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Design Reviews for Capstone Courses*

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Design reviews are required for engineering projects in the workplace, especially where human life and well-being are at stake. However, few engineering undergraduate programs conduct professionally rigorous technical design reviews that prepare students for the demands of the engineering workplace. This article describes the use of technical design reviews in industry and government settings and explains how analogous technical design reviews can be conducted to improve the effectiveness of capstone courses. Criteria are presented for defining and adopting technical design reviews in capstone project courses. These guide the definition of suggested design review questions and scoring rubrics that design educators can use for improving student design, assessing students' design skills, and preparing students for engineering careers. At the same time, by implementing the technical design review, the capstone design course better reflects characteristics of the engineering profession, resulting in student learning and assessment of engineering technical and professional skills that are transferable to the work environment.

Keywords: design reviews; engineering design; industry practice; authentic assessment

1. Introduction

The world depends upon the engineering profession to address some of the great challenges facing people in the twenty-first century [1]. Design ability is defined by ABET (formally, the Accreditation Board for Engineering and Technology) as "an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability" [2].

Some academic programs concerned about graduates developing higher levels of practical knowledge and skills have augmented their programs with multiple authentic engineering project experiences and direct involvement of clients in projects [3–4]. These project experiences provide a context for integrating technical and professional learning and provide both motivation and opportunities for students to achieve higher-level knowledge and skills vital to engineering practice.

Main [5] has defined design as ". . . a creative process that generates new and unique solutions to ever-changing customer demands." Engineering capstone design courses are recognized as ". . . a culminating experience" where students apply ". . . knowledge and abilities to practical engineering problems" [6]. The capstone experience permits students to connect theory and practice in the final academic process of developing professional skills of design and personal relationships through teamwork. Capstone texts each have variations of the design process such as stage-gate, systems engineering, and systems engineering lifecycle [7]. These variations often include general references to technical design reviews (TDRs).

Duesing et al. [8] have described the philosophy behind engineering capstone courses as preparing the engineering student for work in industry. That philosophy implies that capstone is seen as a transition from academia to engineering practice. As the engineering students' capstone experience is realized [9], limited information is reported relative to the use of TDRs in capstone programs as a component of the pedagogy. Lectures, handouts, guidebooks and textbooks also seem to have only modest offerings on developing student abilities regarding the process of TDRs. A review of research literature provides little pedagogy or methodologies for developing knowledge, skills and abilities (KSAs) within students that are useful in preparing them for TDRs post-graduation. A recently published workbook is one explicit attempt to prepare students for technical design reviews [10].

This paper defines issues important to design reviews and presents tools for performing design reviews. Major issues identified at important design development stages lead to sample questions to probe student understanding and performance.

2. Design reviews in engineering practice

When engineers fail in their design work, the world sees impacts that might include major economic losses, environmental disasters, and loss of life.

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Society reacts to engineering disasters by calling for investigations and establishing tougher regulations aimed at preventing similar failures in the future. Two areas in which strict design controls have been established are the medical industry and space vehicle design. The Food and Drug Administration (FDA) medical device design controls [11], the Department of Defense Design Control Regulations (DOD) [12] and the Institute of Electrical and Electronics Engineers [13] provide descriptions of TDRs appropriate for unique design application.

The TDR process is a peer evaluation of a design as it is developed and/or before it is deployed for development, fabrication or production. Peer reviewers are acquired from independent pools in order to provide experienced, unbiased, and objective design oversight. Bruce [14] provides examples addressing critical issues in design practices and provides guidelines for effective design reviews. From design controls, the development of design review procedures, questions, and criteria for judging adequacy of design processes and products can be derived.

TDRs are integral to the Product Lifecycle Management [15]. They are a process of ensuring safe design that meets performance requirements and constraints. The TDR is a process where designers present design and technical work to reviewers who are usually independent of the design, to analyze the design relative to (engineering design) specifications [16]. The goal of the TDR process is to uncover errors, not to resolve issues, and thereby improve design. This is a manual process for the most part for which it is difficult to measure efficacy in terms of return on investment.

Design reviews are recognized to have two objectives: (1) identify deficiencies or problems with the presented design, and (2) improve the design [17]. In industry, design reviews are used to avoid expensive change-orders by having independent experts, sponsors, champions and/or owners verify and validate that the design product meets constraints and objectives [18]. The design review process is the integration of owner perspective, designer perspective, and project requirements [19].

