Rigorous Design Reviews for Capstone Design Projects

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Abstract

Efficacy of design is vital to the success of engineering professionals. A question of importance to engineering educators is: How well are undergraduate students prepared to be thorough and competent in engineering design? This paper identifies factors proven important to design in professional practice for application areas such as biomedical and aerospace, where human life depends upon design efficacy. These factors provide focus for conducting design reviews with students to ensure the adequacy of their design work and to prepare them for rigorous reviews they will face in their professions.

Design reviews are used extensively in professional engineering settings to ensure the efficacy of design at critical stages of solution development: problem definition, concept selection, and solution completion. The paper defines procedures for effective design reviews, along with questions to be addressed and scoring rubrics for assessing the adequacy of design work. These design review tools should enable design educators to more effectively assess student design work and provide students helpful guidance for improving the quality of their designs. These reviews are applicable across a range of engineering disciplines, project types, and institutions.

Background

The world depends upon the engineering profession to address some of the great challenges facing people in the twenty-first century[1]. The National Academy of Engineering has defined abilities seen as vital to effective engineering in coming years[2]. Engineering program accreditation incentivizes some, but not all, of these abilities. Engineering programs must demonstrate that graduates have achieved a level of ability in eleven or more outcomes, many of which should contribute to their ability to design effective solutions to technical challenges. Design ability is defined by ABET 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[3].

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[4,5]. 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. These projects also provide an environment for obtaining authentic assessments of student achievement of knowledge, skills, and professional abilities.

When engineers fail in their design work, the world sees impacts that may include major economic losses, environmental disasters, and loss of life. 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[6] and Department of Defense design control regulations[8] provide examples from which we learn about critical issues in design practices and find guidelines for effective design reviews. From their design controls, we can extract design review procedures, questions, and criteria for judging adequacy of design processes and products.

This paper defines issues important to design reviews and presents tools for performing effective design reviews. First, FDA design control documents are analyzed to identify issues of greatest importance to design reviews; this leads to procedures for making design reviews most effective. Next, major issues are identified for important design development stages; these lead to sample questions to probe the issues of interest. Finally, scoring rubrics are defined for responses to each question, leading to decisions on adequacy of design at the time of a design review.

Issues of Importance to Design

The Food and Drug Administration has established the Quality System Regulation (QSR) to ensure that good manufacturing practices are followed for medical devices. These regulations provide a framework that manufacturers must use when developing and implementing design controls to "ensure that good quality assurance practices are used for the design of medical devices and that they are consistent with quality system requirements worldwide." [6]

What are design controls? FDA guidelines state that "Design controls are an interrelated set of practices and procedures that are incorporated into the design and development process, i.e., a system of checks and balances. Design controls make systematic assessment of the design an integral part of development. As a result, deficiencies in design input requirements, and discrepancies between the proposed designs and requirements, are made evident and corrected earlier in the development process. Design controls increase the likelihood that the design transferred to production will translate into a device that is appropriate for its intended use."[6]

From the design controls perspective, the development process is depicted by a traditional waterfall model. (See Figure 1). The design proceeds in a logical sequence of phases or stages: requirements are developed, and a device is designed to meet those requirements. Design controls guide this entire process. The design is then evaluated, transferred to production, and the device is manufactured. Feedback paths are required between each phase of the process and previous phases, representing the iterative nature of product development.

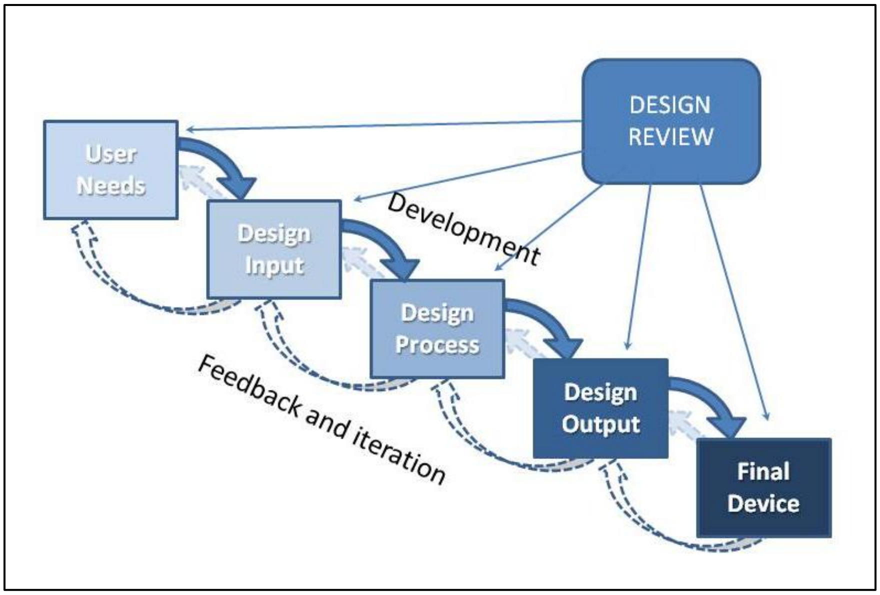

Figure 1. Waterfall model for development process (adapted from FDA 1997)

The terms "verification" and "validation" possess specific meanings in design reviews [FDA 320.30(f)]. As illustrated in Figure 2, verification is an internal set of checks and balances, while validation is a set of checks with the intended users. Design verification is rigorous investigation to determine that a design output meets the design input requirements or specifications. Verification shows that the designers have achieved their targeted specifications as defined for this stage of the design and development process. The verification process used and findings of the review must be documented in project records. On the other hand, design validation is the use of objective evidence to demonstrate that requirements for a product or process to perform in a specific intended use can be consistency fulfilled. Validation takes the design output back to the intended users to determine that the output meets their needs for specific applications.

