Peer Review in Capstone Design Courses: An Implementation Using Progress Update Meetings

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Abstract: Peer review of design progress and artifacts is not very common in engineering design education. Yet, the broader educational literature suggests that the impact of peer (novice) review can be superior to instructor (expert) only review in various ways. This paper describes a systematic implementation of face-to-face peer review in progress update meetings (PUMs) of a management engineering capstone design series of courses. In biweekly PUMs the instructors met jointly with two teams at a time, paired based on topic similarity. Teams took turns presenting to and critiquing each other's presentations and design progress. The format was well-received by students and was successful in increasing the diversity and wealth of knowledge teams could draw from during the meetings. A student survey revealed that students perceived that the regular joint PUMs encouraged them to maintain a steady progress in their design projects, facilitated peer-to-peer sharing of ideas, and were instrumental in helping teams improve on how they communicated their designs by providing multiple opportunities for revisions and refinement.

Keywords: peer review; peer assessment; capstone design; design review

1. Introduction

Peer evaluation and assessment have gained considerable traction and have become a familiar teaching methodology in engineering design courses. Student involvement can take several forms, including peer evaluation of individuals' contributions to a team project [1] and inter-team peer assessment of oral presentations – the latter implemented in a significant portion of capstone courses [2]. The focus of this paper is on inter-team peer *review* of design projects that targets not only oral presentations, but also other facets of the design process, including, but not limited to, design decisions, prototypes, and progress against project plan. It is found that such extensive use of peer review is not common in capstone design courses. The paper describes and evaluates a now-established implementation of systematic peer review in progress update meetings of a capstone design sequence of courses.

2. Background

The broader education literature strongly supports the use of peer review. It has been linked to many positive outcomes such as improving feedback received by students, improving the quality of work submitted, fostering learning autonomy and learning depth, and supporting the development of 'soft' (or 'higher-order') skills such as giving and receiving criticism [3]. In addition, it has been shown to increase collaborative learning and student engagement [4]. Studies comparing the efficacy of peer and expert review have found that while experts can provide excellent feedback and suggestions, their comments are often not well-understood and suggestions are not well-applied by novices. For example, in the domain of technical writing, students can benefit more from the feedback of multiple peers (novices) than the feedback of one expert [5]. Feedback from multiple peers provides students with a large number of comments that are non-directive, resulting in manageable micro-level meaning changes and more complex improvements to their work [6]. Expert feedback on the other hand is not only more limited in quantity, but also more directive, resulting mainly in surface improvements (e.g., spelling corrections) [6].

While rare in engineering design, peer review - the practice of allowing students, in addition to instructors, to participate in evaluating and critiquing design - has been a long-standing instructional practice in the discipline of architecture. Instructional conceptualizations vary [7, 8], but generally, in the typical architecture studio, students work on a complex, open-ended project that spans the entire semester [9], not unlike an engineering capstone design project. Throughout the term, students participate in interactive sessions in which the instructor – central to the activity – reviews each project one by one in the presence of the entire class [10]. In some implementations students are also allowed to participate in the review by providing their own comments. The public nature of the activity allows students to benefit not only from the feedback they receive on their own design, but also the feedback that the instructor provides to other students. Overall, this approach perpetuates a 'culture of critique' where feedback is frequent in both formal and informal settings throughout the design process [9, 10].

Elements of the architecture studio can be found in some components of engineering design courses. For example, a diverse audience of peers, professors, industry representatives, and the larger community are invited to critique capstone designs at final design symposia, common at many universities. In addition, typically, a faculty advisor/supervisor is assigned as a mentor and technical expert to a student group and meets them regularly for progress checking and formative feedback (progress update meetings). Most course designs also include one or more design review meetings – summative assessment milestones - where experts critique student design work. In progress update and design review meetings, review and critique involves expert-to-novice instruction only.

The design review meeting formats typical of many capstone design courses in engineering programs seems to be modeled after the graduate school defense meeting. The graduate school defense meeting is a formal event where experts (faculty) direct questions to the novice (student) in order to assess their knowledge in a summative sense. A qualitative analysis of communication patterns in the graduate school defense reveals that it is largely composed of expert to novice and novice to expert interaction, where the question-answer pattern is required to be focused and succinct. Many faculty have limited work experience in an authentic industry/business/professional practice context, and hence have only this model to go by in designing their courses. In academia then, it is not surprising that design review practice has evolved to model graduate school research practices. While elements of peer review can emerge informally, the systematic and formative use of peer review throughout the design process is rather limited.

In industry, the drive to compete and succeed by creating new products and services demands that new product introduction and design processes be effective and efficient. The practices vary, however it is not uncommon for both informal and formal review activities to occur in an engineering design function. The value of involving all functional groups in peer-to-peer design reviews, again both informally and formally, is a common and valued development practice. Sometimes this also involves informal and formal review meetings with suppliers and customers. This ensures that the products created include the interests of all organizational stakeholders. The culture of effective and continual 'critique' among employee peers is an embedded and necessary practice for successful organizations.