2.1 Design refinement

The complexity of the design review process cannot diminish the need for design reviews which ensure that designs perform, are safe, and conform to necessary requirements before being released to the next phase of development [5]. Work by Ferguson and Sanger [20], Adams [21], and Gharabagi and Ebel [22] identify commonly used industry phase reviews:

- A review to determine that materials and components are properly allocated and resourced to accomplish the design work expected.
- A review of design alternatives, selection, and specification of codes, standards and regulation compliance.
- A review of the final detailed design to detect and resolve design errors and omissions before the design is built or developed further.
- A review that verifies issues identified in the earlier review have been appropriately resolved, test plans are developed and safety/hazards analysis are completed.

Main [5] makes the point that for an efficient design process, the most important design reviews are the early ones. Design inadequacies that are unidentified, unchecked or unresolved until later phases often result in costly design modification. As the design develops, the costs of making and implementing changes increase significantly.

The cost of design defects can be significant. Kemerer and Paulk [18] report research findings that a requirements defect can cost 100 to 200 times as much to repair as it would have cost to resolve during TDRs. Early design defect detection can avoid construction-identified change notices (6–23% of original estimate), as well as reduced maintenance and operating costs throughout the life of the designed product. Liability insurers recognize the value of design reviews in reducing the errors and omissions claims and litigation [23]. Kinnersley and Roelen [24] claim that up to 60% of root causes of accidents stem from design deficiencies. Taylor [25] concludes that design reviews have been estimated to discover and remove between 80% and 95% of the errors made during the design process.

2.2 Design improvement

It is vital that designers and design reviewers recognize the importance of the TDR process as a search for errors and omissions. When reviewer and designer are supportive of this criticism-centric process, they must remain emotionally detached from the design in order to support a value-added discourse leading to robust design [26]. When conducted with the appropriate diligence and attitude, the design is also improved. D'Astous [27] states that design reviews are a "trustful communication" that requires management support and recognition of the importance of the work involved within the TDR process [28].

Bond [23] suggests that the potential for improvement necessitates that TDRs be conducted as soon as technically feasible solutions are identified and continue until the ready-to-build phase is complete. For Bond, the premise is that the ongoing design reviews result in additional and refined alternatives that involve a larger group of people, i.e., more involvement improves design. Bond also recognizes that judgment is often superior to analytical tools and that judgment cannot be replaced. Judgment improves with experience. The National Research Council endorses use of design reviews in capstone design: "Although they are time-consuming and expensive and take reviewers away from their own projects, peer design reviews are immensely helpful in finding and avoiding faults and suggesting alternative approaches" [29].

3. Design reviews in academic programs

In a study of capstone programs' use of TDRs, Dixon [30] found that 90% of surveyed programs included a TDR. The study had 69 participants and included members of the American Society for Engineering Education (ASEE) Design in Engineering Education Division (44%) and representatives from the general capstone design course constituency (56%) who participated in earlier capstone design conferences. The study investigated the frequency of TDR use in capstone courses and components addressed in TDRs.

The study found a mixed frequency of TDRs (Table 1) with most programs conducting two TDRs per semester. The study did not include factor analysis of which TDR users featured one semester or two semester capstone project lifecycles. Participants' comments gave quantitative responses and qualitative explanations. For instance it was noted that computer science projects required continuous industry mentor technical reviews and another discipline provided TDRs "as needed". Over half of responses indicated the use of two or more TDRs per semester.

Dixon's study also asked participants to evaluate the desirability of a list of components in the TDR. The list was identified from various literature sources and was not intended to be comprehensive. Questions were evaluated on a 1–4 Likert response scale (1, Doesn't matter; 2, Maybe good to have; 3, Nice to have; and 4, Must have). The results from Likert scale responses are shown in Table 2. The highest rated component was *Assumptions adequately described and reasonable.* The item rated as having the lowest desirability was *Environmental issues appropriately addressed including sustainability.* The results were, however, not assessed for influencing factors such as project type (process or product) or related engineering discipline/field. These factors could have strong influence on the capstone project's, or program's objectives, so they limit generalized application of the results.

Table 1. Frequency of TDRs (Dixon, 2014)

TDR Frequency	Total	%
1 per project lifecycle	9	16
1 per semester	10	18
2 per semester	19	35
>2 per semester	11	21
Other, please explain	13	24

Dixon's study did point out the need to recognize that TDRs are not universally applicable and must be designed to fit the project. This is consistent with industry practices. For example, nuclear industry TDRs may require much more technical rigor than paper goods industry reviews. Similarly, design projects for lighting within a nuclear facility may permit less technical design oversight than design projects that modify process cooling water flow. Another factor affecting the applicable TDR's components for evaluating the capstone project's technical design would be the project objectives. For instance, designing a protective case for a portable power supply for a personnel mobility device requires a different level of scrutiny than a TDR assessing the technical design for a project providing secondary containment of an alkaline soaking tank.