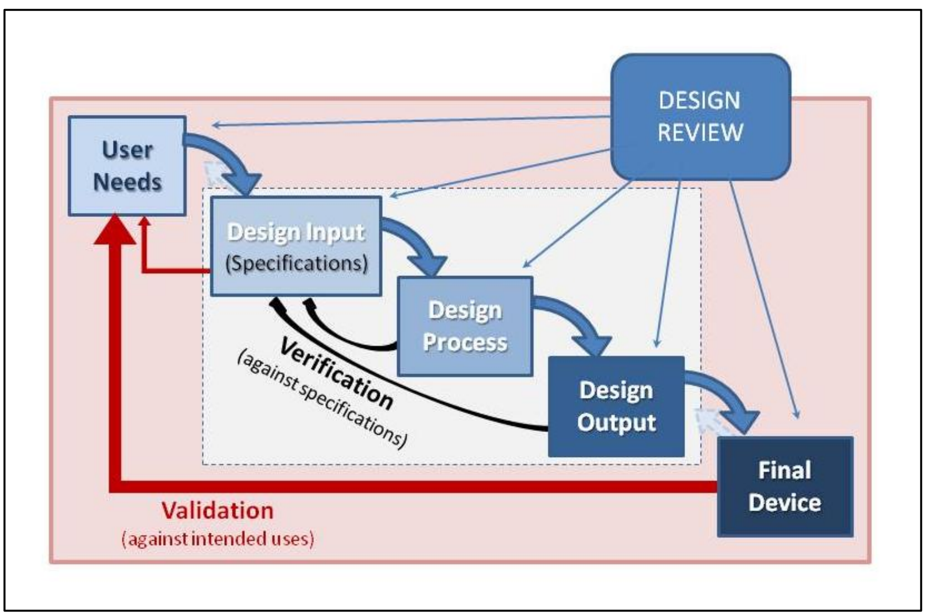

Figure 2. Verification and validation within design reviews

The design input and verification of design outputs are very important for achieving design control. When the design input has been reviewed and the design input requirements are determined to be acceptable, an iterative process of translating those requirements into a device design begins.

The first step is determining user needs and validating that they indeed represent desires of users for their intended applications of the final design solution. The next step is conversion of the requirements into system or high-level specifications. Upon verification that the high-level specifications conform to the design input requirements, they become the design input for the next step in the design process, and so on. This basic technique is used repeatedly throughout the design process: Each design input is converted into a new design output; each output is verified as conforming to its input; and it then becomes the design input for another step in the design process. In this manner, the design input requirements are translated into a solution conforming to those requirements.

Table 1 summarizes important verifications and validations and groups these into three design reviews appropriate for capstone design projects. The design reviews are conducted at natural milestones in the design process. For example, the first design review is conducted to ensure that the design input requirements are adequate, they are converted into representative design specifications, and these specifications adequately reflect needs and intended uses of the solution. The second review is used to ensure that the concept selected adequately meets specifications and offers potential to become a useful solution. The final review ensures that the detailed design is supported by evidence that it meets solution specifications; it also is validated by users before it is approved for production. Generally, design reviews provide assurance that a phase has been completed in an acceptable manner, and that the next phase can begin.

Table 1. Design reviews and corresponding design verifications and validations

Design Review	Type	Purpose
Problem Scoping (Preliminary) Design Review	Verification of design input	• Check that design input adequately represents user needs
	Verification of specifications	• Check that system-level specifications align with design input
	Validation of specifications	• Check that system-level specifications align with users' intended applications of solution
Concept Generation (Interim) Design Review	Verification of solution concept	• Check that concept generation and selection process is adequate • Check that solution specifications represent desired conditions • Check that selected concept meets system-level specifications
Solution Realization (Critical) Design Review	Verification of final solution	• Check that development process is adequate to be credible • Check that solution specifications represent necessary conditions for desired applications • Check that final solution achieves solution specifications
	Validation of final solution	• Check that final solution meets expectations in intended applications

Rigorous design reviews found in engineering practice set expectations for the knowledge, skills, and attitudes engineering students should demonstrate when completing a capstone design experience. The following sections define design reviews suitable for implementation in major design projects at the end of three critical stages of design: problem scoping, concept generation, and solution realization.