Review styles in industry vary widely. Reviews may occur at one's workstation or desk, by peers, management, and/or customers, either as a planned or ad-hoc activity. Reviews may occur in a meeting room with detailed information provided, or via web and telecom links to suppliers and/or customers. Reviews may be planned to be highly formal with a large number of customer representatives attending and a large number of company members presenting and attending, and this over the course of several days. Many of these formats can be characterized as peer-to-peer review, as opposed to expert-to-peer review. Most review implementations demand both direct question and answer and elaborated questioning, responding and dialoguing, amongst peer practitioners. This has a tendency to better educate and reveal opportunities for improvement of the design, particularly if time is available to do so. Additionally many employees are involved in more than one project, and this varied communication structure can provide opportunities for knowledge of one project to be shared with another.

2.1 Peer review in engineering education

In a survey of 94 instructors of capstone design courses, 68% reported using some form of peer assessment of verbal reports (i.e., oral presentations) [2]. A review of the engineering education literature reveals a number of engineering design courses that have implemented peer assessment of course deliverables and design artifacts beyond just oral presentations at various program levels, as early as first year courses. For example, students in a first year engineering design course at Harvey Mudd College participated in open critiques where they not only listened to the instructor's feedback but also participated in the review process itself [11]. Similarly, a recent study reported the implementation of a peer review activity in a first year engineering design class at the University of Strathclyde [12]. In that class, students reviewed their peers' product design specification documents anonymously through a web service. In general students found the experience to be positive and reported learning from both the acts of giving and receiving feedback [12].

In addition to implementations at first year and intermediate levels [13], there are also multiple reported examples of inter-team peer review activities in capstone design courses. For example, in an electrical engineering capstone design course at the University of Alabama, students participated in multiple 'share, review, revise, and report' exercises throughout the design process [14]. Peer feedback was provided in writing and the design components to be reviewed were limited to written documents such as the project definition [14]. Similarly, students in a software engineering design course at an undisclosed university sent each other their artifacts after each design phase and revised their design after receiving formal peer feedback [15]. Finally, in a software engineering course at the University of Virginia, teams presented their developed artifacts to the entire class and then answered questions posed by the instructor and other teams [16]. Interestingly, peer review is more commonly used in software engineering and computer sciences programs (as also observed in [15]).

Overall, implementations of peer review in capstone design courses – some of which described above - vary on multiple dimensions, including, but not limited to:

- Whether the work to be reviewed is done individually or in groups
- Whether the peer review is performed in writing or in face-to-face activities in which students/groups take turns in the role of reviewer/reviewee
- Whether the student review is active and primary to the review activity versus secondary and in support of the instructor's review

Based on the literature review, it appears that direct (i.e., face to face) student-centric peer review activities are rare. Yet, inter-team peer review can be well-suited to progress update meetings, which are a common face-to-face teaching context in capstone design courses. Traditionally, progress update (or progress review) meetings are used to (1) facilitate better project management and 'putting-to-practice' (i.e., to encourage steady project progress and to ensure sufficient participation by all team members) [17], and (2) to communicate progress to the instructor and, in some cases, to the whole class. Moreover, implicitly, progress update meetings can directly address and improve technical aspects of the design project. The rest of this paper describes and evaluates an implementation of semi-structured peer review in progress update meetings.

3. Implementation

3.1 General overview of the program

Management Engineering (i.e. engineering of management systems) at the University of Waterloo is a co-operative (co-op) engineering program accredited by the Canadian Engineering Accreditation Board (CEAB). The program is composed of a total of eight on-campus academic terms and six co-op terms in industry, each four months in length. Akin to other modern industrial engineering programs, it encompasses the themes of applied operations research, information systems, and, to a lesser degree, organizational theory and behavior. Students take a breadth of core courses in all three themes. Many specialize in their theme of choice through a combination of selected technical electives and co-op experiences.

All students participate in the senior capstone design project, which is composed of two consecutive mandatory courses taken in the program's final academic terms. The two terms are scheduled such that students go on their final (sixth) co-op term between the two. The average class size is 47 students. The capstone program as a whole is coordinated by two course instructors who share the tasks of soliciting industry projects, lecturing, and evaluating the students.

In the first course of the series, students form teams of 2-5 (more recently restricted to 4), narrow in on an open ended design problem, secure a faculty advisor, define their design problem, complete a needs analysis, and engage in a conceptual and preliminary design process that culminates in a low-fidelity prototype. Throughout the first course, they also participate in lectures covering relevant topics such as engineering design, engineering impact on society and the environment, project and client relationship management, and conceptual design. In the second course, students proceed with the detailed design phase, progressing to a medium and a high-fidelity prototype, and ending with design verification. The completed designs are showcased and reviewed at a public symposium in conjunction with other engineering disciplines.

In about 50% of cases, projects aim to solve an identified problem at a client company. These projects are commonly sourced from industry by the course instructors, faculty members in the department, or the students themselves through their co-op contacts. The client companies assign a project liaison that communicates with the project team on a regular basis. In some cases the faculty advisor will also serve as the company's liaison with the students. Examples of such projects include assignment and scheduling of resources and facilities in local hospitals, design and optimization of manufacturing and retail facilities, and design of new distribution and inventory management systems for multinational companies.

