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On the Impacts of Panel-based Technical Design Reviews during the Capstone Design Experience at James Madison University: From Implementation to Mixed-Methods Evidence*

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In the context of undergraduate engineering education, capstone design is the central and distinguishing activity required by all ABET accredited engineering programs. At James Madison University, the capstone design experience is a two-year experience where students are guided through key phases of the design process: planning and information gathering, system requirements, concept development, embodiment design, testing and refinement, and detailed design. To guide and facilitate students through capstone, Technical Design Reviews (TDRs) with expert panelists are implemented. TDRs occur each semester and focus on the following reviews: (1) System Requirements Review, (2) Preliminary Design Review, (3) Critical Design Review, and (4) Detailed Design Review. This paper presents details about the JMU Capstone Design Model, the TDR process, and evidence grounded in a mixed-methods approach to provide insight into the impacts of TDRs. Significant improvement and growth was measured in capstone documentation as a result of TDRs, in contrast to documentation prior to TDRs. Students' learning and reflections also showcased valuable benefits to TDRs, which have proven to be successful in facilitating both formative and summative assessment during the capstone design experience.

Keywords: capstone design; design reviews; engineering design process; mixed-methods; assessment

1. Introduction

Design is widely considered to be a central or distinguishing activity of engineering [1–2]. A good education in engineering design can give students the skills required to creatively solve real-world problems and create an opportunity for them to begin developing as engineering professionals. Since the late 20th century, engineering undergraduate curricula have reincorporated design course(s) to "facilitate practical engineering application" and to build upon the engineering science foundation [3]. The most common way engineering programs integrate practical design application is via capstone design experiences, which typically include a project and/or related coursework. As a result of ABET accreditation requirements for capstone design and industry calling for more practically trained engineers, these capstone design experiences continue to be revered as "the most important educational component in almost all undergraduate engineering curricula [4]."

Although the structure of capstone design varies widely across programs, all ABET-accredited programs must attempt to satisfy the following ABET requirement:

> *"Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs. Students must be prepared for engineering practice through a curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating appropriate engineering standards and multiple realistic constraints [5]."*

Although ABET requires that capstone design be a culminating learning experience, ABET does not specify what engineering design entails nor how engineering design or even capstone design projects are to be evaluated.

Evaluation of a capstone experience involves both the outcomes of the project (i.e., the artifacts produced) and individual student learning and contributions to the capstone team [6]. Capstone projects can be assessed by formative and/or summative means [7] through student peer evaluation and self-reflection, faculty advisement and mentoring, client reviews, industry panels, or other methods [7–8]. Often, capstone work is evaluated via both written documentation and oral communications [8].

The James Madison University (JMU) Engineering Department, which admitted its first class in 2008, was founded on the recognition that engineers are no longer constrained to disciplinary bound-

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aries, and instead, must work across disciplines as members of global communities and multidisciplinary teams [8–9]. The program offers a single undergraduate engineering degree that focuses on sustainable design and systems thinking through an innovative and adaptive Problem-based Learning (PBL) model [9–13]. At JMU, the capstone design experience spans two years or four semesters during junior and senior year [14–15].

The purpose of this paper is to measure the impacts of the newly established feature of using Technical Design Reviews (TDRs) during the two-year capstone experience at the Department of Engineering at James Madison University. Although there is a plethora of literature on engineering capstone experiences, from varying capstone models to assessment, there is not a plethora of literature on how TDRs throughout a capstone experience impact student learning and capstone project performance. It is not that TDRs do not exist during capstone experiences, but that literature on specific models with accompanying assessment is quite limited. The innovative aspects of the paper are on the use and measured impacts of TDRs, which are conducted by a panel of experts, which are described later in this paper. The guiding research questions of this study are:

(1) To what extent are capstone documentation, students' learning, and overall capstone performance impacted as a result of introducing Technical Design Reviews during a capstone experience?
(2) What are the impacts, benefits, and challenges to implementing Technical Design Reviews during a capstone experience?

Grounded in a mixed-methods approach, this study presents both quantitative and qualitative evidence in answering the two research questions. A mixed-methods approach is appropriate for this study because triangulation enables us to neutralize the disadvantages inherent in all types of methods, and different methods are needed to understand the complexities of social phenomenon such as how people learn and interact with their environments. More specifically, quantitative evidence of TDR impacts on project performance will include results from systematic evaluation of capstone reports prior to TDRs being a feature of the JMU capstone experience with capstone reports after TDRs were a part of the JMU capstone experience. Qualitative evidence includes thematic analysis (benefits and opportunities for improvement) of student responses in evaluating TDRs and self-reflecting on the TDR process. Further, lessons learned and recommendations about implementing TDRs are provided herein.

This study is relevant to engineering faculty teaching design courses, engineering faculty facilitating design projects, and faculty who contribute to the capstone experience in their programs. More specifically, both implementation and assessment details in this paper would be relevant to design educators, whether they are capstone-related or not. TDRs can be utilized to engage students in design projects, whether such projects are in one class or cornerstone design projects or capstone projects of any duration.

2. Literature review

The following literature review presents a range of current evaluation methods being employed in engineering design courses and then focuses specifically on the limited literature on technical design reviews methods for engineering capstone projects. The review explains the benefits technical design reviews can have on students, faculty, and engineering programs.

Evaluation is a critical step of engineering capstone and design projects. While ABET criteria is important to the success of certified universities, "Program Outcomes" is one of the toughest areas for engineering programs to demonstrate success. As a result, a variety of evaluation is used to analyze student performance [16]. The capstone design literature includes numerous examples of evaluation and assessment criteria and methods applied to capstone design projects [4, 6–7, 14 –17]. Surveying and interviewing of university faculty at multiple institutions found that there are a variety of stakeholders who participate in or use the results of capstone project assessment [18]. Faculty (as advisors, coaches, or experts), administrators, students, and industry sponsors/clients all may play a role in project evaluation, often through oral presentations. The assessments can serve as feedback to capstone faculty on students' performance, as information to non-capstone faculty like administrators for reporting purposes, or as feedback to help capstone students monitor their progress. A variety of methods are used to assess capstone, typically multiple times throughout the projects, but the most common are oral presentations followed by written reports and peer assessment of oral presentations [18–21]. Faculty usually evaluate project outcomes using these reports, although the process of evaluation is not specified [21]. A panel of engineering faculty can also be used for evaluating student and team performance, along with peer review, in an oral presentation setting [21]. An example of such a panel includes faculty, the design course instructor, and a professional engineer in the workforce [21]. Most capstone evaluation is given through periodic feedback [22–23]; however, assessments and evaluations may only be completed twice, once mid-program and once at the end of the program [23]. The occurrence of multiple assessments implies that capstone teams receive both formative and summative feedback, intended to monitor and guide progress and then evaluate outcomes respectively. Evaluation scoring varies, as some programs focus on evaluation of the design process, the communication of the design, student performance, and/or team performance to meet the objectives of the program [23]. In order to adequately prepare engineering professionals, it is important to assess both design product and a team's design process [24].

A rising method of evaluation used by universities and explained throughout several design textbooks is the technical design review (TDR). A design review is an assessment of design, used to verify the feasibility of a design concept or achievement of project requirements [25–26]. In product design, the reviewing of a concept tests that the design is "physically realizable" and "economically worthwhile" [25]. Overall, the constructive format of a design review allows feedback to be obtained easily by the team [27]. The design review process involves what goes into the review, what happens during the review, and what follows the review [25]. The design review(s) can be used as both formative assessment [24, 28–29] but more commonly as summative assessment [22, 30–33]. In general, there is a lack of literature on formative assessment of capstone design projects [31] and no reporting beyond anecdotes on the effectiveness or impacts of design review panels, in particular, for shaping design project outcomes.