The literature of capstone course TDRs shows wide variations on an industry approach using TDRs at critical design gates. Wilson, Cambron,

Table 2. Desirability of Listed Components

What components or characteristics are essential parts of a capstone level technical design review? [items below followed]	Mean	SD
Assumptions adequately described and reasonable	3.81	0.40
Design inputs correctly incorporated into design	3.78	0.40
Reasonableness of design outputs relative to design inputs	3.71	0.52
Input selection complete and correct	3.67	0.63
Engineering judgments identified, technically justified and supported	3.64	0.66
Appropriateness of design methods and computer aids	3.37	0.73
Materials, parts, process and inspection/testing criteria appropriate	3.37	0.75
Design inputs for interfacing systems specified	3.31	0.78
Hazards adequately/accurately assessed for the design and the interface(s) with supporting systems	3.20	0.81
Regulatory requirements properly assessed and addressed	3.11	0.85
Operability, maintainability, recyclability addressed appropriately	2.84	0.88
Environmental issues appropriately addressed including sustainability	2.78	0.83

and McIntyre [31] describe a capstone TDR process that distributes reviews throughout the year and uses students as independent reviewers (see also, [8]). Alternatives include TDRs performed by faculty, sponsors/industry representatives or combinations of faculty and industry. Often faculty provide independent reviews throughout the year, and at the end of each semester a panel of industry representatives performs a review of written design documents for technical adequacy [30]. Archibald, Reuber and Allison [17] report on the use of three to five professionals in performing reviews.

For capstone projects, the quality of the TDR is dependent on students' abilities to communicate design objectives and solutions in written reports and in oral presentations. This parallels industry practices. A professional design presentation aids the efficiency and effectiveness of the design review process. A design presentation should include appropriate analysis of prior art, customer objective(s), customer requirements, design economics, drawings, analytical results, engineering changes, test reports, and an open issues list [8]. Patent search results may also be included. As the design develops, the presentation should provide insights into design activities, design alternatives considered and selected, technical/economic trade-off analysis and justifications, and conclusions [32]. In oral presentations, design assumptions, analysis, alternatives and design methods are challenged during question and answer (Q&A) portions of the TDR. Duesing [8] states that it is ". . . critical that engineers explain their concepts and designs to an engineering and management audience" as well as, ". . . answer questions regarding their concepts and designs for these same audiences." The Q&A portion of the TDR requires students to prepare for, and anticipate, questions. One of the critical learning opportunities of the Q&A process has been for students to learn the delicate skill of defending design and not arguing for their design. This requires students to hone their KSAs of communicating their work and being sensitive to reviewers' insights for improving their work.

3.1 Design review issues in capstone

TDRs are not universally applicable and must be designed to fit the project, and while capstone is uniquely an academic work, the issues commonly found in capstone project technical design reviews are not unlike issues found in the workplace. This section provides anecdotal observations regarding capstone TDRs based on the authors' combined 29 years in industry and 40 years in academic capstone programs.

Design Safety. Capstone projects run the gamut from basic research, to process improvement, to product development. Senior engineering design students generally have a paucity of exposure to industrial safety, product safety and OSHA guidance and regulations dealing with product, process and worker safety [34]. Because of that limited exposure, the TDR process is important to student learning, protecting the user of the design output, and risk mitigation for the sponsor in providing a TDR that includes design safety. While risk ownership may very well belong with the sponsor, a thorough design safety analysis can protect students from the mental anguish associated with a consumer or customer injury associated with the capstone product. The need for a professional engineer review of any designs that migrate from campus to community requires a risk mitigation process addressing not only user protection but design for X (safety, ergonomics, etc.) training as part of the capstone design process.

Resource Commitments. During instructional periods, the authors inform students that an industry TDR has both soft and hard costs. The soft costs relate to morale and ego as discussed earlier. The hard costs are associated with actual resource costs associated with the conduct of a TDR. Students are told that billing hours for engineers include direct pay and overheads. Overheads include at a minimum benefits and facility costs, both direct and indirect. For instance, the authors commonly suggest to students that the minimum cost for a TDR would be on the order of 175% of (salary/TDR participant/hr) + additional overhead burdens. Students have some feel for what that means when salary levels are discussed, however, the dollar cost for an industry TDR must be related to the time commitments required of students in conducting or being involved in a capstone TDR. Senior engineering students have many commitments, one of which is securing a job. The commitment required of a capstone TDR is a time commitment for students, faculty, sponsors, and subject matter experts. Students do understand time commitments at this point in their academic programs.