Opportunities to work with external customers involved in sponsoring design projects are highly valued for the rich context of professional practice that they bring into the program and design courses. However, at the same time, entrepreneurship and innovation are actively promoted and valued at the University of Waterloo. The institution has an inventor-owned intellectual property (IP) policy. It is not surprising then, that this spirit is imbued into students over the course of their academic and work term experiences. Therefore, many students choose to 'find' a design problem/opportunity of their own to use as the vehicle for their learning. Some design projects in this program have resulted in new venture start-up companies that continue to be successful. The 'customer' in this case, may be less directly accessible, since it may be a customer 'type' in a market segment and demographic. In some cases the products developed are for their peers who are readily available for feedback. Typical examples are various web and mobile applications to help with tracking of production data, project management, expense management, e-learning, and e-commerce.

The capstone courses include a series of assessment milestones. Throughout the two-course sequence, teams receive *formative* assessment in biweekly, semi-formal progress update meetings (PUMs). In each PUM, students present their progress in a 20-minute presentation to the course instructors. Depending on the stage of the design, the presentation may also include a demo of the design prototype. In addition to verbal feedback received during the meeting, teams also receive a written assessment of the demonstrated progress and detailed comments and suggestions. Teams give similar presentations and demos to their client companies' liaisons (i.e., the customer). Generally, feedback received in PUMs is used to improve later presentations to the customers.

Teams also receive *summative* assessment, which is provided in design review meetings (DRs) scheduled at the completion of each design stage. Normally, assessment in DRs is provided by the design review committee, composed of the course instructors, faculty advisors, and customer representatives (when available). While their attendance is not strictly enforced, the entire class is encouraged to attend DR presentations of all teams. Figure 1 illustrates the sequence of PUMs and DRs throughout the two courses.

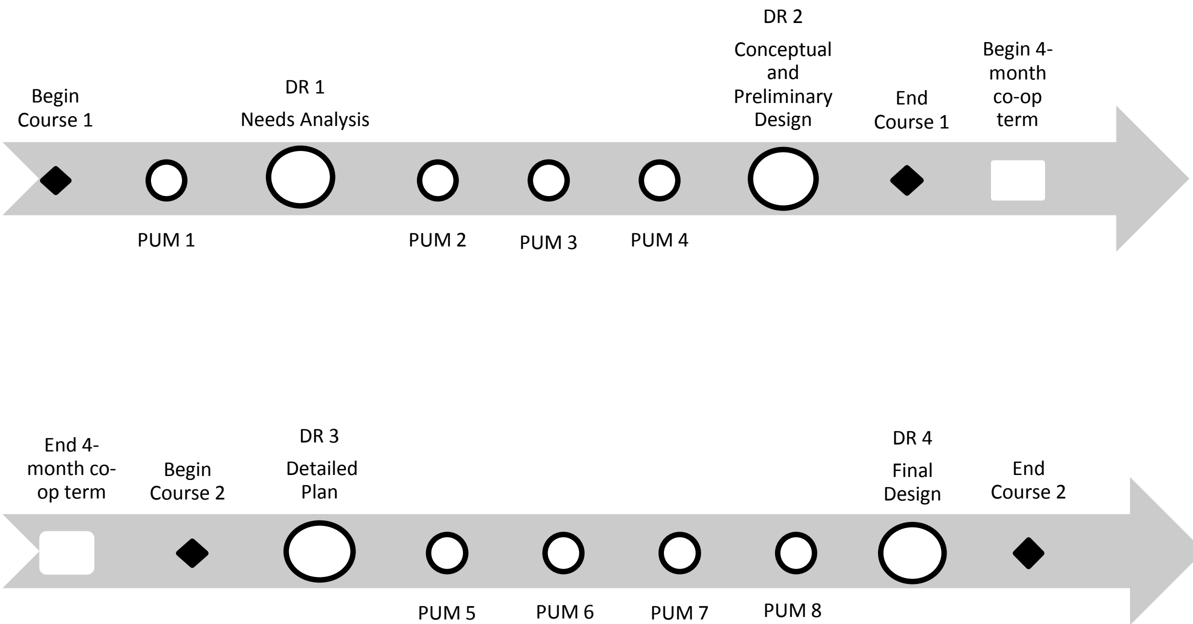

Figure 1 Sequence of PUMs and DRs in the two-course sequence of the capstone program

3.2 Two-team joint progress update meetings

In the first two offerings of this capstone program, PUMs were only attended by one group at a time. Groups were thus fairly isolated in their design experience, seeing the work of other groups only at DRs. Poor knowledge of other groups' design projects, progress, and challenges was a common student complaint. In the third iteration of the program groups were paired in joint PUMs. In this new format, piloted in Spring 2013, each team presented their progress not only to one of the course instructors but also to another team, seeking feedback and suggestions from everyone in attendance. The physical setup of the meeting space in both formats is illustrated in Figure 2. In its latest iteration in Winter 2014, each PUM was 80 minutes in length, allowing for a 20-minute presentation by each team and for sufficient discussion time during and after the presentations. Team pairings were based on their project topic and specialization; for example, a team working on a facility design was paired with a team working on a different facility design in PUM 1, with a team designing a schedule that reduced changeover at a client plant in PUM 2, and with a team designing a battery-generator switching policy in PUM 3. While in earlier iterations some teams were partnered with the same team in all PUMs, this practice was ended in Spring 2014. The question of whether teams should be placed in stable or alternating pairs is further discussed in Section 4.