Technical design reviews often involve design review panels, used to assess the design presented and the ability of the students presenting [31]. There is no set form for a design panel, although panels usually consist of people from a variety of roles, such as industry representatives, graduate students, sponsors/clients, design course instructors and other faculty [22, 26, 31]. A design review often uses the panel to review written reports, oral presentations, and/or prototypes and provide feedback. Design reviews can occur live in an interactive manner involving questions and answers with the teams [34] or from pre-recorded presentations [32]. In either case, a panel can score the quality of the design and decisions made, as well as student performance [23, 29]. A freshman engineering design course uses design reviews to evaluate student projects and consists of written reports, oral presentations, and question-answer feedback sessions [29]. Feedback in a question-answer discussion setting gives immediate feedback to the students on their performance and design [34]. Design review feedback is often documented for the benefit of the project, noting improvements and conclusions from the panel [29–35]. Student reflections on design reviews helps students evaluate their own performance for future design reviews and how to progress in their project. Based on qualitative interview and observation data, successful design teams prepared for the design reviews using self-assessment and input from the project coach and then reflected on the design reviews and incorporated feedback and suggestions as they moved forward [24].

The frequency of TDRs throughout a project can vary depending on the length of the project (i.e., one, two, or more semesters) and the purpose of the reviews, either formative or summative assessment. Typically, a review is valuable after each design stage or major design task [29, 36]. Cornerstone projects in a freshman design class consisting of one semester used design reviews twice throughout the projects, once during midterm and once at the end of the term [30]. Depending on the duration of the project, reviews could take place four to five times in a single semester [28]. Dieter and Schmidt recommend reviews occurring between three and six times in the duration of a project, with the minimum being a beginning, midterm, and end term design review [25].

3. James Madison University capstone design experience

The capstone design model at James Madison University (JMU) provides students with four successive semesters working on the same design project, and a technical design review model was recently implemented to assist students with progressing through the design process and to critically assess their design decisions. The JMU Capstone Model and the Technical Design Review process are described in sections 3.1 and 3.2 respectively.

3.1 Overview of JMU Capstone design model

The decision to design a four-semester capstone experience was driven by the fact that a longer duration capstone project would enable students to apply the engineering design process more thoroughly in both breadth and depth, while yielding modern professional skills [36]. Previous publications detail the content coverage of the courses that align with the capstone design experience at JMU [37]. In short, there are four required design courses that encompass the capstone experience: Engineering Design III (*ENGR 331*), Engineering Design IV (*ENGR 332*), Engineering Design V (*ENGR 431*), and Engineering Design VI (*ENGR 432*). Each course is scheduled for three weekly 100 minute

Table 1. Junior and Senior Design Course Content Overview (ENGR 331, 332, 431, and 432) in regards to "Advanced Design Thinking, Principles, and Methods"

ENGR 331 (Fall Junior Year)	**ENGR 332 (Spring Junior Year)**
• Engineering Design Process (from problem definition to testing & refinement) • Planning & Information Gathering (research, benchmarking, etc.) • Defining System Requirements (quantitative and qualitative, collect and translate customer needs into technical specifications, benchmarking, functional modeling, mathematical modeling) • Sustainability Criteria and Evaluation of System Requirement (economic, environmental, social)	• Qualitative System Modeling • Advanced Concept Generation Methods/Analysis (Directed methods, TRIZ, Design by Analogy) • Advanced Concept Evaluation and Selection Methods/Analysis (mathematical modeling, AHP) • Defining the Design Space • Linking Ethics, Sustainability, Broader Impacts, and Trade-offs to Decision Making
ENGR 431 (Fall Senior Year)	**ENGR 432 (Spring Senior Year)**
• Basics of Human Factors and Psychology of Design • Reliability Analysis (Failure Modes & Effects Analysis, Fault Tree Analysis, Probabilities of Failures, Safety Factors) • Design of Experiments for Robust Design • Modeling in Design • Embodiment Design • Parametric Design	• Detailed Design • Cost Evaluation and Economic Decision Making • Design for the Environment • Product and Process Sustainability Evaluation • Ethical Decision Making • Human-Centered Design • Data Analytics & Decision Making via Case Studies • Engineering Cultures

meeting times, one dedicated to lecture and two dedicated to capstone project work. There are five threads running developmentally through these courses: (1) Advanced Design Thinking, Principles, and Methods, (2) Ethical Reasoning, (3) Communication Skills, (4) Team Skills, and (5) Professional Career Development. Table 1 shows the "Advanced Design Thinking, Principles, and Methods" developmental thread as a means of showcasing the design process and methods students are taught in the curriculum. This thread is also most relevant to TDRs because it showcases the content students are exposed to in support of their capstone projects.

JMU's capstone design vision was inspired by the Dieter and Schmidt "Engineering Design" textbook [26] used in the design courses as well as an industry design model summarized in terms of four design reviews: Systems Requirement Review (SRR), Preliminary Design Review (PDR), Critical Design Review (CDR), and Detailed Design Review (DDR). Table 2 illustrates the vision of the JMU engineering capstone model in terms of semester foci and key design deliverables.

During *ENGR 331*, the students begin the two-year capstone project in groups of approximately four to six with typically one or two capstone faculty advisors. In order to graduate, all JMU engineering students participate in four-semester capstone design sequence. Given the non-discipline specific nature of the engineering major and the diverse

Table 2. Two-year JMU capstone design model

Semester	**Key Design Review Deliverables**
ENGR 331 Engineering Design III (Fall Junior Semester)	
Planning and Information Gathering	*System Requirement Review (SRR)*—problem statement, literature review, market analysis and/or stakeholder analysis, customer needs and system requirements, system modeling, project management plan (budget, timeline, team member roles and responsibilities), etc.
ENGR 332 Engineering Design IV (Spring Junior Semester)	
Concept Generation, Evaluation, & Selection	*Preliminary Design Review (PDR)*—iteration of system requirements, target specifications, concept generation, concept evaluation, and concept selection, functional modeling, iteration of project management plan, etc.
ENGR 431 Engineering Design V (Fall Senior Semester)	
Design Embodiment (e.g. Prototyping, Modeling &Testing)	*Critical Design Review (CDR)*—design embodiment, analytical and physical modeling, testing procedures and analysis, reliability analysis, evaluation of concept with system requirements, iteration of project management plan, etc.
ENGR 432 Engineering Design VI (Spring Senior Semester)	
Detailed Design (e.g. Testing, Modeling & Production)	*Detailed Design Review (DDR)*—analytical and physical modeling, testing and analysis, sustainability evaluation, manufacturing and production, commercialization, marketability, project management plan, etc.