Design Efficiency. Capstone students have the benefit of a recent exposure to engineering theory. What they lack is design experience. Design experience can come in the form of design speed, e.g., knowing industrial fastening processes commonly used in the industry or sponsor's facility. The sponsor's in-house engineering staff can quickly provide those details during an in-house design exercise. Capstone students, lacking that experience may be forced to plod through design text books, handbooks, or their sponsors' design procedures and methodologies in order to discover what experience knows. The discovery process takes time. The TDR offers the opportunity for experienced engineers to provide experiential-based design efficiencies. Too often, due to the space and time limitations for TDR, students may find that they have invested significant design resources on something that in-house design engineers can complete in moments.

The three design review issue categories described above actually focused on resource investment. For capstone courses, where students are working on completing their projects and where sponsors have limited resources to guide projects, the time required for thorough TDRs can be a limiting factor. The resource limitations include scheduling the right sponsor representatives to participate at a time that interfaces with student academic and personal (internships or part time work) schedules. Faculty also have limited availability, as do other subject matter experts. From experience gained in industry, providing a focused TDR agenda, completing preparations for the TDR by reviewing documents beforehand, developing and sharing direct questions before the TDR, and careful time management during the TDR, the effectiveness of the TDR can be increased.

4. Selecting questions for capstone design reviews

Design reviews in capstone courses are intense examinations of design. At each stage of design the focus must be the critical issues that determine adequacy of design work at that stage. In addition, design reviews must be structured to give participants (students, faculty, others) maximum value for their time invested. For capstone design reviews, the following concerns are relevant to the success of the TDR.

1. Compatibility: Design reviews fit the nuances of individual projects and the learning and project completion goals of the program.
2. Authenticity: Design reviews develop students' skills that are authentic to the engineering profession.
3. Adoptability: Design reviews have attributes similar or familiar to current capstone practices that make them adoptable.

Table 3. Review questions for the Problem Definition Review

Concern	Elements of Importance in Response	Lead-in Question
Overall problem scope and opportunity	• Problem scope and focus address right opportunity • Envisioned solution offers potential to address needs • Most significant benefits are being pursued	In 30-seconds, state your problem, desired solution, and envisioned benefits.
Understanding of stakeholder needs	• Appropriate sources/methods are used to understand needs • Needs and views of project clients are understood • Needs and views of other stakeholders are understood	Describe your efforts to understand stakeholder needs, and explain your findings.
Understanding prior art (state of technology)	• Proper methods are used to research technologies • Current states of technologies, relevant patents are known • Industry standards are known	Describe your efforts to understand current art for your project; summarize findings.
Understanding standards and regulations	• Proper methods are used to find standards, policies, etc. • Relevant standards, codes and regulations are known • Relevant legal, political, societal trends are known	Describe your efforts and findings for codes, standards and regulatory policies.
Ability to establish design focus	• Appropriate methods and criteria used to prioritize needs • Diverse stakeholder needs are prioritized • Greatest design challenges are identified	Describe your process for prioritizing the many needs to give focus to your design.
Ability to write engineering requirements	• Criteria for good engineering requirements are understood • Acceptable process is used to derive requirements • Established requirements allow creativity in design	Describe your process and criteria for defining useful solution requirements.
Adequacy of technical requirements	• Important design functions are specified • Important technical attributes of design are specified • Technical requirements are testable	Defend your most critical technical specifications for design attributes and function.
Adequacy of financial requirements	• Important financial requirements are specified • Requirements make business sense • Financial requirements can be tested by economic principles	Identify critical financial requirements for your design and how they will be assessed.
Adequacy of social/ safety requirements	• Important safety requirements are specified • Important social responsibility requirements are specified • Safety/responsibility requirements can be tested	Explain where and how you will focus your design to be safe and socially responsible.
Adequacy of project risk assessment	• Important risks to project success are identified • Important opportunities for project success are identified • Actions to address risk/opportunity are identified	Explain the most important project risks and opportunities and how they will be managed.