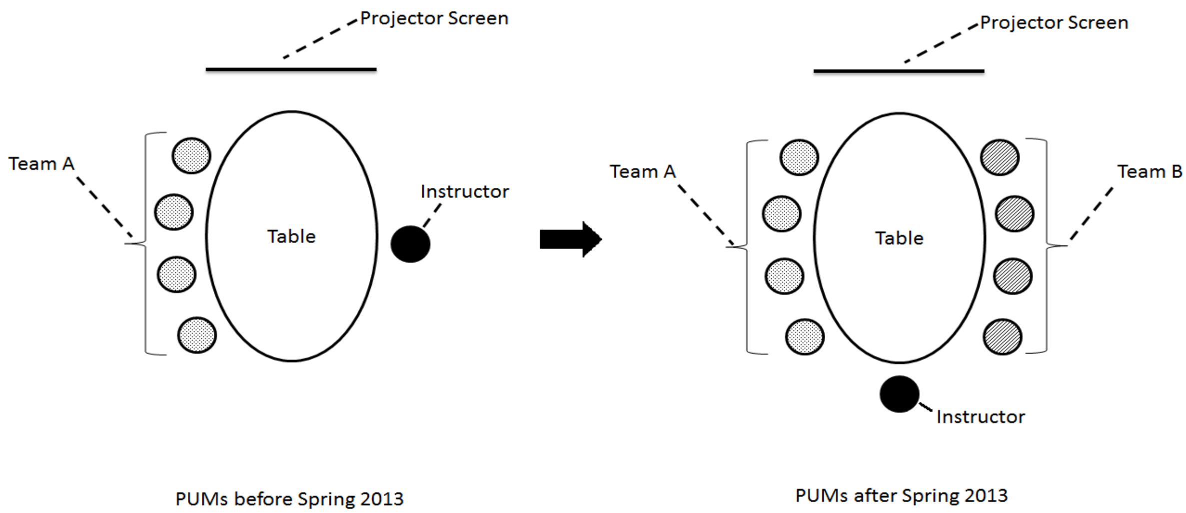

Figure 2 Physical setup of the meeting space in PUMs in the traditional and joint formats

Prior to Spring 2014, at the end of each meeting teams summarized their feedback in 2-page memos, not unlike the experience in at least one other capstone program [14]. Teams did not formally assess their peers; rather the feedback provided by each team was used to inform the instructors' evaluation of the assessed team. Each team was also evaluated on the quality of their peer feedback, with the main criteria being its thoroughness. However, it was found that students were not receptive to the requirement of writing formal feedback memos. Many saw this as significantly increasing their workload with little direct benefit to them or to the teams for which the memo was written. Therefore, beginning in Spring 2014, the written feedback component was removed. While students were encouraged to follow up with their peers outside of the PUMs, they were only expected to participate in the peer review during the meeting – the quantity and quality of the peer review provided verbally was graded as part of the overall PUM grade.

4. Evaluation

The first time they were implemented, joint PUMs were very well received and were recognized by the course instructors and the students as highly effective. In midterm course critiques conducted in Spring 2013, over 70% of the students identified joint PUMs as a specific component of the course that they found helpful as they progressed in their designs. Some of the student comments were:

"PUMs are good. Interesting to get fresh set of eyes and ears in on the presentations. Valuable feedback."
"PUMs are very helpful. Discussions with profs/class/other groups provide a lot of additional input that help verify project decisions, etc."
"Like the PUMs – very informative and gives an opportunity to 'expand your team' in a way, to [get] more heads thinking about the project"
"Progress update meetings continue to be essential."

While this type of informal feedback was helpful, efforts were taken to more formally assess the impact of peer review. Section 4.1 reports on a student survey that aimed to gauge the student-perceived value of joint PUMs. Of interest were potential benefits such as maintaining steady progress in the design project (Hypothesis 1) - especially motivated by competition (Hypothesis 2), receiving valuable feedback and ideas from faculty and peers (Hypothesis 3), and improving the communication of their design project (Hypothesis 4). The findings and results are further discussed in section 4.2.

Ultimately, the critical question is what overall impact the peer review activity has on the quality of the achieved designs; however, that analysis is beyond the scope of this initial assessment. That and other future research directions are considered in section 4.3.

4.1 Student perception of the effectiveness of joint PUMs

While informal student feedback and anecdotes pointed at an effective implementation, it was not clear what specific aspects of the PUMs students were finding most helpful. The following analysis seeks to unpack what were believed to be the main advantages.

As discussed in Section 2, one of the primary uses of PUMs was intended to be the encouragement of steady progress in the design project. If students had to formally report on their progress to the instructor, they would actively manage their project so that they actually *had* progress to report at each meeting. It was thus hypothesized that:

Hypothesis 1*: PUMs helped teams maintain a steady progress throughout the course*

In industry, organizational practices occur in both collaborative and competitive contexts. While collaborative practices are more desirable, the reality of organizations means that competitive contexts within organizations also exist. Similarly, it was expected that joint PUMs would become a catalyst for inter-team interactions that increased not only learning and cooperation, but also competition. When teams attended joint PUMs, it was believed that there would be more pressure to increase the quality and amount of progress presented. Learning about another team's progress, even if they were working on a different project topic (as was always the case) would help teams gauge whether their own progress was adequate. It was thus hypothesized that:

Hypothesis 2*: Joint PUMs encouraged competition between teams and thus encouraged them to work harder*