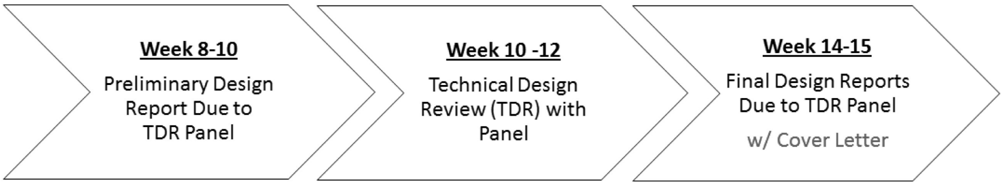


Fig. 1. Typical semester timeline for TDR process.

disciplinary representation of the faculty, project topics vary considerably and require knowledge and skills from throughout the curriculum and varying engineering disciplines. Over the past five years, cohort sizes for juniors starting the capstone sequence has ranged from approximately 55 to 95 students distributed amongst fourteen to sixteen project teams. Overall, the first semester of the project is focused on problem formulation, research, and planning with some teams moving on to the concept development design phase [37]. The capstone teams continue to move through the design process through both in-class instruction and out-of-class project work as indicated in Table 2.

3.2 Technical design review panels and process

In Fall 2013, Technical Design Reviews (TDRs) were introduced to the JMU Capstone Model to facilitate in the progression and evaluation of capstone projects. To pilot the practice, TDR Panels were initially assigned to each senior team during their fall semester. Currently, TDR Panels are assigned to all junior capstone teams at the start of their capstone experience and teams maintain the same panels for four semesters.

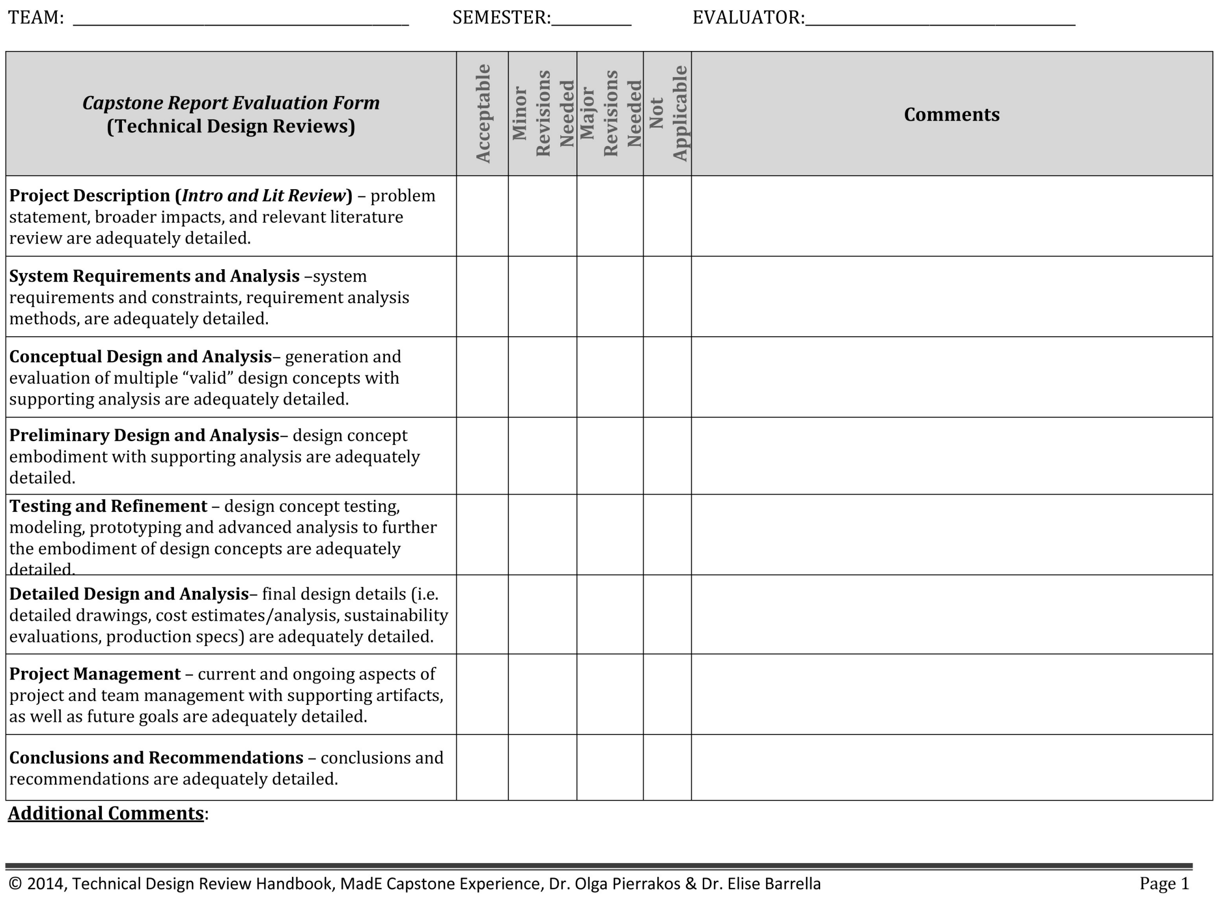
In this study, the composition of TDR Panels included at least four members: Capstone Advisor(s), one Design Course Instructor (in the case that one was not already a capstone advisor), and other Engineering Faculty or Staff based on area of expertise. Project partners, such as external advisors, clients, or sponsors, are also invited to review and provide feedback on team progress. The three key goals of the TDRs were to: (1) provide capstone teams constructive and collective feedback on the technical details and progress of their capstone project, (2) evaluate individual team member understanding of the technical and non-technical aspects of the capstone project, and (3) evaluate a capstone team's process of making project decisions within design phases and informed by pertinent engineering analysis. A typical semester timeline (Fig. 1) for TDR process included the submission of the preliminary design report by the capstone team within week 8 to 10, the oral TDR two weeks later, and the submission of the final capstone report during the last week of the semester.

During the oral TDRs, each team had 45 minutes with the Panel. No formal presentation was required, but many capstone teams elected to spend the first few minutes orienting their TDR Panel with progress made during the semester and key output. The primary format of the TDRs was questions posed by panelists followed by student responses and then feedback from the panelists. A moderator was assigned to each TDR to ensure adequate tracking of time as well as adequate time allowance for each student to respond to questions. In all cases, the moderator was one of the Capstone Advisors.

Evaluation during the TDRs involved the use of the Capstone Report Evaluation Form (CREF), Fig. 2, to provide ratings on each section of the capstone report and feedback to improve the capstone design documentation and overall project progress.

CREF aligns with the JMU Capstone Design Report Template, which is common to all capstone teams from junior year until senior year. The expectation is that students will update and revise their capstone design report each semester showing progress and iteration of the design process. The report aligns with the design process described in Table 2. A key focus in the design report is analysis within each phase of the design process: system requirements, conceptual design, preliminary design, testing and refinement, and detailed design. Students are expected to use methods and analysis from throughout the curriculum to make design decisions. More specifically, CREF includes eight criteria for evaluation: (1) project description, (2) system requirements and analysis, (3) conceptual design and analysis, (4) preliminary design and analysis, (5) testing and refinement, (6) detailed design and analysis, (7) project management, and (8) conclusions/recommendations. Across each of the eight criteria, ratings are based on a 4-pt scale: an "acceptable" rating, a "minor revisions needed" rating, a "major revisions needed" rating, and a "not applicable" rating which designates that a team has not reached that phase of the design process.