Problem Scoping Review

The first design challenge in a student design project is properly scoping the design problem to be addressed. Students must understand the limits of the problem they will address and the requirements that must be satisfied for a useful design solution. They must have agreement with project stakeholders (instructor, project advisor, expected users, investors, etc.) on the extent of the project, what is and is not to be addressed, resources available, cost and performance expectations on the solution, required deliverables, responsibilities of parties involved, etc. A design review at the end of the problem scoping stage of the project should examine the processes used in this stage as well as the outputs (system-level specifications) of the stage. The following paragraphs detail the respective questions to be asked and factors to be considered in scoring the adequacy of the designers' responses.

QUESTION: How adequate is information gathering for understanding the problem or opportunity? The first question for problem scoping probes the adequacy of the design team's information gathering. Did they consider all sources that might shed light on the real challenge? To what extent did they seek information that explains desired functionality of the solution, its initial or lifetime cost, how it needs to be implemented and maintained, or ways in which it interfaces with human needs to provide safety and satisfaction? Did the students identify and obtain appropriate information to understand regulations or standards important to this type of solution? In short, do they really understand the problem and the expectations of stakeholders?

The metric proposed for judging adequacy of information gathering is shown in Table 2. The types and credibility of information sources are examined. Identified needs must be broad enough to address solution function, cost, implementation, and human/social impact issues. Relevant regulations and standards must be properly identified and adopted. Because documentation of information gathering is absolutely essential, the maximum score for each question is five points, two of which reflect documented support for the students' response.

Table 2. Questions and scoring for information gathering

INFORMATION GATHERING: *How adequate is information gathering for understanding the problem or opportunity?*							
		Acceptability Score			**Documentation**		
Probing Question	**Addressed in Response**	***1 Unacceptable***	***2 Acceptable***	***3 Outstanding***	***0 Little***	***1 Marginal***	***2 Complete***
List **information sources** you used to determine needs and expectations for your solution.	□ Possible users: □ Other people: □ Patents, copyrights or products: □ Reports or studies: □ Rules, policies, standards:	Few, narrow, or unreliable sources	Moderate variety and credibility in sources	Widely varied, necessary, and authoritative sources	Very little record; unclear on sources	Sporadic, some well-defined sources	Complete, dated, full citations on sources
Show examples to illustrate the **breadth** of the needs and expectations you identified.	□ Physical characteristics: □ Functional performance: □ Financial constraints: □ Building, servicing, disposal issues: □ Human, societal concerns:	Few, narrow, unclear, or unbelievable	Moderate variety, clarity, importance, credibility	Comprehensive, clear, important, authoritative	Very little record, unclear needs	Mixed record, some clear needs	All clear, well-defined needs
What **regulations** or **standards** apply to development or use of your solution?	□ Health or safety: □ Environmental: □ Manufacturing: □ Other:	Missing important ones	Suitable but not complete	Thorough, correct, valuable	No record of attempts	Vague, weak definitions	Fully referenced & quoted

QUESTION: How adequate is understanding of project scope, solution, and impact? A design team must be able to articulate their problem and its envisioned solution concisely and with relevance to an audience. The team's problem statement or "elevator pitch" should explain to a specific audience the problem or opportunity being addressed, central features of the envisioned solution, and benefits important to the audience – all in approximately thirty seconds. The metric proposed for measuring the adequacy of this elevator pitch is presented in Table 3.

Table 3. Questions and scoring for elevator pitch

PROBLEM STATEMENT: *How adequate is understanding of project scope, solution and impact?*							
		Acceptability Score			**Documentation**		
Probing Question	**Addressed in Response**	***1 Unacceptable***	***2 Acceptable***	***3 Outstanding***	***0 Little***	***1 Marginal***	***2 Complete***
In 30 seconds or less, summarize the **need** you are addressing, your envisioned **solution**, and **benefits** it will deliver.	□ Clear, compelling need: □ Need connects with audience:	Unimportant or unclear need	Moderate need, clearly stated	Great need; urgent; motivates action	Very little record; unclear	Single acceptable entry	Clear, refined, prominent
	□ Solution fits stated need: □ Solution is achievable:	Vague or unlikely solution	Relevant, maybe feasible solution	Great solution; very likely achievable	Very little record; unclear	Single acceptable entry	Clear, refined, prominent
	□ Promises real benefits to users: □ Promises potential broader benefits:	Unclear or unlikely benefits	Probable benefit to users, others?	Likely big benefits to users & others	Very little record; unclear	Single acceptable entry	Clear, refined, prominent

QUESTION: How adequate are system-level solution specifications? The design team must be able to translate needs and desires of stakeholders into engineering specifications for the solution to be developed. This set of specifications will serve as criteria for successive stages of solution development, so they must sufficiently represent needs while also providing testable conditions against which solution concepts can be evaluated. At this stage of design, system-level specifications are reviewed because they are essential to the development of the conceptual design stage coming next. The problem scoping design review must examine the process used for conversion of needs into specifications—identification of appropriate types of requirements and setting target values or states to be achieved. The specifications also must be broad enough to encompass functional, cost, implementation, and human/societal concerns. Because validations require objective evidence, specifications must be testable or observable. An important part of specifications development is the realization that specifications must be continually reviewed and revised as new information becomes available.