Table 4. Review questions for the Conceptual Design Review

Concern	Elements of Importance in Response	Lead-in Question
Ability to contextualize the concept	• Need for design solution is understood in context • Concept meets needs and justifies further development • Concept promises important benefits desired by others	In 30-seconds, state the problem, selected concept, and envisioned benefits.
Adequacy of searching for existing ideas	• Effective methods are used to find relevant design concepts • Concepts identified provide value and diversity • Search results identify areas with difficult design challenges	Explain how the team located existing ideas that might offer value to your project.
Adequacy of new idea generation	• Idea generation focused on difficult design challenges • Individual and group idea generation are used • Methods are used well and provide valuable ideas	Describe the creative processes you used to address a difficult design requirement.
Adequacy of concept evaluation	• Evaluation process is defined and followed consistently • Importance of requirements drives selection of components • Selected components are validated	Describe the process used for evaluating alternative ideas.
Adequacy of concept synthesis	• Synthesis process considers subsystem relationships • Cost, performance, simplicity, system integration achieved • System concept is validated	Explain the processes of integrating elements of the concept into a viable whole.
Understanding of concept function	• Function of selected concept is explained well • Required function is proven feasible (e.g., prototyping) • Concerns about function are identified	Explain how the design concept will achieve required functionality.
Understanding of concept reliability	• Robustness of selected concept is explained well • Required robustness is proven practical (e.g., analysis) • Concerns about robustness are identified	Explain how engineering analysis has been used to justify the concept selected.
Understanding of concept finances	• Financial soundness of concept is explained well • Required financial attributes are predicted (e.g., models) • Concerns about financial attributes are identified	Explain how financial analysis has been used to justify the concept selected.
Understanding of concept social impact	• Safety and social impacts of concept are explained well • Impacts are defended relative to regulations, standards, etc. • Concerns about safety/social impacts are identified	Explain how your concept addresses safety and/or social responsibility concerns.
Adequacy of concept risk assessment	• Greatest risks with the concept are explained • Greatest opportunities with the concept are explained • Plans forward address risk/opportunity analysis	Explain the greatest design challenge risk and how it will be managed.

4.1 Compatibility

Formal TDRs in a capstone project course must be compatible with goals of the project and goals of the course. They must be implementable with student teams engaged in projects that meet specified needs and that have realistic constraints (e.g., economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability). Students may also be required to demonstrate ABET outcomes such as abilities to: function on multi-disciplinary teams, identify-formulate-solve engineering problems, understand professional and ethical responsibility, communicate effectively, understand the impact of engineering solutions in a global-economic-environmental-societal context, and recognize the need for and have an ability to engage in life-long learning.

4.2 Authenticity

TDRs should bring authentic engineering practices to the capstone course, giving students perspectives and skills of the profession. TDRs should be a rigorous examination of engineering work at critical stages of a project, ensuring that no substandard work is approved. For efficiency and effectiveness, the TDR should focus questioning on items that determine adequacy of design work at the project's current stage of development. Questioning probes processes and products to identify weaknesses, which lead to prescribed revisions that ensure the desired quality of the design solution. Questions can be derived from those used in industry, with wording and contextual refinements to fit the capstone project setting. TDRs should bring a rigor that ensures that design solutions are well-focused, functional, safe, responsible, manufacturable, and implementable as intended.

4.3 Adoptability

TDRs must be attractive to faculty and students if they are to be adopted successfully into capstone design courses. Any new or revised educational practices to be adopted readily must: (1) offer benefits over current practices, (2) be adopted easily into capstone courses, and (3) possess elements that are familiar to faculty [34]. The authenticity of rigorous

Table 5. Review questions for the Final Design Review

Concern	Elements of Importance in Response	Review Question
Ability to abstract the solution	• Needs of stakeholders are understood in context • Solution fits needs, promises desired performance • Solution benefits justify implementation and user testing	In 30-seconds, describe the problem, final solution, and realized benefits.
Adequacy of requirements validation	• Requirements have been reviewed and revised over time • Requirements have been validated with key stakeholders • Requirements align with industry standards	Explain how you have revised solution requirements over the duration of the project.
Appropriate focus of detail design effort	• Design risks and benefits have been assessed • Time was prioritized where maximum gain was expected • Design effort was invested for effective use of time	Explain where most effort was invested in detail design and the basis for this decision.
Adequacy of solution evaluation	• Engineering analysis was used to prove design adequacy • Formal testing was used to prove design adequacy • Evaluation results are interpreted correctly	Explain how you used data and/or engineering analysis to prove solution adequacy.
Proof solution has desired functionality	• Important functions are tested to prove performance • Functional performance meets critical requirements • Areas of functional weakness are identified	Cite examples of key solution features and functionality that meet engineering requirements.
Proof solution gives desired financial value	• Important financial performances are tested • Financial performance meets critical requirements • Areas of financial weakness are identified	Explain how specific financial requirements are satisfied by the final solution.
Proof solution is safe and responsible	• Issues of solution responsibility are tested • Solution is found safe and meets societal expectations • Concerns about ethics and responsibility are identified	Explain how the solution meets safety and social impact requirements.
Adequacy of solution validation	• Solution is tested in the hands of intended users • Solution meets needs and applications of intended users • Areas of concern about solution validity are identified	Explain how the solution will meet user needs and applications.
Adequacy of solution risk assessment	• Risks encountered in detail design were mitigated • Risks for solution implementation are identified • Actions for risk mitigation are described	Explain how a (project/design) risk was mitigated in solution realization.

design reviews and their value for assessing and improving the quality of designs delivered to stakeholders are critical here. Ideally, the TDRs can be readily substituted for current progress reviews. Much of the TDR process is familiar to faculty, so any new elements will require relatively small changes for most faculty. The defined structure, questions, and rubrics for design reviews can also be attractive time-savers for faculty.