The multidisciplinary nature of the Management Engineering program is reflected in a great diversity of multidisciplinary capstone projects, which in turn require a wealth of expertise in differing fields such as software engineering, data analytics, supply chain and operations management, mathematical optimization, and user behavior studies. By their fourth year, through their technical electives, co-operative work experiences in industry, and self-directed learning, students have already begun to concentrate in one of the program's major specializations. Having two teams present at each PUM increased the probability that students with varying interests, skills, and experiences would be present to critique each project. It was also informally noted that there was an increased number of ideas generated at the PUMs, especially in the first phase, when groups were in their initial stages of scoping their design projects and wrestling with different design concepts. The joint PUMs created an economies-of-scale effect: at least during the duration of each meeting, the number of students working on each project virtually doubled. In addition, it was observed that many students found that they were facing similar challenges or had faced similar challenges in the past. The shared problems resulted in sharing of solutions, thus increasing inter-team collaboration and overall problem-solving effectiveness. In earlier iterations, when groups were also required to submit feedback memos after each PUM, it was noted that the memos contained additional advice and ideas – evidence that each group continued to think about their paired group's challenges even after the meetings. It was thus hypothesized that:

Hypothesis 3*: Students received valuable suggestions and constructive criticism from both the instructor and students of other teams in joint PUMs*

Technical communication is best learned in an authentic engineering task environment and especially when the quality of communication is judged by how well the medium of communication successfully exchanges information, not how well it fits an instructor-imposed template [18]. Joint progress update meetings have the potential of making the communication of design progress an authentic activity. If the goal is to ultimately learn how to communicate engineering design to a variety of audiences, why not start by learning how to communicate to a variety of peers? It was hypothesized that:

Hypothesis 4*: Varying the pairings in each PUM helped teams improve their project communication*

4.1.1 Method

An anonymous student survey was administered to the class who participated in the described peer review activity in Spring 2014, then enrolled in their first course of the two-course design project series. The survey was embedded in a larger course critique survey and was completed by 31 students (of 55 total) at the end of the term. Students were asked to note their level of agreement (or disagreement) with the following statements on a 5-point scale:

1. The PUMs have helped our group maintain a steady level of progress in the project
2. We have received good feedback (suggestions and constructive criticism) from *[the course instructor]*
3. We have received good feedback (suggestions and constructive criticism) from *students from other teams*
4. The PUMs helped us refine the communication of our project need and design
5. The PUMs helped us share valuable ideas with students from other teams
6. Seeing the progress of other teams made us want to work harder
7. Meeting with a different team in each of the PUMs was beneficial to our team
8. In [the second design course of the sequence], I would like our team to continue meeting with a different team in each of the three PUMs
9. The format of the PUMs (length, structure, level of formality) was appropriate

The instructors received the raw student feedback weeks after the completion of the course. Student answers were manually recorded and analyzed.

4.1.2 Results

Hypothesis 1 predicted that regular progress update meetings would push the teams to maintain a steady progress level between meetings. It was also hypothesized (Hypothesis 2), that added peer pressure of inter-team competition would be one of the ways by which PUMs drove progress. These hypotheses were tested using the answers to survey questions 1 and 6 respectively. Student answers are summarized in Figure 3.

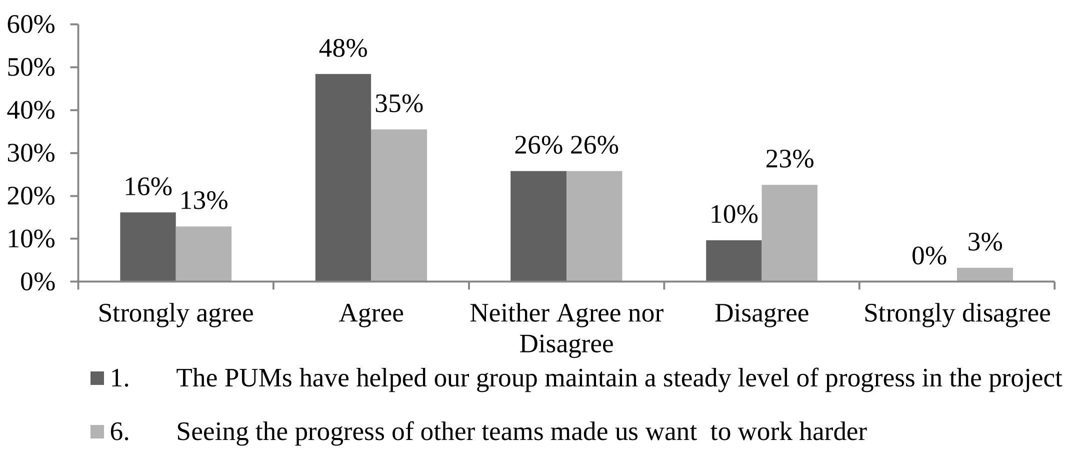

Figure 3 Student perception of the effect of joint PUMs on design progress (survey questions 1 and 6)

The student responses provided some support for the two hypotheses. There is an overall agreement (16% strongly agree and 48% agree) that PUMs drove steady progress; however, only about half the surveyed students reported benefiting from a sense of competition with other teams. In fact, over a quarter of them disagreed with this. In hindsight, this result can be easily explained. Assuming that in most pairings one team had progressed more than the other, seeing this progress would be motivating to the team that had progressed less, and it would likely be of little motivation to the better-progressing team.