Table 4 presents questions and scoring definitions for measuring the adequacy of system-level solution specifications. The first question explores the thoroughness of the process used to derive specifications from identified needs. Next the breadth of these specifications is reviewed to determine if they encompass all appropriate types of specifications. Specifications are reviewed for their ability to yield objective evidence of achievement, making them useful in future design reviews. Finally, the design team is asked to tell how specifications will be used in succeeding steps of the design process –probing the team's valuing of specifications and realization that specs are subject to ongoing review and revision.

Table 4. Questions and scoring for system-level solution specifications

SYSTEM-LEVEL SPECIFICATIONS: *How adequate are system-level solution specifications?*							
		Acceptability Score			**Documentation**		
Probing Question	**Addressed in Response**	***1 Unacceptable***	***2 Acceptable***	***3 Outstanding***	***0 Little***	***1 Marginal***	***2 Complete***
What **process** (steps) did you use to define solution requirements or specifications (specs)?	□ Synthesis of needs: □ Prioritization of needs: □ Conversion to specifications: □ Selection of targeted state/value: □ Validation of specs with stakeholders:	Unclear or very incomplete process	Moderately complete and clear process	Very complete, clear, and rigorous process	Very little record; unclear process	Sporadic record, parts of process	Complete, record of process & issues
Show examples to illustrate the **breadth** of your solution specifications.	□ Physical or function: □ Production or service: □ Financial or value: □ Safety or societal:	Very narrow; important types missing	Important types included, some barely adequate	Comprehensive inclusion of all important types	Very little record, not coherent	Mixed, some parts coherent	All clear, complete, coherent
Show two of your specifications that are **testable** and **central** to user expectations.	□ Clear and relevant: □ Allows creativity: □ Testable: □ Conforms to needs and uses:	Marginally understandable ; few testable	Understandable ; most relevant and testable	Very clear; vital to success, testable; allow creativity	No record of attempts	Vague, weak definitions	Fully referenced & quoted
Explain how specs will be **used/changed** in future design effort.	□ Criteria for design decisions: □ Basis for verifying solution: □ Evolve as project progresses:	Vague use in design effort	Clear use in design decisions	For decisions & evaluation; refine by new information	No context given for specs	Tied to design process	Focus for reviews; revised

An effective review of problem scoping positions a design team to advance to the concept generation stage of their design project.

Concept Generation Review

Once solution specifications are established and approved to guide solution development, the design team commences to generate a conceptual design solution that meets specifications. Students must be thorough in their search for relevant ideas that may grow into the elements of a solution. They must follow systematic process steps to screen and select ideas, improve upon them, and synthesize them into a solution concept. Before proceeding to the next design stage, the team must be able to articulate an improved problem statement and revised solution specifications that will guide and test the outcomes of the detail design phase of solution development. Questions and scoring definitions for review of the concept generation work are presented in the following paragraphs.

QUESTION: How adequate is idea generation for solution concepts? Adequate idea generation is essential for building a base of good and varied ideas that can lead to a creative, competitive, and effective solution. Good ideas can come from other existing solutions (patents, competing products, other applications with relevant elements, etc.), from people expert in the field, from team member creative ideas, and other sources. Generating ideas requires a process that includes: a team culture that encourages creativity, being diligent to capture all ideas, and using strategies that stimulate out-of-the-box thinking. An effective idea generation stage will produce many ideas, some truly creative ideas, and a wide range of ideas. Table 5 presents questions and defined scoring for the idea generation activity as part of concept generation.

Table 5. Questions and scoring for idea generation

IDEA GENERATION: *How adequate is idea generation for solution concepts?*							
		Acceptability Score			**Documentation**		
Probing Question	**Addressed in Response**	***1 Unacceptable***	***2 Acceptable***	***3 Outstanding***	***0 Little***	***1 Marginal***	***2 Complete***
What **sources** did you use to identify ideas for your design?	□ Other designs: □ Knowledgeable people: □ Member creativity: □ Other:	Few, narrow, or irrelevant	Moderate variety and relevance	Widely varied, relevant, credible	Very little record; unclear on sources	Sporadic, some well-defined sources	Complete, dated, full citations on sources
Describe your **process** for "brainstorming" to generate ideas for your design.	□ Encouraging creativity: □ Recording ideas: □ Building on ideas: □ Other:	Few efforts; not purposeful; not engaging	Specific times; clear purpose; useful process	Many purposeful, valuable, varied, engaging efforts	Very little record; unclear process	Sporadic record, parts of process	Complete, record of process & issues
Show your **results** (ideas) from idea generation efforts.	□ Large number of ideas: □ Creative or out-of-box ideas: □ Varied yet relevant ideas:	Few ideas; little creativity	Moderate number; some creativity	Many ideas; very creative ones; good relevance	No record of ideas	Incomplete record of ideas	Very complete record

QUESTION: How adequate is development and acceptance of a solution concept? Concept development and acceptance activities draw from ideas generated to identify the best ideas for components of the solution, integrate components into a whole concept, and accept the concept as one that satisfies solution specifications. Both the process and the outcomes of this design phase must be rigorous to ensure that the best ideas are identified and that they are selected, integrated effectively, and the whole checked to ensure that it satisfies design requirements.