The number and timing of design reviews used for a capstone design project will depend upon the project scope, duration of the project, other demands and constraints of the capstone course(s), and the availability of review participants. In the following sections, three technical design reviews are described that commonly fit into two semester capstone projects:

- Problem Definition Review (PDR)
- Conceptual Design Review (CDR)
- Final Design Review (FDR)

4.4 *Problem definition review (PDR)*

The Problem Definition Review focuses on the design team's definition of the problem to be addressed. The PDR ensures that the design team understands the scope of the problem addressed, needs of important stakeholders of the project, criteria that determine the acceptability of the design produced, and deliverables expected throughout the project. Table 3 summarizes the categories of concerns to be addressed in the PDR, elements of importance in student responses, and suggested lead-in questions to draw out the desired responses. These questions can be used in written design reviews, oral face-to-face reviews, or combinations of the two.

4.5 *Conceptual design review (CDR)*

The conceptual design review (CDR) focuses on the generation and selection of a design concept that merits development into a full design solution. This review will ensure that concept selection is based on the requirements for the solution, a thorough search of possible concepts, effective combination of components into an integrated design concept, and suitable consideration of risks and potential value that can emerge from the solution. Table 4 summarizes the categories of concerns to be addressed in the CDR, elements of importance in student responses, and suggested lead-in questions to draw out the desired responses. The questions may be used in written and/or oral design reviews.

Table 6. Exam/assignment questions for the Problem Definition Review

Concern	Elements of Importance in Response	Reflective Question: In 5 sentences or less . . .
Overall problem scope and opportunity	• Problem scope and focus address right opportunity • Envisioned solution offers potential to address needs • Most significant benefits are being pursued	. . . state the problem, your envisioned solution and anticipated benefits.
Understanding of stakeholder needs	• Appropriate sources/methods are used to understand needs • Needs and views of project clients are understood • Needs and views of other stakeholders are understood	. . . explain why the team has confidence in its understanding of stakeholder needs.
Understanding prior art (state of technology)	• Proper methods are used to research technologies • Current states of technologies, relevant patents are known • Industry standards are known	. . . describe how your team has gained understanding of relevant prior art.
Understanding standards and regulations	• Proper methods are used to find standards, policies, etc. • Relevant standards, codes and regulations are known • Relevant legal, political, societal trends are known	. . . describe how your team has embraced relevant standards and regulations.
Ability to establish design focus	• Appropriate methods and criteria used to prioritize needs • Diverse stakeholder needs are prioritized • Greatest design challenges are identified	. . . explain how your team has set priorities for your design effort.
Ability to write engineering requirements	• Criteria for good engineering requirements are understood • Acceptable process is used to derive requirements • Established requirements allow creativity in design	. . . explain how your team developed useful design requirements.
Adequacy of technical requirements	• Important design functions are specified • Important technical attributes of design are specified • Technical requirements are testable	. . . give examples of your most important technical design requirements.
Adequacy of financial requirements	• Important financial requirements are specified • Requirements make business sense • Financial requirements can be tested by economic principles	. . . give examples of your financial requirements.
Adequacy of social/safety requirements	• Important safety requirements are specified • Important social responsibility requirements are specified • Safety/responsibility requirements can be tested	. . . give examples of safety or social responsibility requirements for your solution.
Adequacy of project risk assessment	• Important risks to project success are identified • Important opportunities for project success are identified • Actions to address risk/opportunity are identified	. . . what are the greatest risks you see for this project and how will you address them?

4.6 Final design review (FDR)

The final design review focuses on the design solution after detail design and preliminary testing are completed. The FDR determines if the design is ready for further testing or limited-scale implementation with stakeholders. The purpose of this review is to determine if evidence available ensures that the proposed solution performs and delivers value as intended. Table 5 lists principal concerns for this stage of design, identifies elements desired in student responses, and presents a suggested lead-in review question for each design review concern. Questions are suitable for written and/or oral design reviews.

5. Implementation of design reviews

The TDR process described above has been formally introduced into a general engineering program that was initiated in 2004. The program currently supports approximately 30 capstone projects each year across all the engineering fields supported by the curricular program. Students are assigned to teams of 3–5, with 4 being the team size mode. Team sizes vary due to project scope or student attrition (associated with gaining sponsor's facility access). The capstone projects are two semesters each, and reports indicate that 400–600 hours per project per student team are invested. Advisor time has not been tracked to date. Project types range from research support to new product development and process improvement. The TDR process used has become the focus of more attention over the last three years in order to improve design efficacy.

