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Design Argumentation on Multidisciplinary Teams: An Analysis of Engineering Design Team Communication Effectiveness

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Abstract

Modern engineering challenges are complex and require multidisciplinary teams of designers to successfully solve these problems and communicate their design solutions to stakeholders. While past literature has documented how engineering students use rhetorical features such as linguistic cues and gestures as they prototype and design, few scholars have investigated how students use disciplinary language while working in teams, and in particular multidisciplinary design teams. As many capstone engineering experiences seek to embed authentic multidisciplinary experiences into their settings, instructors may wonder whether if and how interdisciplinarity affects the outcomes of the engineering projects or the quality of the final design pitch. In this study, design pitches were analyzed from n = 45 senior-level multidisciplinary engineering design teams at a large research-intensive university using a framework adapted from prior literature to evaluate the quality of disciplinary discourse. Qualitative content analysis methods were used to calculate a design argumentation score (i.e., a measure of how effective the team was in advocating for their design) for each group comprising the mean disciplinary discourse score of the group over the occurrences of disciplinary communication. This score (captured by a quantitative measure of the diversity of engineering disciplines represented in the group) was examined in relationship to the disciplinary diversity of each team. Results show that for the teams involved in this study, disciplinary diversity of design teams did not have a statistically significant effect on design argumentation quality, indicating this factor does not need to be considered in future research. This paper also presents a novel framework to assess the quality of argumentation in design pitches and could be useful for future research or practice applications.

Keywords

engineering education, design communication rubrics, presentation analysis, undergraduate capstone project

Introduction and Literature Review

The Engineering Grand Challenges [1] represent the fourteen most important engineering problems to be addressed in the 21st century. These multidisciplinary challenges include making solar energy economical, restoring and improving urban infrastructure, providing access to clean water, and developing carbon sequestration methods. To address these design challenges, engineers in multidisciplinary teams must be able to communicate and justify their designs effectively for their work to be valued and implemented by stakeholders. Therefore, it is essential that graduating engineering students can work in interdisciplinary teams and communicate effectively. However, as Berdanier [2] noted, communication skills are an undervalued component of engineering competence. In addition, Trevelyan [3] observed that many students perceive these communication skills as less important than technical skills, and many graduates enter the workforce without the skills to effectively collaborate in a team composed of people with varied technical expertise.

While engineering design instruction and practice have been extensively studied across K-12 [4], undergraduate [5,6], and practitioner contexts [7], Dym [8] accurately proposes that engineering practice, for the most part, is not aligned with undergraduate curricula. Furthermore, most curricula are very structured and focused on analysis, not design or the associated inter-personal skills which constitute much professional practice. Engineering education that emphasizes culminating skills in lieu of a list of courses would provide a better alignment between professional practice skills and undergraduate education [9, 10]. Research also discusses the role of internal reflective conversations in creating effective designers. Literature has shown that accomplished designers reflect on their design experiences to improve their future work and practiced engineering designers thoroughly engage in problem setting and reflective conversations [11-13].

Conversation during engineering design is not only important in internal reflective conversations but also in external communications with colleagues and stakeholders to successfully advocate for a solution. Researchers have examined how engineering design language is used to communicate design work and how this language evolves over time during undergraduate and practitioner settings [14-18] – even finding that effective argumentation can result in improved designs [19]. There are multiple forms of communication that are used to advocate for a design, such as linguistic cues [25,26], engagement with props and prototypes [20-24], written reports [27-30], and gestures [31]. However, students are typically only taught communication through a few traditional methods. For example, Morton and O'Brien [32] observed that students are usually taught two methods of oral design argumentation: a public speaking approach and a genre-linguistic approach. They also observed that instruction in public-speaking usually consists of motivational advice concerned with performance strategies and does not tend to offer specific advice for appropriate structures and language forms for effective speaking in design presentations. The authors noted that a genre-linguistic approach can best offer a description of performance strategies and rhetorical structures.

While some scholars have begun to analyze engineering communication [27, 33-35], effective design argumentation in multidisciplinary teams has not been well-studied. As educators are working to make design education more practical and realistic, multidisciplinary design challenges are becoming common in capstone design courses (e.g., [36-40]). However, little research has examined whether, and to what extent, the multidisciplinarity of a team drives communication and argumentation decisions. This study investigated how team multidisciplinary (denoted "disciplinary diversity" of the design team) affects the communication strategies employed by senior-level engineering design students at a large, public university.

Methods

Context and Data Collection. This study was conducted on transcripts of student presentations given for the Fall 2019 Senior Design Showcase at a large R1 university in the Mid-Atlantic United States. The Senior Design Showcase projects were scoped to solve real-world engineering problems experienced by industry sponsors. One of the core components of the Senior Design curriculum is that teams are multidisciplinary (i.e., the teams include students from multiple disciplines within the College of Engineering). The teams were composed of students from three colleges: Engineering, Earth and Mineral Sciences, and Information Sciences and Technology and were interdisciplinary in composition. Ninety-eight percent of the project teams contained students from multiple departments from these colleges, while sixty percent of the teams consisted of students from three or more departments.

The capstone design projects were facilitated over the course of a semester through regular class meetings supervised by engineering faculty members across the College of Engineering. As part of the course, students were prepared to communicate their final projects at a public end-of-semester showcase event, where design teams presented their project pitches, posters, physical prototypes, final products, and/or other design artifacts.