Table 6 presents questions and definitions of scoring for concept development and acceptance. First the process is reviewed to determine the extent to which it uses criteria (specifications) to screen and select the best ideas, and how well it combines and refines ideas as it synthesizes them into a full conceptual solution. How well is the solution concept verified by testing it against the solution specifications? The rigor of the selection process is probed through an example of component selection provided by the design team. The concept is checked for acceptance by a review by project stakeholders to ensure that it has potential to satisfy needs for desired applications (i.e., concept validation).

Table 6. Questions and scoring for concept development and acceptance

CONCEPT SELECTION: *How adequate is concept development and acceptance?*							
		Acceptability Score			**Documentation**		
Probing Question	**Addressed in Response**	***1 Unacceptable***	***2 Acceptable***	***3 Outstanding***	***0 Little***	***1 Marginal***	***2 Complete***
What **process** (steps) did you use to evaluate and improve ideas for your design?	□ Criteria-based evaluation of ideas: □ Combination and refinement of ideas: □ Synthesis of concept from components: □ Verification of concept against specs:	*Ad hoc* process or not by team consensus	Moderately complete and clear process	Very complete, clear, and rigorous process	Very little record; unclear on sources	Sporadic, some well-defined sources	Complete, dated, full citations on sources
Show an example of a **rigorous** evaluation of competing ideas for a specific component.	□ Used criteria (specs) as basis: □ Used data in evaluation: □ Discussion by all members: □ Concept validated with overall goal:	Vague criteria; no data; little discussion	Scored ideas by criteria; member involvement	Data guides team consensus scoring; reality checking	Very little record; unclear process	Sporadic record, parts of process	Complete, record of process & issues
Explain why your selected solution **concept is "best"** among other options.	□ Meets key specs: □ Well integrated, simple: □ Supported by data or models: □ Concept validated by users:	Vaguely justified; lacks data, validation	Some evidence that specs met; parts integrated	Well integrated; simple; specs met per data & users	No record of ideas	Incomplete record of ideas	Very complete record

QUESTION: How adequate is understanding of problem status and specifications? At the conclusion of concept generation, a design team should possess deepened understanding of the project being addressed, its status, and the specifications to be satisfied. Thus, the design review should also probe their current understanding of these issues and how these impact the next stage of development. Table 7 presents questions and scoring definitions for addressing these issues.

Table 7. Questions and scoring for project status and solution specifications

PROBLEM STATUS: *How adequate is understanding of problem status and solution specifications?*							
		Acceptability Score			Documentation		
Probing Question	Addressed in Response	*1 Unacceptable*	*2 Acceptable*	*3 Outstanding*	*0 Little*	*1 Marginal*	*2 Complete*
In 30 seconds or less, summarize the **need** you are addressing, your envisioned **solution**, and **benefits** it will deliver.	□ Clear, compelling need: □ Need connects with audience:	Unimportant or unclear need	Moderate need, clearly stated	Great need; urgent; motivates action	Very little record; unclear	Single acceptable entry	Clear, refined, prominent
	□ Solution fits stated need: □ Solution is achievable:	Vague or unlikely solution	Relevant, maybe feasible solution	Great solution; very likely achievable	Very little record; unclear	Single acceptable entry	Clear, refined, prominent
	□ Promises real benefits to users: □ Promises potential broader benefits:	Unclear or unlikely benefits	Probable benefit to users, others?	Likely big benefits to users & others	Very little record; unclear	Single acceptable entry	Clear, refined, prominent
How do you see your project status relative to the schedule?	□ Realistic assessment: □ On or nearly on schedule:	Very unrealistic OR far behind	Somewhat realistic AND not far behind	Accurate AND on schedule	No record of status vs. schedule	Some schedule tracking	Detailed monitoring of schedule
How has your problem definition changed during concept selection?	□ Better vision for solution: □ Improved specifications: □ See specs-solution in dynamic balance:	No changes in understanding or definitions	Minor new understanding of solution or requirements	Rich new learning about solution and specifications	No reflection or revisions to problem definition	Some review OR revision to specs	Distinct review & revision to specs

Completion of a design review for the concept generation stage of the project positions the design team to proceed with confidence that their solution is progressing toward a well-justified solution that will be acceptable to principal stakeholders. Thus, the review gives assurance to all that the design outcomes will not be a surprising disappointment in the end.

Solution Realization Design Review

The solution realization design review examines processes used and outputs from the detail design process. During the solution realization stage, the design solution is defined in detail, prototypes constructed and tested, specific component parts specified for purchase, others parts specified for fabrication, and test results made ready for review. This review seeks to examine the thoroughness of the development process, the extent to which important solution specifications are achieved, and the extent to which users are convinced that the solution will successfully perform in their specific applications. The solution realization design review determines if the solution requires more development or testing before being approved for initial stages of manufacturing.

QUESTION: How adequate are elevator pitch and solution specifications? By the time the solution has been defined and tested, the design team should have a thorough understanding of the problem, their solution, and its broad impact. They also should have thoroughly tested definitions of the specifications they must satisfy. Thus, the solution realization design review begins with a review of the team's elevator pitch and solution specifications.