During the last week of the semester, teams provide their TDR Panels with two documents: (1) an electronic submission of the final capstone design report of the semester, and (2) an accompanying



TEAM: ____________________ SEMESTER:________ EVALUATOR:____________________

Capstone Report Evaluation Form **(Technical Design Reviews)**	**Acceptable**	**Minor Revisions Needed**	**Major Revisions Needed**	**Not Applicable**	**Comments**
Project Description (*Intro and Lit Review*) – problem statement, broader impacts, and relevant literature review are adequately detailed.					
System Requirements and Analysis –system requirements and constraints, requirement analysis methods, are adequately detailed.					
Conceptual Design and Analysis– generation and evaluation of multiple "valid" design concepts with supporting analysis are adequately detailed.					
Preliminary Design and Analysis– design concept embodiment with supporting analysis are adequately detailed.					
Testing and Refinement – design concept testing, modeling, prototyping and advanced analysis to further the embodiment of design concepts are adequately detailed.					
Detailed Design and Analysis– final design details (i.e. detailed drawings, cost estimates/analysis, sustainability evaluations, production specs) are adequately detailed.					
Project Management – current and ongoing aspects of project and team management with supporting artifacts, as well as future goals are adequately detailed.					
Conclusions and Recommendations – conclusions and recommendations are adequately detailed.					

Additional Comments:

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Fig. 2. JMU Capstone Report Evaluation Form (CREF).

cover letter summarizing the feedback received during the TDR and how the capstone team addressed this feedback. Using the aforementioned CREF instrument, panelists review and evaluate the final capstone design reports. Panelists focus their feedback on the technical aspects of the project, particularly how engineering analyses informed engineering decisions within each phase of the design process. Course Design Instructors, on the other hand, focus their evaluation on overall design process/methods and technical writing. If capstone teams had not adequately addressed the feedback provided by the TDR Panel to the extent to which *Major Revisions* were still needed, all team members received an incomplete for the course. Students were allowed to enroll in the next Design Course, but ineligible to graduate unless all "incomplete" requirements have been met. Students are given about a month into the next semester to assure all the "incomplete" requirements have been met. During the 2013–2014 academic year, 4 out of the 14 senior capstone teams received incompletes in *ENGR 431* (Fall 2013) and were ineligible to progress without meeting TDR comments in *ENGR 431*. These four teams worked over the holiday break in December and January to address TDR concerns. They submitted a revised *ENGR 431* reports at the beginning of February, while still expected to continue their *ENGR 432* course work and project work.

4. Methodology

This study is a longitudinal study of measuring the impacts of implementing Technical Design Reviews (TDRs). In this section, the mixed-methods research design, data collection, and data analysis are explained.

4.1 Research design

In answering the two research questions, a mixed-methods approach was utilized. "A mixed methods study involves the collection or analysis of both quantitative and/or qualitative data in a single study in which the data are collected concurrently or sequentially, are given a priority, and involve the integration at one or more stages in the process of research" [38]. More specifically, a concurrent (qualitative and quantitative data collection and analysis occurring simultaneously) triangulation design was chosen for this study as shown in Fig. 3. In a concurrent triangulation design, separate analysis

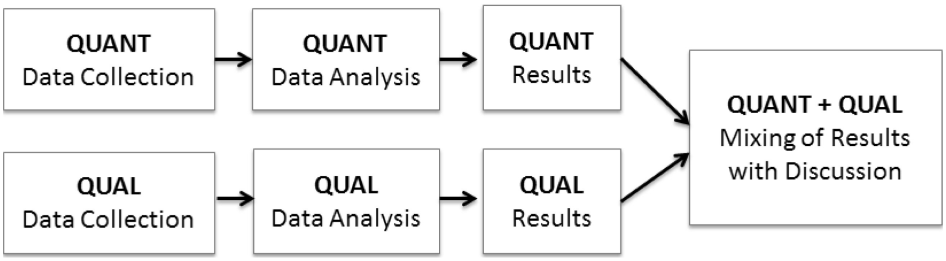

Fig. 3. Diagram of Concurrent Triangulation Design.

is performed for both the quantitative and qualitative data with a clear indication of the data integration phase at the end. Details about the quantitative and qualitative data collected are described next.

4.2 Quantitative data and analysis—Capstone report evaluation

The data samples in this study included two sets of senior-level capstone reports—one set representing student work the year prior to TDRs being a part of the JMU capstone experience (N = 14), and the other set representing student work after Technical Design Reviews were a part of the JMU capstone experience (N = 14). Evaluation of the samples of capstone reports involved the use of the JMU Capstone Report Evaluation Form (CREF), Fig. 2, which was designed to align with the capstone design report template and the JMU capstone design process (portrayed in Tables 1 and 2). More specifically, CREF includes eight criteria for evaluation: (1) project description, (2) system requirements and analysis, (3) conceptual design and analysis, (4) preliminary design and analysis, (5) testing and refinement, (6) detailed design and analysis, (7) project management, and (8) conclusions/recommendations. Across each of the eight criteria, reviewer ratings were based on a 4-pt scale: an "acceptable" rating counted as a 3, a "minor revisions needed" rating counted as a 2, a "major revisions needed" rating counted as a 1, and a "not applicable" rating counted as a 0. CREF ratings utilized for the analysis of this study reflect both TDR panelist ratings (for the year that TDRs were implemented) and 3 faculty reviewers' ratings (for the year prior to TDRs being a feature of the program). Descriptive statistics were the primary means of data analysis. Cohen's d was computed for calculating the effect size of the mean differences [39].

4.3 Qualitative data and analysis—Feedback from students on technical design reviews (TDRs)

To supplement the quantitative data, qualitative data was also collected from senior engineering capstone students. At the end of students completing the first TDR, students were asked to evaluate the TDR process. Several open-ended questions were administered in the design course to gain deeper insight into students' learning outcomes. More specifically, senior students were asked to anonymously answer two questions: (1) what were positive aspects of the Design Review Process? (2) what could be improved about the Design Review Process? Fifty students chose to participate in this evaluation and this corresponded to a 92% response rate.

Data analysis of the qualitative items began with the iterative development of a coding framework. Thematic network analysis, recommended by Attride-Stirling for interpreting qualitative data [40], was deemed most appropriate because it allows for the systematic extraction of common themes and evaluation of the relative importance of each. Two researchers developed a coding framework by noting common thematic threads surfacing in the responses. The final coding framework was evaluated by a third researcher and was used to code the data into thematic groups. Subsequently, these groups were merged into common themes. Tables 3 and 4 show the themes that emerged from the open-ended questions with sample quotes. There were seven themes that emerged as positive aspects of TDRs and nine themes that emerged as opportunities to improve TDRs. These themes are discussed in more detail in the results section.

5. Results and discussion

In following with the concurrent mixed-methods triangulation design, this section is organized in three sub-sections: quantitative results, qualitative results, and quantitative and qualitative triangulation with a discussion.