The responses to questions 2, 3, and 5 were used to test Hypothesis 3. The prediction was that the open discussion with another team and the course instructor would result in helpful feedback and valuable ideas shared from all participants. Based on the survey results (displayed in Figure 4), 58% of students agreed or strongly agreed that they received good suggestions and constructive criticism from the instructor. An even higher portion (62%) reported this with respect to feedback provided from their peers. Finally a strong majority of students (70%) reported sharing valuable ideas with students from other teams. The results of the survey provide good support for Hypothesis 3.

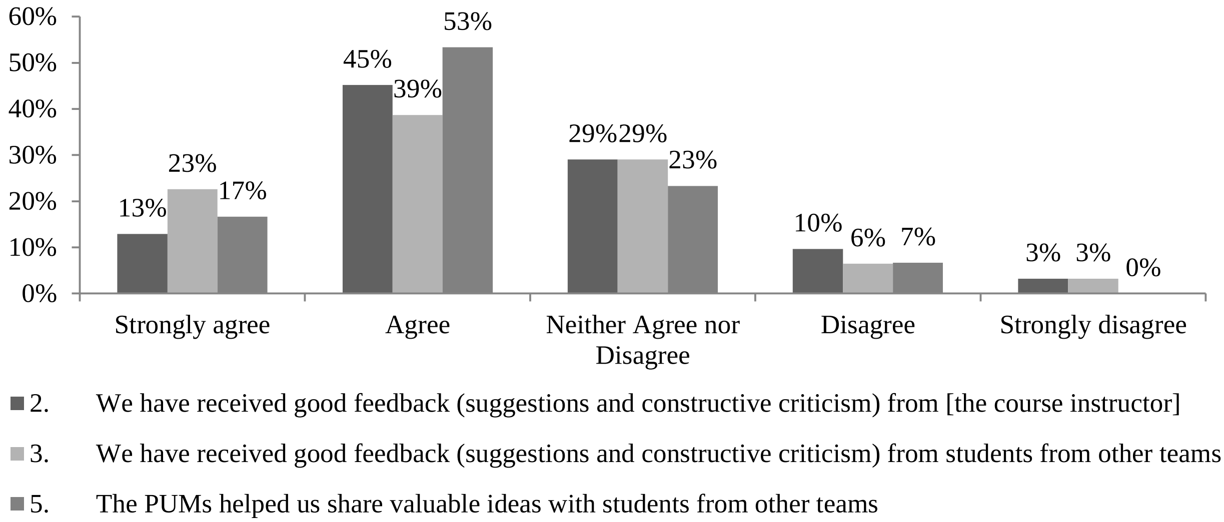

Figure 4 Student perception of feedback and ideas received in joint PUMs (survey questions 2, 3, and 5)

A final prediction (Hypothesis 4) was that the joint PUM format would be beneficial to students in terms of learning how to communicate the various stages of their design effectively. A summary of the answers to survey question 4 - which was used to test this hypothesis – is given in Figure 5. Of the surveyed students, 70% agreed or strongly agreed that this was the case.

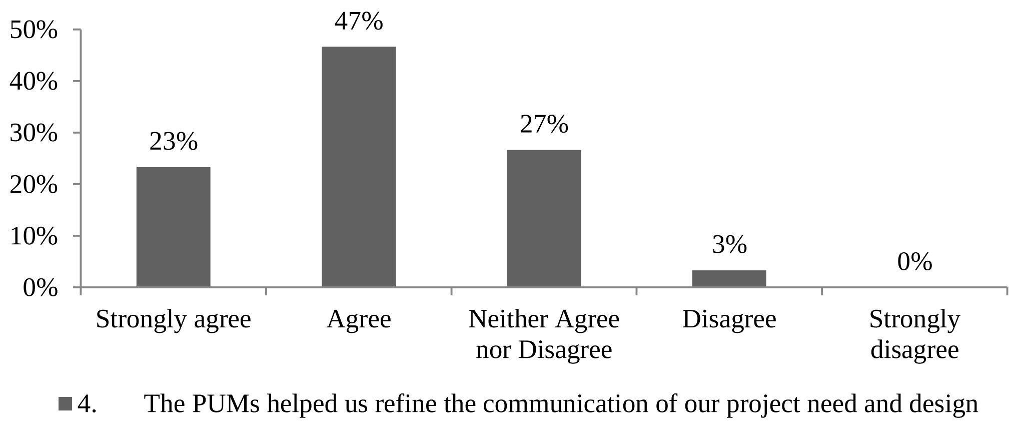

Figure 5 Student perception of the effect of joint PUMs on improving communication of design (survey question 4)

In the first implementation of joint PUMs, some of the teams alternated pairings in each PUM, while others were in stable pairings throughout the term. Anecdotal evidence at the time suggested that some students preferred being matched in stable pairs throughout the term. Their reasoning was that this made them comfortable and well familiarized with the other team's project. However, limiting the pairings to be fixed reduced the benefits that come from having a project peer-reviewed by a larger number of students. In the Spring 2014 implementation, all teams attended each of their PUMs with a different team. Questions 7 and 8 of the survey asked students directly about their experience with this format. Survey answers are summarized in Figure 6.