Table 8 presents questions and definitions of scoring for the elevator pitch and solution specifications at the end of solution realization. First the elevator pitch is reviewed for its effectiveness in motivating audience interest, describing a good-fit solution, and promising broad and beneficial impacts. Next, the team is asked how they have checked the validity of their solution specifications (meeting needs of users). Then they are asked to present examples of specifications for solution function, financial expectations, implementation issues, and human safety and concerns—a sample that reveals the quality of their solution specifications.

Table 8. Questions and scoring for elevator pitch and solution specifications

PROBLEM DEFINITION: *How adequate are elevator pitch and solution specifications?*							
		Acceptability Score			**Documentation**		
Probing Question	**Addressed in Response**	***1 Unacceptable***	***2 Acceptable***	***3 Outstanding***	***0 Little***	***1 Marginal***	***2 Complete***
In 30 seconds or less, summarize the **need** you are addressing, your envisioned **solution**, and **benefits** it will deliver.	□ Clear, compelling need: □ Need connects with audience:	Unimportant or unclear need	Moderate need, clearly stated	Great need; urgent; action motivated	Very little record; unclear	Single acceptable entry	Clear, refined, prominent
	□ Solution fits stated need: □ Solution is achievable:	Vague or unlikely solution	Relevant, maybe feasible solution	Great solution; very likely achievable	Very little record; unclear	Single acceptable entry	Clear, refined, prominent
	□ Promises real benefits to users: □ Promises potential broader benefits:	Unclear or unlikely benefits	Probable benefit to users, others?	Likely big benefits to users & others	Very little record; unclear	Single acceptable entry	Clear, refined, prominent
How sure are you that specs align with needs of stakeholder? Why?	□ Ongoing communication and revisions: □ Final specs validation: □ Other:	No review of specs with stakeholders	Check with stakeholders before end	Ongoing and final check with stakeholders	Reason for quality not documented	Some record of process	Process and result recorded
State an important specification for **functionality**	□ Important: □ Correct/accurate: □ Well-stated:	Not important OR weak OR incorrect	Moderate importance AND useful	Important, correct, well-stated	Spec not recorded	Spec recorded unclearly	Spec clear and prominent
State an important specification for **cost or financial return**	□ Important: □ Correct/accurate: □ Well-stated:	Not important OR weak OR incorrect	Moderate importance AND useful	Important, correct, well-stated	Spec not recorded	Spec recorded unclearly	Spec clear and prominent
State an important specification for **repair or endurance**	□ Important: □ Correct/accurate: □ Well-stated:	Not important OR weak OR incorrect	Moderate importance AND useful	Important, correct, well-stated	Spec not recorded	Spec recorded unclearly	Spec clear and prominent
State an important specification for **safety or human well-being**	□ Important: □ Correct/accurate: □ Well-stated:	Not important OR weak OR incorrect	Moderate importance AND useful	Important, correct, well-stated	Spec not recorded	Spec recorded unclearly	Spec clear and prominent

QUESTION: How adequate are processes used in solution development and testing? Processes used in the development of the final solution and its testing are critical for ensuring that analysis is done thoroughly, components are selected carefully, risk and failure are addressed, and testing has proven achievement of specifications. Inadequate processes can lead to improper test results and incorrect decisions, which in turn produce products that fail and create serious damage or harm. Strong processes give credibility to the outcomes from the solution realization work.

Table 9 presents the questions and scoring definitions for use in a solution realization design review. First, the design team is asked to identify methods used to advance the design solution – revealing the appropriateness and rigor of methods and information sources used. A question about iteration provides a way to probe students' purposefulness in use of iteration and gains they achieved from iteration—revealing metacognitive elements of their design effort. The question about their approach to dealing with potential failures reveals the rigor in which they identified and addressed the most likely causes of failure—revealing how prone to failure the solution might be. The question about a rigorous test procedure for verifying achievement of a specification provides a sample from which the rigor of their testing can be judged. In total, the scoring of these processes gives a measure of the rigor in their design processes for the solution realization stage of development.

Table 9. Questions and scoring for solution development and testing process

SOLUTION REALIZATION: *How adequate are processes used in solution development and testing?*							
		Acceptability Score			**Documentation**		
Probing Question	**Addressed in Response**	***1 Unacceptable***	***2 Acceptable***	***3 Outstanding***	***0 Little***	***1 Marginal***	***2 Complete***
What **methods** did you use to develop and advance your concept to a final design?	□ CAD or other models: □ Prototyping: □ Research or expert input: □ Other:	*Ad hoc* methods; no engineering tools used	Suitable use of engineering design tools	Competent use of engineering tools & resources	Very little record; unclear on methods	Sporadic, some tools OR methods	Complete record of methods & tools
Give an example to show how revision or **iteration** was vital to your design process.	□ Problem recognized, forced revision: □ Criteria used to guide revision: □ Learning articulated: □ Improvement achieved:	No iteration OR futile struggles to fix problems	Some clear effort to revisit & improve design	Actions to learn & revise work; achieved major improvement	Very little record; unclear process	Sporadic record, parts of process	Complete, record of process & outcomes
What steps have been taken to minimize **likelihood** of solution **failure**?	□ Sources of failure identified: □ Risks quantified: □ Risks reduced:	No risk identification or assessment	High risks identified; steps to reduce risk	Risks assessed; risks strategically reduced	No record of risks or reductions	Some risks recorded as such	Record of process and results
Show an example of a **rigorous** test used to verify achievement of a specification.	□ Proper outcome measured: □ Suitable test procedure: □ Proper analysis, interpretation: □ Desired achievement verified:	Vague effort to test; no clear process or definitive result	Defined testing process; results used properly in evaluation	Sound testing & analysis; results verify vital specs achievement	No record of tests or results	Incomplete record of tests and results	Thorough record of tests and results