5.1 Quantitative results—Capstone report evaluation

The year prior to TDRs being a part of the JMU capstone experience, 14 capstone teams submitted final capstone reports at the end of the two-year capstone experience and ultimately graduated from the program. Table 5 showcases average reviewer ratings from the evaluation of the final capstone

Table 3. Themes that emerged from student feedback as "Positive Aspects" of TDRs (n = 50)

Emergent Theme	**Sample Quotes**
Relevant and Valuable Feedback to Improve the Project	*"There was tons of valuable feedback"* *"A very eye-opening experience that was very much needed to reevaluate our project"*
Unique Perspectives Identified to Better the Project	*"The Design Review gave us a fresh viewpoint and many suggestions that our team never thought of before."* *"Fresh eyes and new perspectives were offered"*
Relevant and Valuable Feedback on the Report and Documentation	*"Design Reviews allow us to have a stronger report"* *"Good to hear ways we can improve our report"* *"Encouraged me to create our binder and document everything"*
Including Panelists External to Project was Valuable	*"The review really showed me how engineers evaluate others' work"* *"It was so nice to get feedback from other people other than our advisors"*
The Semi-formal Setting and Format was Effective	*"Liked the conference-like environment"* *"I liked the feel that it wasn't just another presentation. It was the panel presenting us with questions they had from the report and major issues that needed improvement."* *"It was nice to have an atmosphere that was not strictly formal"* *"The semi-formal setting made it more comfortable to ask questions"*
The Composition of the Design Review Panel was Good and Appropriate	*"Review Panels consisted of faculty knowledgeable in the field and with relevant experience"* *"The review panel was balanced in terms of background and expertise"* *"Panel members were picked well for the group (given background knowledge)"*
TDRs Provided a Need for Accountability	*"The Design Review provided the team a good reality check and evaluation of the project status"* *"The Design Review helped to get our group out of a dis-involvement rut"* *"Panel was great. A good wake up call."*

Table 4. Themes that emerged from student feedback as "Opportunities for Improvement" on TDRs (n = 50)

Emergent Theme	**Sample Quotes**
TDRs Should be Conducted Throughout the Capstone Experience and Earlier	*"Nice to have reviews earlier. At the end of the spring semester junior year in addition to senior year"* *"Should have this panel more often for capstone"* *"Reviews like this should come earlier to help keep teams on track"*
Feedback was Unclear or Out of Context	*"Questions were asked that were outside of the scope of our project"* *"Some questions asked were not relevant to furthering the project"* *"Advisor could have been more clear with questions asked"*
Panelists Did Not Seem Prepared	*"Some questions that panelists asked, it was clear that they were not prepared and had not read the report yet"* *"It was clear that the panel member with the most negative feedback had not read the report."*
Panelists Seemed Unclear about the Purpose of the TDRs	*"The combination of grilling us and providing helpful ideas made the setting a little confusing. Panelists seemed unclear what role they play."* *"Some faculty seemed unsure of the format of the review session"*
Students Did Not Know How to Prepare for the TDRs	*"Unclear expectations. Didn't know how to prepare for the panel"* *"Format of the review seemed uncertain and I didn't know what to expect"*
TDR too short	*"I was hoping there was more time the get through the entire report"* *"Adjust time (longer) as needed for each team"* *"The 50 minutes was not enough for each panelist to ask questions and provide feedback."*
Poor Time Management During the TDR	*"There was a lot of pause moments because there were no specific guidance on the use of time during the TDR"* *"Not all students had time to speak and answer questions. Better management would help."*
Students Experienced Hostility by some TDR Panelists	*"One panel member was antagonistic and hostile. We felt attacked."* *"One panelist was quite combative and this was counterproductive"*
Contradictory Feedback Among TDR Panelists	*"Feedback from client was contradictory to the rest of the panel"* *"Not all panelists were on the same page"*

reports using CREF as the instrument, which was described in the methods section. At the bottom of Table 5, the percentage of capstone reports that received satisfactory ratings is presented. This value was determined by looking at the average reviewer scores. A score above 2 designated satisfactory performance and a score below 2 designated unsatisfactory performance (because major revisions would still be needed). Results in this table show that the *Project Management* section of the report was the only section that reviewers found satisfactory for all capstone teams. This was followed by the *Project Description* section, of which 79% (11 out of the 14 reports) were deemed satisfactory. The major design sections of the report—*System Requirements, Conceptual Design, Preliminary Design, Testing and Refinement, and Detailed Design*—were not deemed satisfactory for the majority of the capstone reports. In fact, all capstone teams had at least three sections of the reports that were deemed to still require major revisions and most teams had four to six sections that required major revisions. All this in part drove the department to a different evaluation format and thus the development of a panel-based TDR process during the capstone design experience.

The year during which TDRs were implemented for the first time, 14 capstone teams submitted final capstone reports at the end of the two-year capstone experience and ultimately graduated from the program. It is important to note that TDRs during this initial year only occurred during the senior year of capstone and not the junior year of capstone. Thus it is anticipated and hypothesized that TDRs implemented both junior and senior years would result in even greater benefits. Table 6 showcases average

Table 5. Average reviewer ratings of final capstone reports *before* TDRs were a part of the capstone experience. Shaded cells correspond to unsatisfactory ratings (below 2.0, suggesting major revisions would still needed). A 3 corresponds to "acceptable", "minor revisions needed" is a 2, "major revisions needed" is associated with 1, and not applicable corresponds to 0

BEFORE TDRs Teams N = 14	Project Description	System Requir. & Analysis	Conceptual Design & Analysis	Prel. Design & Analysis	Testing & Refinem.	Detailed Design & Analysis	Project Mngmt	Concl. & Recomm.
Team 1	2.00	1.00	1.00	1.00	1.50	1.00	3.00	1.00
Team 2	1.50	2.00	1.50	2.00	1.50	1.00	2.50	2.50
Team 3	2.50	1.00	1.00	1.50	2.00	1.50	3.00	2.00
Team 4	1.50	1.00	1.50	1.00	1.00	1.00	2.50	1.50
Team 5	2.00	1.50	1.00	2.00	1.50	1.50	2.50	1.00
Team 6	1.50	1.00	2.00	1.50	1.00	1.00	3.00	1.50
Team 7	2.00	1.50	1.00	1.00	1.00	1.00	3.00	1.00
Team 8	2.00	1.50	2.00	1.50	2.00	1.00	2.50	1.50
Team 9	2.00	2.00	1.33	1.67	2.33	1.00	3.00	2.33
Team 10	2.67	1.33	1.33	1.67	2.33	1.00	3.00	2.00
Team 11	2.00	1.00	1.00	1.00	1.50	1.00	2.50	2.00
Team 12	2.00	1.50	1.00	1.00	1.00	1.00	2.50	2.00
Team 13	2.67	1.33	1.33	1.33	1.33	1.33	2.33	2.33
Team 14	2.00	1.00	1.00	1.50	2.00	1.00	2.50	2.00
Average	**2.02**	**1.33**	**1.29**	**1.40**	**1.57**	**1.10**	**2.70**	**1.76**
Standard Dev.	**0.38**	**0.36**	**0.36**	**0.36**	**0.49**	**0.19**	**0.27**	**0.51**
% of Reports with Satisf. Ratings	**79%**	**14%**	**14%**	**14%**	**36%**	**0%**	**100%**	**57%**

Table 6. Average reviewer ratings of final capstone reports *after* TDRs were a part of the capstone experience. Shaded cells correspond to unsatisfactory ratings (below 2.0, suggesting major revisions would still needed). A 3 corresponds to "acceptable", "minor revisions needed" is a 2, "major revisions needed" is associated with 1, and not applicable corresponds to 0