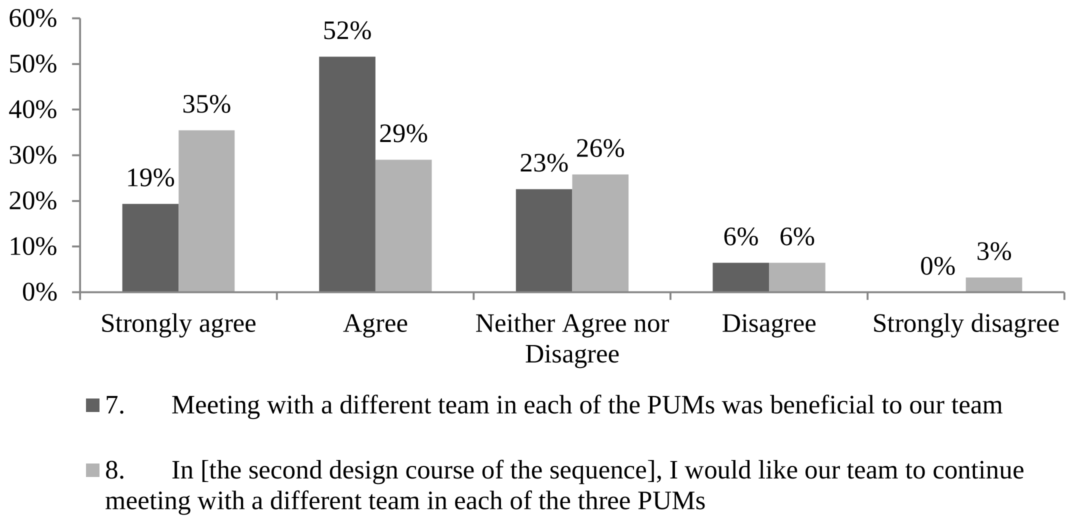

Figure 6 Student perception of the utility of alternating paired teams in each PUM (survey questions 7 and 8)

Overall, students reported being happy with this choice. Of those that completed the survey, 19% strongly agreed and 52% agreed that they saw benefit in meeting with a different team in each PUM. Similarly, 35% strongly agreed and 29% agreed that they would like the same format to be continued in the second course of the sequence. However, this data only support the choice of changing pairings to some extent. None of the surveyed students had participated in a stable-pairing sequence of PUMs, therefore they were limited in their ability to judge one format over the other. Nevertheless, it was encouraging to see that students supported the format enough that they did not want it changed in the second course of the sequence.

Finally, question 9 on the survey was used to assess the overall effectiveness of the PUM format. In particular, the question asked students to consider the length, structure and level of formality employed in the meetings. The answers to question 9 on the survey are summarized in Figure 7. A strong majority of the surveyed students (84%) reported finding the format appropriate. Only 1 student disagreed with this statement.

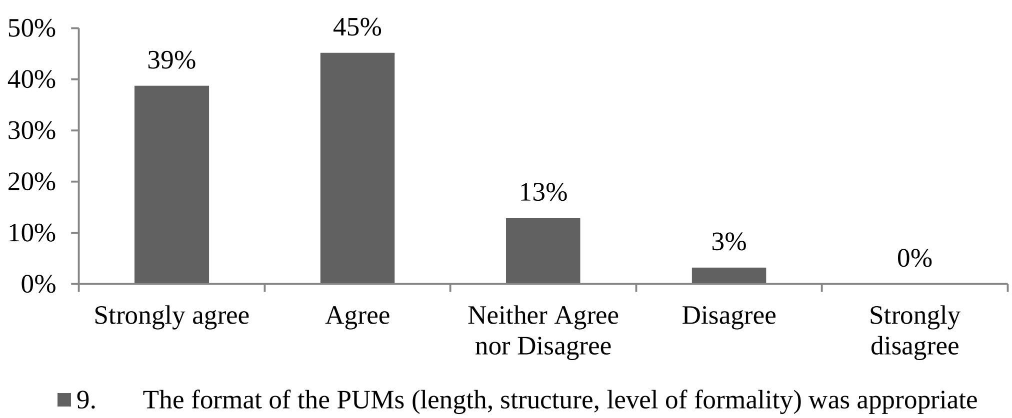

Figure 7 Student perception of the organization and format of joint PUMs (survey question 9)

4.2 Discussion

It is clear from the results of the student survey that the inclusion of an additional student group in the PUM is beneficial in several important ways. First, students found the biweekly meetings useful in driving steady progress in the design project. For about half of the respondents, witnessing another team's progress was in itself a source of competition that motivated them to work harder. Second, students received valuable feedback and ideas not only from the course instructor, but also from their peers. Third, the practice of presenting to a diverse and, in most cases, changing audience helped teams refine how they communicated their design problem and solution. Overall, students' perceptions of the usefulness of the meeting format and conduct were very positive. This is important; it is known in the motivational literature that student engagement leads to mastery [19] and that this is crucial to deep learning [20]. This is in contrast to the more traditional review meeting where students 'wait' for questions to be asked and then respond, as opposed to being actively engaged in dialogue with their peers.

The meetings' informal format, the sometimes significant difference in quality between paired projects, the considerable effort that teams put in working on the projects, and (as a result) the considerable attachment of teams to their project topic, all contributed to sometimes poor reception to criticism or negative feedback. While most meetings were cordial and supportive, proper handling of criticism was not seen at all times. Joint PUMs reinforced the importance of knowing how to provide and receive criticism (often categorized under CEAB's graduate attribute of 'professionalism' [21]) and provided a recurring opportunity for students to practice it and for the instructors to evaluate it. Joint PUMs sought to establish a standard of ego-less [22] design, where the critique of the design progress and artifacts was not a critique of the designers.