The technical design reviews are implemented in ways that achieve course objectives while also modeling design reviews used in the engineering profession. Because many capstone courses require formal oral and/or written design reports, technical design reviews may be used to complement these common reports. Ideally, the written design reports are completed and distributed to reviewers a week before a scheduled TDR. TDR reviewers are expected to come to the review with reports marked up and questions noted. In this model, written design reports are the 'homework' for TDR reviewers. Review of the written reports followed by a brief

Table 7. Exam/assignment questions for the Conceptual Design Review

Concern	Elements of Importance in Response	Reflective Question: In 5 sentences or less . . .
Ability to contextualize the concept	• Need for design solution is understood in context • Concept meets needs and justifies further development • Concept promises important benefits desired by others	. . . state the problem, selected concept, and envisioned benefits.
Adequacy of searching for existing ideas	• Effective methods are used to find relevant design concepts • Concepts identified provide value and diversity • Search results identify areas with difficult design challenges	. . . explain how the team identified and used related prior art.
Adequacy of new idea generation	• Idea generation focused on difficult design challenges • Individual and group idea generation are used • Methods are used well and provide valuable ideas	. . . describe the creative processes used to address design requirements.
Adequacy of concept evaluation	• Evaluation process is defined and followed consistently • Importance of requirements drives selection of components • Selected components are validated	. . . describe the process(es) used for evaluating alternatives.
Adequacy of concept synthesis	• Synthesis process considers subsystem relationships • Cost, performance, simplicity, system integration achieved • System concept is validated	. . . explain the processes of integrating elements of the concept into a viable whole.
Understanding of concept function	• Function of selected concept is explained well • Required function is proven feasible (e.g., prototyping) • Concerns about function are identified	. . . explain how the design concept will achieve required functionality.
Understanding of concept reliability	• Robustness of selected concept is explained well • Required robustness is proven practical (e.g., analysis) • Concerns about robustness are identified	. . . explain how engineering analysis was used to justify the selected concept.
Understanding of concept finances	• Financial soundness of concept is explained well • Required financial attributes are predicted (e.g., models) • Concerns about financial attributes are identified	. . . explain how financial analysis has been used to justify the preferred concept.
Understanding of concept social impact	• Safety and social impacts of concept are explained well • Impacts are defended relative to regulation, standards, etc. • Concerns about safety/social impacts are identified	. . . explain how the preferred concept addresses safety and/or social responsibility concerns.
Adequacy of concept risk assessment	• Greatest risks with the concept are explained • Greatest opportunities with the concept are explained • Plans forward address risk/opportunity analysis	. . . explain a design risk and how it will be managed.

oral presentation and focused questioning supports rigorous review and feedback to improve student learning and design efficacy.

The formal design reports should provide detail adequate to enable the work to be recreated with little 'schooling' on progress-to-date. The technical design review probes the design (detailed analysis, processes, and especially results of processes applied). Reviews determine flaws in the design that yield less than desired or unacceptable design or design quality. The Q&A portion of a TDR may also require students to reference design records to support their responses. The TDR should enable reviewers to critique both oral and written design communication in addition to design adequacy.

To model engineering practice, the technical design review should be conducted by the project advisor (and course instructor, if different) along with technical experts or project stakeholders. Early design reviews might be conducted by student peers to enable students to experience the review process under less intimidating conditions. Including non-students as reviewers provides important technical and user perspectives in evaluating design team performance. After the Q&A session, the reviewers confer and make a judgment on project advancement. The design team leaves the review knowing the advancement decision and general ideas about weaknesses to be addressed or improvements to be considered. A follow-up memo to the team confirms the advancement decision and details any remedial work required.

To model pedagogies of reflection, student teams are tasked with performing a TDR within their teams. This affords students an opportunity to build KSAs associated with reviewing their own designs, practicing introspective questioning, exploring broader applications, and preparing for the formal faculty/expert TDR process. The intra-team TDR process should require modest time commitments and be thought-provoking in content. This requires a minor modification to Tables 3–5 as shown in Tables 6–8.