AFTER TDRs Teams N = 14	Project Description	System Requir. & Analysis	Conceptual Design & Analysis	Prel. Design & Analysis	Testing & Refinem.	Detailed Design & Analysis	Project Mngmt	Concl. & Recomm.
Team 1	3.00	3.00	2.67	2.67	2.33	2.67	3.00	2.67
Team 2	2.50	2.25	2.25	1.75	1.75	1.50	2.50	1.75
Team 3	3.00	3.00	3.00	3.00	2.67	2.67	3.00	3.00
Team 4	2.67	3.00	3.00	3.00	2.67	2.67	2.67	2.67
Team 5	3.00	2.67	3.00	1.67	2.67	2.67	3.00	1.67
Team 6	3.00	2.67	2.67	3.00	3.00	2.67	3.00	3.00
Team 7	2.50	2.00	1.50	1.50	2.00	1.00	3.00	2.50
Team 8	3.00	3.00	2.50	2.50	2.50	2.50	2.50	2.50
Team 9	3.00	3.00	2.75	2.75	3.00	3.00	3.00	3.00
Team 10	3.00	3.00	3.00	3.00	2.50	2.50	3.00	3.00
Team 11	3.00	3.00	3.00	3.00	2.75	2.75	3.00	3.00
Team 12	3.00	2.50	3.00	3.00	2.00	2.50	3.00	2.50
Team 13	3.00	3.00	3.00	3.00	2.50	3.00	3.00	3.00
Team 14	3.00	3.00	3.00	3.00	2.33	2.33	3.00	3.00
Average	**2.90**	**2.79**	**2.74**	**2.63**	**2.48**	**2.46**	**2.90**	**2.66**
Standard Dev.	**0.19**	**0.33**	**0.43**	**0.56**	**0.37**	**0.55**	**0.19**	**0.46**
% of Reports with Satisf. Ratings	**100%**	**100%**	**93%**	**79%**	**93%**	**86%**	**100%**	**86%**

reviewer ratings from the evaluation of the final capstone reports of the seniors who first experienced TDRs. Results in this table show that panel reviewers found the *Project Management*, *Project Description*, and *System Requirements* sections of the report satisfactory for ALL capstone teams. After TDRs were implemented, the major design sections of the report—*System Requirements, Conceptual Design, Preliminary Design, Testing and Refinement, and Detailed Design*—were deemed satisfactory for the majority of the capstone reports. In fact, only 3 of the 14 capstone teams (~21%) received unsatisfactory ratings and of these three teams two to four sections of the reports were deemed to need major revisions.

Figure 4 visually showcases the average reviewer ratings across all capstone teams prior to TDRs (N = 14, from Table 5) and after TDRs (N = 14, from Table 6). The comparison in Fig. 4 showcases improvement from the prior year when TDRs were not a part of the JMU capstone experience. It is evident looking at this figure that TDRs helped improve the capstone reports, which suggests that student learning was deepened, technical depth was improved, design thinking was enhanced, and accountability was increased. More specifically, as a result of implementing TDRs, the biggest differences and impact to the capstone report was in the technical design sections of the report—*System Requirements, Conceptual Design, Preliminary Design, Testing and Refinement, and Detailed Design*. Thus, TDRs helped to support the design and analysis sections of the report. Table 7 presents Cohen's *d* values which represent the effect size of the mean differences [40]. Mean differences are considered to be practically significant when Cohen's $d \geq 0.8$ (large effect size) or when $0.5 \leq$ Cohen's $d < 0.8$ (moderate effect size) [40]. Table 7 shows very large Cohen's *d* values suggesting large effect sizes and significant increases across all sections of the capstone design reports after TDRs were implemented. Such results suggest impacts and benefits to implementing TDRs to enhance student learning which can be inferred by the much stronger capstone reports submitted after TDRs.

In addition to comparing final capstone reports prior to and after TDRs implementation, preliminary capstone reports, which are submitted every semester, were also compared and showed improvement over time as a result of TDRs. Such longitudinal data shows the growth of each team semester by semester. Figure 5 depicts average

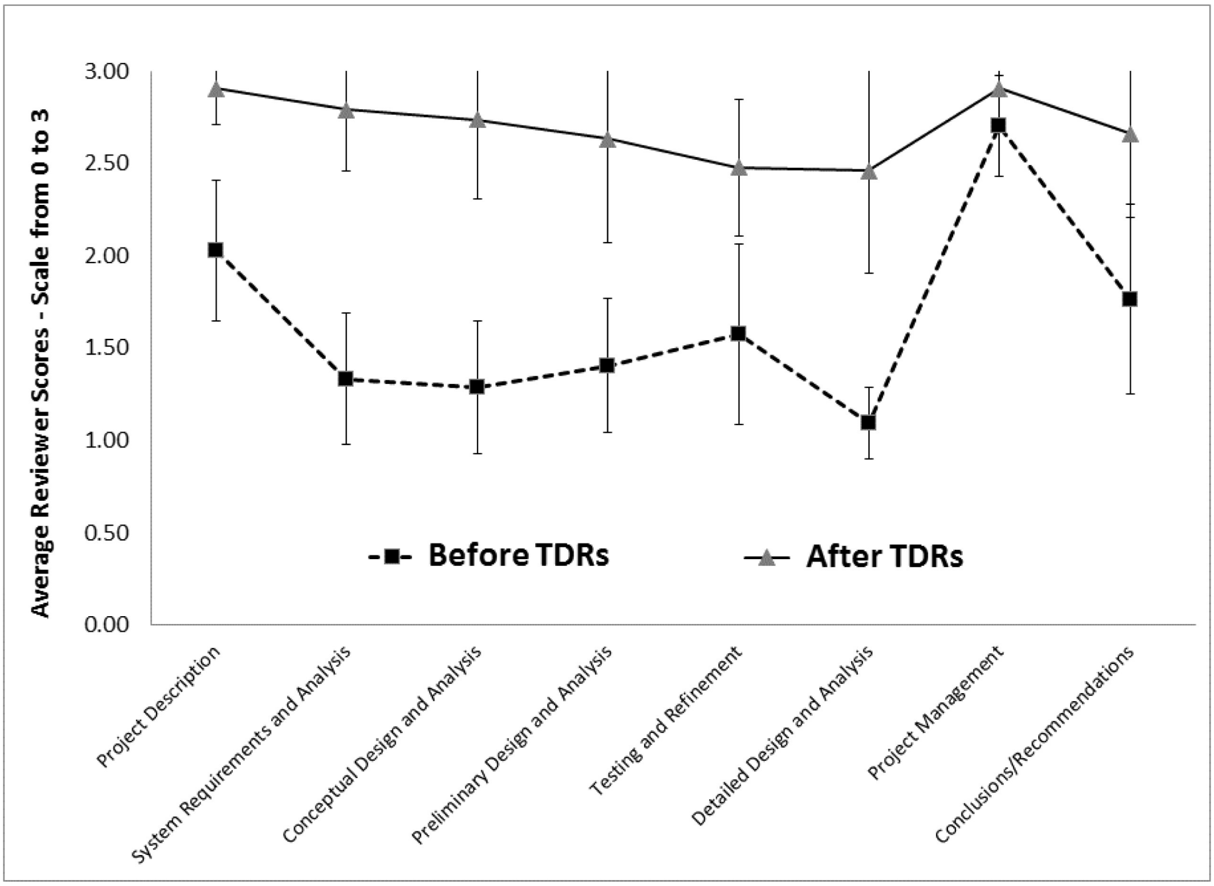

Fig. 4. Average reviewer scores of all capstone reports before TDRs and after TDRs. The data is based on results shown in Tables 5 and 6.

Table 7. Average Technical Design Review Scores for the Class of 2014 (Cohort 3) at the start and end of the Design Review Process during senior year (2013–2014 academic year) with Cohen's d effect size calculations. Scores are listed with standard deviation in parentheses.