In "Educating the Reflective Practitioner" [23], Donald Schon speaks of the dual orientation of a professional school – one 'discipline-oriented' and the other 'practice-oriented.' He goes onto espousing the importance of the school containing a 'reflective practicum', where "the role and status of a coach take precedence over those of a teacher as teaching is usually understood" [23]. The joint PUM format is conducive to creating a context of 'coaching' rather than a context of 'professing' for the instructor. This context allows students to 'try' while coaches 'adjust' and provide 'advice', as things unfold. In this case, we also have the other students present practicing their ability to provide advice as well.

This leads to a variety of potential misuses of the method. For example, instructors who are uncomfortable with providing negative feedback can often fall into the trap of trying to use the students in the PUM to back them up on their points of criticism. Musing about the role of the instructor in the architecture studio, Dinham describes a particular professor who "when she doesn't approve of a student's solution she hints to the student and asks other students to comment, which they often seem loath to do. She often persists, however, in eliciting from the on-looking students the judgments she herself has made, after which she can assume her customary – and presumably more comfortable – role of summarizing and advising" [7, p. 9] In addition, one may wonder if in this new role, the authority of the course instructors to override unhelpful or misleading critiques from students is compromised.

Another question that arises is with respect to how teams should be paired. Certainly, beyond exposure to different ideas, assigning teams to different pairs in each PUM also has an impact on how students' progress in improving the communication of their project. When teams met with the same team in each PUM, they remained in a comfort zone of only explaining their problem once in the first PUM and then only reporting on their progress in the following PUMs. Teams that met with different teams in each PUM were forced to explain and re-explain their design problem to someone new each time. In every PUM their audience questioned the presented problem definition in various ways. This not only helped improve the teams' understanding of the problem itself but also helped the team refine how they communicated their design projects.

Whether fixed or changing, so far, all pairings have been based on the similarity of topic; however, it is possible that groups may have something to gain from participating in a peer review process with dissimilar teams/topics. In later implementations of joint PUMs, especially in the second capstone course in the series, teams have been given the opportunity to voice their preferences on which teams they would most want to be paired with. There is evidence from the literature that this approach can improve the review [24].

As previously mentioned, the feedback memos were not perceived by students as adding significant value to the peer review process, but instead, were classified as 'non-design' overhead course work. It is worth considering changing this requirement to better suit course learning outcomes. Feedback memos, while onerous for the students, provide valuable data on students' reflections of the designs critiqued and the review meeting effectiveness. This should likely be extended to instructors and review committee members as well.

4.3 Future research

While the preliminary evaluation of peer review as implemented in the capstone courses reported in this paper provides some justification as to its benefits, there are yet more questions that can be asked and improvements that can be made to the evaluation methodology. Future work on peer review as a useful formative assessment tool in capstone design could indeed take many forms:

A starting point would be a better characterization of peer review, in particular from a descriptive point of view. Refinement of the data collection can also be used to characterize quantity and quality of feedback received in PUMs. The impact of both quantity and quality of feedback provided, by novices and by experts, on design project outcomes and, separately, deep learning of design and other graduate attributes is still to be assessed. Do experts offer potentially more significant feedback than novices, and if so, why?

In addition, what role does dialogue play in contributing to design project outcomes and students learning of design? This is distinguished from direct question/answer behavior in the course, since one answer may lead to further question(s) and 'lines' of questions. How do these 'lines' evolve and how do they contribute to design project outcomes and to the learning outcomes?

Finally, the method of collecting data can be improved. Video recording during PUMs and DRs would refine the collection and shed better light on not just the type and number of questions, but also on the nature of the dialogue that ensues during exchanges where enlightening feedback is provided. This may provide additional insight into the structure of the dialogue and reveal important communication patterns in peer-to-peer (i.e., novice-to-novice) and expert-to-novice channels.

5. Conclusions

It is broadly recognized that the lecture method of teaching can only go so far in facilitating the learning of important technical and non-technical learning outcomes in a capstone design sequence of courses. New educational strategies and practices are required – strategies and practices that achieve deep learning of cognitive, affective and behavioral outcomes while respecting the constraints of human, financial and material resources of an educational institution.

Most engineering programs do not have the studio as the central culture or physical environment that architecture programs require. As a result, the culture of combined instructor, practitioner and peer critique is not common. Common approaches to critique include assessment of reports, instructor-alone assessment of the group, class level peer assessment or practitioner/expert-only assessment formats.

This work provides some evidence of an improved critiquing model and practice that is feasible within current curricular designs and educational resources. In the new model, student peers, in addition to instructors, become participants in the design review. This model better reflects the long-standing practice of critique in design-centric programs like architecture and provides students an opportunity to learn and practice the art of critique by active participation and reflection. A preliminary assessment of the model's implementation has shown that it positively impacts student learning in several ways, including providing motivation for maintaining steady progress in the design project, allowing for the sharing of feedback and ideas between teams, and helping students refine the communication of their design project. This optimized format is very promising and requires further work in the future to assess learning impact by using outcome-based assessment methods and/or protocol analysis of the student discussions.

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Tables and Figures

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