Another option would be to include the TDR as an exam question. The reflective TDR has sometimes been used as a design related question on first and second semester final exams by the authors as a way to reinforce the KSA of continually evaluating

Table 8. Exam/assignment questions for the Final Design Review

Concern	Elements of Importance in Response	Reflective Question: In 5 sentences or less . . .
Ability to abstract the solution	• Needs of stakeholders are understood in context • Solution fits needs, promises desired performance • Solution benefits justify implementation and user testing	. . . describe the problem, final solution, and realized benefits.
Adequacy of requirements validation	• Requirements have been reviewed and revised over time • Requirements have been validated with key stakeholders • Requirements align with industry standards	. . . explain how you have revised solution requirements over the duration of the project.
Appropriate focus of detail design effort	• Design risks and benefits have been assessed • Time was prioritized where maximum gain was expected • Design effort was invested for effective use of time	. . . explain where most effort was invested in detail design and the basis for this decision.
Adequacy of solution evaluation	• Engineering analysis was used to prove design adequacy • Formal testing was used to prove design adequacy • Evaluation results are interpreted correctly	. . . explain how you used engineering analysis to prove solution adequacy.
Proof solution has desired functionality	• Important functions are tested to prove performance • Functional performance meets critical requirements • Areas of functional weakness are identified	. . . cite examples of solution feature and functionality that meet engineering requirements.
Proof solution gives desired financial value	• Important financial performances are tested • Financial performance meets critical requirements • Areas of financial weakness are identified	. . . explain how specific financial requirements are satisfied by the final solution.
Proof solution is safe and responsible	• Issues of solution responsibility are tested • Solution is found safe and meets societal expectations • Concerns about ethics and responsibility are identified	. . . explain how the solution meets safety and/or social requirements.
Adequacy of solution validation	• Solution is tested in the hands of intended users • Solution meets needs and applications of intended users • Areas of concern about solution validity are identified	. . . explain how the solution will meet user needs and applications.
Adequacy of solution risk assessment	• Risks encountered in detail design were mitigated • Risks for solution implementation are identified • Actions for risk mitigation are described	. . . explain how a (project/design) risk was mitigated in solution realization.

design in process. This TDR was performed by individual team members working independently on their final exam. The modified tables (Tables 6–8) are presented as an exam question based on the progress of the capstone projects within the class. The TDR was prompted by the question, "(30 pts) For your project, complete a technical design review using the guide provided in Appendix 2." One of the tables (PDR, CDR or FDR) would then be selected based on whether project progress supported problem definition review, conceptual design review, or final design review. The authors have provided this exam question both at the conceptual design review phase and the final design review phase in the most recent course offerings. The responses for the most part were acceptable and provided evidence that the TDR was performed seriously. Unacceptable answers were observed when students just placed a check mark in the third column of the table for each area of concern. The reason for this response to the exam question is not understood at this time.

Another alternative would be to select one or more of the Concern areas from the appropriate Table (PDR, CDR or FDR) and present some derivative question. The exam questions could also serve as assignments throughout the semester as a prelude to the more formal TDR presentations. The use of exam questions also enables the instructor to see individual student responses to questions, thereby making visible the understanding and performance of individual students within a team project.

6. Capstone TDR effectiveness

Evidence of TDR effectiveness at this point is anecdotal for the capstone, not only on the design efficacy but also on career preparation for the engineering students. Quantitative metrics have not been developed and no comparable industry metrics have been identified to date. The ability to measure mitigated risk is a complex problem beyond the scope of this work. The authors plan to continually pulse design efficacy through assessment processes and to evaluate feedback from employers as to the level of preparation to perform design that they see in graduates from the program.

7. Summary

Technical design reviews are an important part of engineering practice and therefore vital to the experiences of engineering students. Because application of design reviews varies markedly in capstone design courses, engineering educators need to consider the importance of TDRs to student preparation and the value that may be gained from well-implemented design reviews. Three important benefits are described below.

1. Design Quality. As with the industrial TDR process, the capstone TDR process is used to verify and validate that the design satisfies sponsor requirements accurately and fully within constraints (including regulatory requirements) without causing harm to the public.
2. Experiential Learning of Professional Skills. The capstone TDR process mimics the industrial TDR process. Students develop familiarity with the TDR process as a minimum and can learn oral and written communication skills related to communicating design. Of particular importance in the capstone TDR process may be the opportunity to recognize the problem solving processes associated with having a design and/or design method critiqued by the TDR panel in a way that causes the student team to recognize weaknesses and strengths.
3. Assessment Data. The capstone TDR process provides an opportunity to collect ABET assessment data through the use of associated rubrics used in performing a TDR. TDR questions can be aligned with different KSAs and ABET outcomes to provide scores for the corresponding outcomes.

For two-semester capstone courses, three to four design reviews seem to be appropriate. This paper describes three important design reviews that can be implemented easily in a two-semester project course:

- Problem definition review
- Conceptual design review
- Final design review

For each of these reviews, a set of review questions is proposed for use, and items of importance are identified to guide scoring of student responses. Thus, this paper provides a framework for conducting technical design reviews in capstone design courses.

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