	Project Description	**System Requir. & Analysis**	**Conceptual Design & Analysis**	**Prel. Design & Analysis**	**Testing & Refinem.**	**Detailed Design & Analysis**	**Project Mngmt**	**Concl. & Recomm.**
Before TDRs N = 14	2.02 (0.38)	1.33 (0.36)	1.29 (0.36)	1.40 (0.36)	1.57 (0.49)	1.10 (0.19)	2.70 (0.27)	1.76 (0.51)
After TDRs N = 14	2.89 (0.20)	2.80 (0.33)	2.76 (0.43)	2.54 (0.60)	2.46 (0.35)	2.45 (0.55)	2.89 (0.20)	2.57 (0.50)
Cohen's d	**2.93**	**4.23**	**3.66**	**2.61**	**2.10**	**3.31**	**0.86**	**1.85**

reviewer ratings for each of the 14 teams at two time instants—at the onset of TDRs when the preliminary capstone reports were submitted fall semester of senior year and at the end of the senior year when final capstone reports were submitted. Two TDRs took place during that timeframe, one in each semester of the senior year. In reviewing Fig. 5, it is evident that the growth and impact of implementing TDRs was large for all capstone teams. It was not that just a few teams improved within one year with two TDRs, but that all teams improved and deepened their learning as evidenced in the stronger capstone reports.

5.2 Qualitative results— Feedback from students on Technical Design Reviews (TDR)

As described in the Methods section, open-ended questions were asked of students so as to gauge the positive aspects of TDRs and also aspects that could be improved. Such open-ended questions came from written reflections which were administered in class.

Tables 8 and 9 present themes that emerged from the two open-ended questions administered in class. Frequency of responses is also tabulated. The frequency of responses shown in the tables, indicate that the positives of implementing TDRs exceeded the negatives but that there was room for improvement and some variability in students' experiences with the panels.

The most frequently mentioned "positive aspects" of TDRs were about the value, relevance, and uniqueness of the feedback received in improving the capstone project. The feedback that the capstone students received helped them improve the direction of their capstone project, but also their capstone reports. The feedback received from third party panelists (i.e. other faculty beyond capstone advisor, external sponsors, or engineering staff) was valued by the capstone students, as were

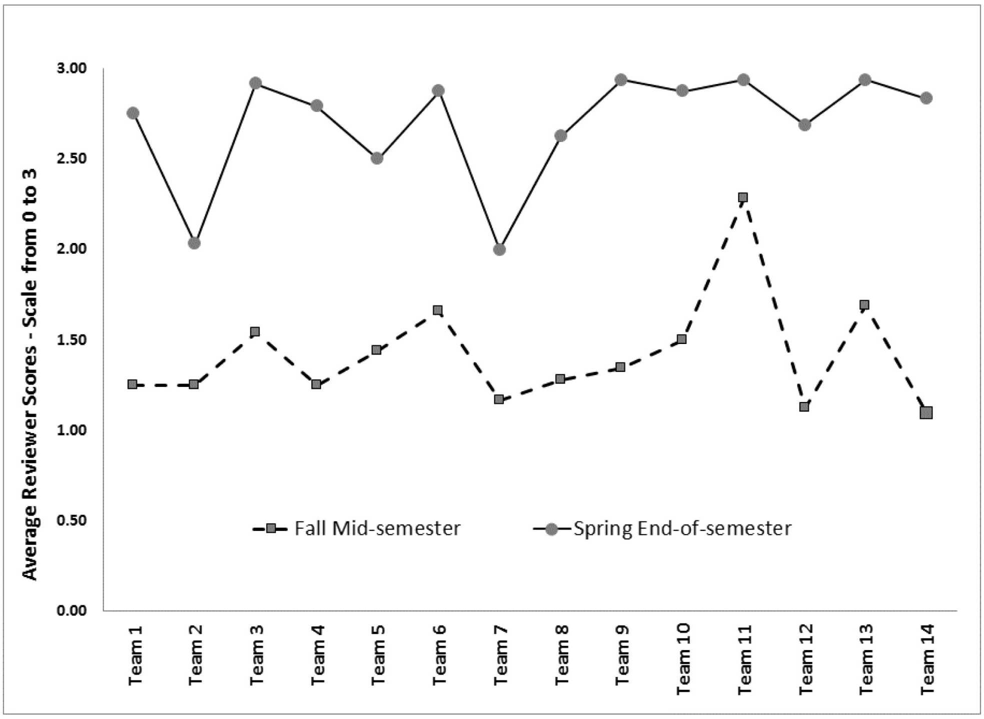

Fig. 5. Average TDR Ratings for the 14 Teams that Experienced TDR during their Senior Year. Ratings represent CREF Ratings from Fall Mid-Semester to Spring End-of-Semester (Final) Capstone Reports.

Table 8. Themes and frequencies that emerged from student feedback as "Positive Aspects" of TDRs (n = 50)

Emergent Theme	**Frequency**
Relevant and Valuable Feedback to Improve the Project	40
Unique Perspectives Identified to Better the Project	35
Relevant and Valuable Feedback on the Report and Documentation	23
Including Panelists External to Project was Valuable	18
The Semi-formal Setting and Format was Effective	17
The Composition of the Design Review Panel was Good and Appropriate	15
TDRs Provided a Need for Accountability	15

Table 9. Themes and frequencies that emerged from student feedback relevant to "Opportunities for Improvement" of TDRs (n = 50)

Emergent Theme	**Frequency**
TDRs Should be Conducted Throughout the Capstone Experience and Earlier	32
Feedback was Unclear or Out of Context	23
Panelists Did Not Seem Prepared	20
Panelists Seemed Unclear about the Purpose of the TDRs	15
Students Did Not Know How to Prepare for the TDRs	15
TDR too short	15
Poor Time Management During the TDR	13
Students Experienced Hostility by some TDR Panelists	10
Contradictory Feedback Among TDR Panelists	8

new perspectives identified. Some quotes from the students are reflected herein:

> *"I thought the design review panels were extremely helpful with making sure the project is on track and for delivering the best possible product in the end."*
>
> *"Review Panels were a pivotal part for our project in what it is now, at the end."*
>
> *"The most valuable component of the project was its evaluation by the review panels and their feedback. This taught us how engineers think and helped us greatly improve our work."*
>
> *"The design reviews and panels were very helpful and informative. They provided a great way to interact with professors other than our advisor and the design professors about our capstone project. . ."*
>
> *"Loved the design reviews. Extremely helpful in letting us know areas of improvement within not only our capstone but as real-world project preparation."*

Students also appreciated the semi-formal setting of the TDRs and the composition of the TDR panels which brought together the appropriate expertise. TDRs also provided a means of accountability for the teams and the following student quotes reflect this built-in accountability.

> *"The design reviews definitely helped with accountability. After the mid semester grades were received from the design review where my partner did not do so well, I saw significant improvement in his motivation. I thought the grade was a little harsh, but it definitely got the message across."*
>
> *"Design Review Panels are a great idea. They force you to make sure you know your project thoroughly and point out any weaknesses in your project or process."*

In regards to opportunities for improvement, Table 9 shows the themes that emerged and the corresponding frequencies. The most prevalent theme was that TDRs should occur earlier and throughout the two-year capstone experience. Requesting earlier and more frequent reviews showcases the value students place on TDRs as described above. Another prevalent theme for improving TDRs was that sometimes the feedback seemed unclear or out of context. This was probably related to another theme suggesting that TDR panelists did not always come prepared for the TDRs. Some quotes reflecting these themes are:

> *"Some questions that panelists asked, it was clear that they were not prepared and had not read the report yet."*
>
> *"Questions were asked that were outside of the scope of our project."*

Further, it appears that some additional clarity about the purpose of the Design Reviews would benefit both the faculty/Design Review Panelists as well as the students. Some students suggested longer TDRs to fully cover the amount of feedback received by the Design Review Panelists and to allow ample opportunity for all capstone team members to respond to questions. Allowing more time to discuss feedback could improve the clarity of feedback provided, which was also cited as an area for improvement. There was also some hostility experienced by some students by some TDR panelists which was not constructive to help students understand and grow. Clearer expectations and roles during a TDR process could help in this process. Lastly, several students perceived some of the feedback by panelists as contradictory and with more time during the TDR to clarify feedback, some of these perceived contradictions could be better addressed.