QUESTION: How adequate is the final design solution? A rigorously proven design solution must achieve solution specifications (solution verification) and must convince users that it will perform as they desire in specific applications (solution validation). It must be supported by objective evidence for its achievement of all important solutions specifications. It must also have received approval, with objective evidence, that its performance in specific applications of interest to users meets their expectations. Thus, this design review requires detailed descriptions of the design solution as well as test data designed to document how well individual solution specifications are met by the solution.

Table 10 presents questions and definitions of scoring for the final design solution. First, the design team is asked to identify specifications which they believe are most important to the solution – revealing that a verified solution will be aligned with these critical specifications. Then, objective evidence (e.g., analysis, simulations, test results, surveys, research findings) is requested to verify that example specifications have been achieved for different types of needs. These latter questions also check to see if validation with users is part of the evidence presented. Finally, the team is asked to identify an aspect of the project that is inadequate and to explain how this should be addressed—revealing possible weaknesses and whether they are fixable. Scores for this set of responses give objective evidence for specifications validation and for solution verification and validation—a very rigorous review process.

Table 10. Questions and scoring for final design solution

PROPOSED SOLUTION: *How adequate is the final design solution?*							
		Acceptability Score			**Documentation**		
Probing Question	**Addressed in Response**	***1 Unacceptable***	***2 Acceptable***	***3 Outstanding***	***0 Little***	***1 Marginal***	***2 Complete***
What are the most valuable **features** of the proposed solution?	□ Centrality to need or opportunity: □ Innovation or proven superiority: □ Other:	Little value or value not where needed	Moderate value to meet need	Significant value for need and competitiveness	Vague record of features	Acceptable record of features	Excellent records of features
Give **evidence** that solution achieves a vital **functionality** specification.	□ Analysis or simulation: □ Model or prototype testing: □ User validation:	Not achieved or no evidence or not credible	Reasonable evidence of achievement	Solid evidence & user validation of vital achievement	No record of tests or results	Incomplete record of tests and results	Thorough record of tests and results
Give **evidence** that solution achieves a vital **financial** specification.	□ Analysis or simulation: □ Market research: □ User validation:	Not achieved or no evidence or not credible	Reasonable evidence of achievement	Solid evidence & user validation of vital achievement	No record of tests or results	Incomplete record of tests and results	Thorough record of tests and results
Give **evidence** that solution achieves a vital **technical** specification.	□ Analysis or research: □ Model or prototype testing: □ User validation:	Not achieved or no evidence or not credible	Reasonable evidence of achievement	Solid evidence & user validation of vital achievement	No record of tests or results	Incomplete record of tests and results	Thorough record of tests and results
Give **evidence** that solution achieves a vital **societal/human** specification.	□ Compliance with codes/standards: □ Research or prototype testing: □ User validation:	Not achieved or no evidence or not credible	Reasonable evidence of achievement	Solid evidence & user validation of vital achievement	No record of tests or results	Incomplete record of tests and results	Thorough record of tests and results
Identify an outcome of the project that is **inadequate**. What must be done?	□ Clearly stated problem: □ Strong plan forward: □ Other:	Little understanding of issues or solution	Moderate understanding of issue and solution	Understood problem; solution clear & achievable	No or vague record of issue	Some record of issue, thoughts	Excellent record of issue & solution

In summary, the solution realization design review provides comprehensive evidence about the extent to which the design solution is valid for specific uses and is verified to meet specific design requirements. Information is also provided to support the rigor of design, improvement, and testing processes to give credibility to design judgments made. This review process informs the students about the adequacy of their design work and informs project stakeholders about the quality of design products. To the extent that the review processes are conducted in project environments that model professional practice, design reviews also provide authentic assessments of students' abilities to design products and processes in the professional workplace.

Benefits from Design Reviews

Design reviews offer five major benefits that can be gained by students, instructors, and degree programs.

1. Design reviews add authenticity of engineering practice to design projects conducted in academic environments. This authenticity motivates students to learn and perform and it builds in students authentic design and professional skills.
2. Design reviews focus on critical issues for guaranteeing solution quality. Reviews validate that stakeholder needs are addressed adequately in specifications and verify that the solution achieves these specifications.
3. Design reviews teach and assess design skills vital to engineering practice. Students display evidence that they have learned to validate specifications, generate concepts that meet specifications, and produce solutions that both meet specifications and satisfy users.

