e**stablish specifications (metrics/parameters)**; s**et target specifications
Concept Generation	**Generate alternative concepts: P**erform functional decomposition**; d**efine major subsystems and interfaces**; s**earch for working principles and working structures**; g**enerate concepts **Select concept: E**valuate concepts**; s**elect a concept**; s**et final specifications
Solution Realization	**Design product: G**enerate product embodiment (architecture/layout)**; m**odel/simulate/analyze design**; d**esign for X (performance, robustness, reliability, etc.)**; t**est, evaluate, refine, optimize, validate design **Communicate design:** Develop detail drawings (representations) and support documentation**; d**ocument and communicate design**; i**mplement production

Table A-4. Performance Factors for Design Processes Derived from References

Performance Factor	References
Process Mechanics: Time spent on steps, design steps used, methods/tools used in steps, use of social processes in design	[32] [33] [34] [35] [36] [37] [38] [39] [40] [41] [42] [43] [44] [45]
Reflection in Design: Transitions to readdress actions, learning by reflection, developing adaptive expertise, advancing the design	[46] [32] [47] [48] [49] [44] [50] [51] [52] [53] [21] [54]
Informing Design: Gathering information, specifying the problem, articulating problem and solution impacts, using prior knowledge	[55] [56] [57] [58] [33] [46] [57] [59] [45]

Table A-5. Performance Factors for Solution Assets Derived from References

Factor	Description	References
User Function	User needs (variety), performance, accuracy and time, functionality, application, ergonomic, features, simplicity, reliability, durability, ease, consistency, meets needs, logistical, human factors, physical requirements, capabilities, operability	[46] [32] [60] [61] [31] [62] [25] [63] [64] [65] [66] [29] [67]
Business Value	Uniqueness, cost efficiency, aesthetics, workmanship, craftsmanship, marketability, innovation, novelty, cost, economy, business value, inexpensive, cost/benefit	[46] [32] [60] [61] [31] [62] [25] [63] [64] [68] [65] [66] [29] [67]
Technical Feasibility	Technical feasibility, serviceability, practical, technical excellence, layout, production, quality control, assembly, schedules, maintenance, manufacturability, technical, time, packaging, materials, testing	[46] [60] [61] [31] [62] [25] [63] [56] [64] [66] [29] [67]
Social Impact	Protection from injury, accident reduction, safe, conformance to regulations, recycling, social, environmental, political, ethical, health, sustainability, natural, damage, global, natural environment, meaning to others, social value, cultural, emotions, social impact, life cycle concerns, standards, disposability	[46] [32] [60] [61] [31] [62] [25] [63] [56] [59] [69] [64] [68] [70] [65] [66] [29] [67]