5.3 Quantitative and qualitative triangulation

In mixing the quantitative and qualitative results, this study is focused on connecting the two types of data during the data analysis and discussion phase. This occurs when "analysis of one type of data leads and connects to the need for the other type of data [39]." Herein, analysis started with the quantitative data focusing on evaluating capstone reports prior to TDRs being part of the capstone experience and comparing to capstone reports after two TDRs during the senior year. Such quantitative data provided evidence to the impact of TDRs on design documentation such as capstone reports, but in-depth insight about the benefits of TDRs and opportunities to improve TDRs came from the qualitative data. Together, quantitative and qualitative data tell a broader and deeper story about the impacts of TDRs. The results show that within one year of implementing panel-based Technical Design Reviews, valuable and statistically significant (based on Cohen's d effect size calculations) improvements in students' design report documentation and learning is achieved. The multiple perspectives offered by the varying TDR panelists certainly is a powerful feature that enables students to gain a broader and deeper perspective of their own project. The feedback received from the diverse set of panelists, most of whom did not interact with the students on day-to-day aspects related to their capstone projects thus truly being external to the project, provided students an opportunity to reflect on their project, to defend or reevaluate their decisions, and truly enrich the direction of the project. Building accountability was also a key outcome of the TDRs because students knew that they would have to stand in front of this same panel the next semester to show the progress made, the decisions made, and their justifications. Overall, this mixed-methods approach truly provided richer data and richer results to sustain TDRs in the program and to continue improving the TDR experience throughout the capstone experience.

6. Conclusions and implications

In summary, Technical Design Reviews have benefited the James Madison University Engineering Department tremendously. The impacts and benefits are many. Challenges still remain though and in this section, the impacts and challenges of TDRs are summarized in the hope that other educators can benefit from what has been learned throughout this process. This section starts with a summary of answering the two research questions guiding this effort and ends with implications and future work.

6.1 Research Question One—To what extent are capstone documentation, students' learning, and overall capstone performance impacted as a result of introducing Technical Design Reviews during a capstone experience?

A comparison of capstone reports prior to TDRs being a feature of the JMU capstone experience with capstone reports after TDRs were implemented revealed statistically significant growth and improvements. More specifically, as a result of TDRs, significant improvements were evident in all sections of final capstone reports, but most significant in the sections of the report related to the technical design phases—System Requirements, Conceptual Design, Preliminary Design, Testing and Refinement, and Detailed Design. Such improvements in the capstone documentation also infer deeper student learning. Qualitative reflections by students also suggest that TDRs enabled them to receive relevant and valuable feedback, including feedback that offered unique perspectives they had not considered previously. The feedback was relevant to the technical details of the project, the capstone report and documentation, as well as project progress. The breadth of expertise represented in the panel was also perceived to offer great value to students and the composition of the panels was good. The semi-formal setting was conducive to learning and effective in receiving feedback.

6.2 Research Question Two—What are the impacts, benefits, and challenges to implementing Technical Design Reviews during a capstone experience?

The impacts and benefits of TDRs were many and in a list format, here are a few that stood out.

(1) TDRs enabled students to receive multi-source and multiple-perspective feedback on technical and non-technical aspects of their project.
(2) TDRs mimicked real-world engineering practice for students and helped strengthen their professional identity as engineers.
(3) TDRs served as a venue to deepen and broaden technical knowledge and skills.
(4) TDRs enhanced the performance of capstone projects and capstone teams.
(5) TDRs enriched the capstone experience.
(6) TDRs served as motivation for students to complete and make strong progress on the project.
(7) TDRs raised the bar and the expectations.
(8) TDRs built in accountability for team members.
(9) TDRs helped to enforce curricular integration as faculty panelists helped build connections for the students.

(10) TDRs aided the teams to justify design decisions.
(11) TDRs enabled student teams to engage with relevant stakeholders.
(12) TDRs supported program assessment and ABET efforts.

There are also challenges to implementing TDRs. From the student point of view, clarity in expectations would aid to make the TDR process more seamless for both the students and TDR panelists. Such clarity would result to more constructive feedback, better preparation, and a more effective TDR session. Time management during the TDR session can also be a challenge. From the panelist point of view, anecdotal evidence suggests that clarity in expectations would also help support a more effective TDR process. Suggestions are presented in the following section. From the capstone coordinator point of view, a challenge that persists is more consistent evaluation of capstone documentation among the panelists. Efforts are currently being made to establish some calibration mechanisms to achieve greater consistency in panelist evaluations. In summary, though, the benefits of TDRs for the JMU engineering capstone experience far outweigh the challenges, so TDRs will persist and be a strength of the JMU capstone design experience.

6.3 Implications and future work

Although TDRs are not a new concept in the evaluation of capstone design or any design project, this study does offer an evidence-based perspective in support of TDRs. Based on a review of available literature, this is the first study to showcase not only a model of TDR being implemented, but also supporting evidence and assessment data in measuring the impacts of TDRs. Although the TDR model presented herein is part of a two-year capstone design experience at James Madison University, the TDR model offers transferability to other capstone models independent of the project duration. A critical facet to transferability is the timing of when a TDR should be implemented. Certainly, any curricular innovation requires time, effort, and faculty buy-in. Implementing TDRs requires coordination, recruitment of panelists, documentation, evaluation forms, etc. Once the benefits of TDRs are well-established though and it is evident that the benefits outweigh any costs, the process and buy-in can become more seamless.

At JMU, steps are being taken to continuously improve the TDR process. For example, starting in fall 2014, JMU Engineering Alumni were recruited to serve as TDR Panelists. This has further enriched the capstone experience and allowed the program to engage and build partnerships with Alumni. Such a model offers many benefits to current students as well. They are able to engage with the Alumni and even receive some mentoring. The program has improved the documentation for the TDR process and developed a TDR Handbook that guide students and TDR panelists (faculty, Alumni, clients) in the process. The TDR Handbook includes: (a) critical milestones and deadlines each semester, (b) TDR Panel compositions, (c) evaluation forms, (d) expectations, (e) report templates, (f) TDR guiding questions and key artifacts organized by design phase/section, and (f) responsibilities of capstone students, TDR Panelists, TDR Moderators, Capstone Advisors, and the Capstone Coordinator during the TDR process. Having the TDR Handbook has helped streamline the process and serves as the common document that facilitates the process. Improvements are ongoing though and include improving evaluation procedures, evaluation consistency and calibration, capstone report template updates, etc. This entire process has also helped the faculty and students get on the same page in terms of what the capstone experience represents and what the expectations are. We believe that this process will lead to improved capstone project scoping as well.

Overall, this paper shows the value and impacts of TDRs which are scalable and transferable, both in terms of the number of occurrences throughout the design experience and the scope of the reviews (in terms of mapping to the design process). TDRs increase student engagement and motivation and help to reinforce capstone advisor and design instructor feedback. The mixed-methods approach utilized herein is replicable and offers an approach for gathering evidence.

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