4. Design reviews teach and assess professional skills vital to engineering practice. They display evidence that they have learned to document design processes and outputs, self-assess and make improvements to performance, and plan and manage projects to deliver high quality outputs.
5. Design reviews enable effective and efficient assessment of design. Questions and scoring for design reviews simplify assessment and focus results on measures important to design—giving educators critical data and guiding students in their learning and performance at the same time.

The combined merits achieved by these reviews justify their use in major design projects. By implementing proposed design reviews, an instructor can simultaneously improve student learning of design and professional skills, improve quality of outputs from design projects, and obtain assessment data for both assigning project grades and for documenting student design outcomes achievement. The next section discusses practical issues related to the implementation of the proposed design reviews.

Design Review Guidelines

Procedures for conducting design reviews should be adapted to fit the context of design projects in the specific academic environment where they occur. The number and formality of design reviews should fit the time available. For example, in a yearlong design project, it may be appropriate to conduct a problem scoping design review and a concept generation design review in the first half of the year, and the final solution design review at the end of the year. However, in a one-semester project, the earlier reviews may be informal and lead up to one formal final solution design review at the end of the project.

The audience for a design review should include all involved parties, as appropriate. In all cases, the instructor and project advisors should be present, but other participants will depend upon the project. For example, an entrepreneurial project should include business and engineering representatives, as well as any potential investors and prospective users. A medical device project should include technical experts, clinical staff, investors, and patient representatives. Outside experts are always valuable participants because they elevate the level of the review and motivate students to address non-academic issues. Participants with diverse interests and expertise are important to keep the design team accountable in the many aspects of the project to ensure that it meets the many diverse requirements of the project stakeholders.

For design reviews to be practical and effective, the design team and reviewers need appropriate preparation and instruction. Designers (students) should know in advance the questions they will be asked and the types of documentation expected to support their responses. These individuals must know that they should be prepared to answer questions clearly, directly, with examples, and with suitable documentation. Reviewers must exercise discipline to follow the agenda of the review design review. They are expected to follow the question template but with flexibility to drill deeper or skim over parts, as appropriate. Reviewers must be focused on judging adequacy of design achieved and on providing constructive feedback to the design team.

A given design review should be orchestrated by a person who will keep the review on track to ensure that any design weaknesses are identified and that an informed judgment will result. This person must also focus the review discussions on factual information supported by documentation. Unless the design processes and products are documented as stated by the design team, they are not admissible as work accomplished by the team.

Outcomes of a design review include: (1) a judgment on readiness to proceed and (2) feedback to guide rework or next steps. Reviewers should submit to the review facilitator completed score sheets with identified deficiencies in the work reviewed. The reviewers should deliberate on whether the design work is adequate to support project continuation. Those with authority over the project will negotiate a decision and identify any deficiencies requiring rework. As appropriate, the reviewers should give oral feedback to the design team upon completion of the decision.

The review leader summarizes the decision and writes specific instructions for any required rework, as well as instructions for proceeding on the project. The team should receive a written report on the decision to proceed or not, and a brief summary of strengths and weaknesses perceived by the reviewers. If the team must complete remedial work, the report must list specific items to be completed and conditions to be satisfied before the team may proceed. All feedback documents (score sheets and written instructions) must become part of the team's design documentation.

Summary

This paper has presented a rationale for design reviews that can improve students' design learning and design performance, while also providing authentic measures of students' design competence. The proposed design reviews are the product of rigorous public scrutiny of critical design work affecting safety and human well-being. These design reviews are formal meetings in which focused questioning probes the design team's understanding of design, design activity, and design products – seeking to identify any weaknesses that may delay or stop the project. In order to proceed, all work must demonstrate sound research, problem definition, concept generation, decision making, evaluation, and compliance with stakeholder needs.

Three design reviews are suggested for major design projects in undergraduate engineering programs. The design reviews focus student and reviewer attention on critical issues for the design project so that poor quality design solutions do not slip through undetected. Students' responses to design review questions must be supported by design documentation. Students must demonstrate achievement by objective evidence such as test results, examples, engineering analysis, and stakeholder feedback. This rigorous review sharpens students' abilities to perform and defend design work of the highest quality. Because students are responding to design challenges they will face in professional practice, they learn authentic design skills and produce evidence for authentic assessment of design learning and performance. The proposed design reviews are applicable to many types of projects, either single discipline or multidisciplinary in nature, and conducted in widely ranging institutional settings.

Design educators are encouraged to adopt formal design reviews as described in this paper for the following reasons:

1. Design reviews are authentic to professional practice, so they motivate and prepare students for engineering practice and provide authentic assessment measures.
2. Design reviews focus attention on issues that determine success of design projects, thereby enhancing the likelihood of successful design project outcomes.
3. Because design reviews scrutinize project work throughout the project life, weaknesses can be detected early and improvements be made to enhance project success.
4. Templates provided for design reviews establish a format, provide questions, and define scores so that assessment is standardized for simplicity and for tracking improvement.
5. Because design reviews are based on best practices in engineering, assessment results may be seen as gold standards for promoting projects, programs, and students.

Adoption of design reviews offers potential to transform academic design experiences into authentic design experiences. Authentic design experiences yield authentic design skills and authentic assessment results.

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