To investigate engineering communication patterns on these multidisciplinary design teams, the data for this project comprised audio recordings of final pitches from the design teams. As part of a broader National-Science-Foundation-funded and Institutional-Review-Board-approved project investigating communication and prototyping, the design teams were videorecorded at the design showcase; the audio from these video recordings comprised the data for the present research. As described in prior literature (see Krishnakumar et al. [41]), a team of ## undergraduate and graduate research assistants were deployed with video cameras to film and collect data on the design teams as they presented their final pitches. The audio files for this project were transcribed by a professional transcription service.

Analysis Procedures: Determining a Measure of Disciplinary Diversity. The extent to which teams were multidisciplinary was quantified by an established metric called "disciplinary diversity" as proposed by Krishnakumar et al. [41], which resulted in a single metric for each team that represented multidisciplinarity. As such, a score of 0 would represent a team that was fully homogeneous (all students from the same department of engineering) and higher scores would represent more diverse teams. Sufficient data regarding student engineering disciplines were available to calculate the disciplinary diversity of the 45 design teams represented in the present study.

To calculate the disciplinary diversity of each of the student design teams, we employed a method called Shannon's Information Entropy established in prior literature which originated in ecological sciences [42] but has been expanded to describe groups of people by other [43,44] and in our related research [45]. As shown in Equation 1,

$$H = \sum_{i}^{n} p_i \ln(p_i) \tag{1}$$

the entropy of a system, H, will be higher when the probability of the i^{th} outcome in the system is low, capturing the fact that the system has higher information information). In our case, if the probability that a team member is a member of a single discipline is low, that represents the disciplinary diversity of the team, and the resulting H will be higher. Conversely, a system with a higher probability of an outcome (i.e., more students belonging to the same discipline), the resultant H value will be lower, capturing a lower amount of information entropy between participants. In this way, this information entropy value can represent the disciplinary diversity of the teams: A more homogenous team will have a lower H score, and a more diverse team will have a higher H score, which will be the measure of team disciplinary diversity in this paper.

Analysis Procedures: Development of Qualitative Codebook for Argumentation Quality in Design Pitches. To analyze the data, a codebook was developed to assess the fidelity of the argumentation employed in each sentence of each of the 45 design pitches. The goal of the codebook was to act as a rubric of quality to determine the effectiveness of the design argumentation in the pitches. This codebook, shown in Tables 1 and 2 along with examples from the transcripts representing each category, was developed through iteration in research team members conversation, and then employed as a coding schema for content analysis for all 45 pitches for this paper to create more consistency in the analysis of the presentations [57-60].

To understand how argumentation strategies were employed by teams, two different analysis methods were used. Method One consisted of analyzing only the "design pitch" sentences of the presentations (omitting sentences scored as "0"), while Method Two involved analyzing all sentences in the presentation. In general, each sentence was coded individually using the rubric in Table 1, except in a few cases when multiple sentences were combined to represent a single thought, due to the fragmented way spoken language is transcribed into sentence format. For both methods, a single value representing the argumentation quality was determined by averaging the score by the number of sentences analyzed in that method.

Table 1: Rubric for design argumentation analysis and example of coding – Method One (design pitches only).

Score	Description	Example
Novice (1)	Sentence has a minimal connection to the design and lacks detailed information or explicit connection to the strengths of the design. Sentence indicates client is not satisfied.	"Yeah. So after the design phase, we 3D printed those parts and we combined them, and then we began the testing phase."
Intermediate (2)	Sentence has a moderate connection to the design but lacks detailed information and/or explicit connection to the strengths of the design. Sentence is unclear as to whether or not client is satisfied.	"We started by making this (word unclear) claw this semester which will eventually be further automated with LIDAR and computer vision type of things."
Proficient (3)	Sentence has a strong connection to the design and contains detailed information and explicit connection to the strengths of the design with justification. Sentence includes evidence of client satisfaction with design. Design strength can be evidence by comparison to other alternatives.	"This sensor is actually even more accurate than LIDAR sensors because they can pick up, uh, measurements half a meter or up to 100th of a millimeter."

Table 2: Rubric for design argumentation analysis and example of coding – Method Two (all sentences in presentation).

Score	Description	Example
Off Topic (0)	Passage has no relation to design (ex: team introductions).	"All right, so good afternoon. I'm (name 1) and, uh, these are

		my teammates, (name 2), (name 3), (Name 4) and (name 5)."
Minimal (1)	Passage is related to project but is not design argumentation (ex: discussion of design process, future work, and/or how team worked together). Passage consists of repeated information already presented.	"And then the final step would be to automate this process using different sensors such as LIDAR and cameras, and then developing a computer vision algorithm to help make it fully autonomous throughout the citrus groves."
Novice (2)	Passage has a minimal connection to the design but lacks detailed information and explicit connection to the strengths of the design. Sentence indicates client is not satisfied.	"And lastly, we recently found this new material, lightweight PLA that when printed at a slow rate, will expand, the density will go down, making it a much lighter material in the end."
Intermediate (3)	Passage has a moderate connection to the design but lacks detailed information and/or explicit connection to the strengths of the design. Sentence is unclear as to whether or not client is satisfied.	"The arm itself is currently scaled down for simplicity and for our sake and transportability. But it has 5 servos all throughout to provide a very large range of motion to accommodate any tree that we need to."
Proficient (4)	Passage has a strong connection to the design and contains detailed information and explicit connection to the strengths of the design with justification. Sentence includes evidence of client satisfaction with design. Design strength can be evidence by comparison to other alternatives.	"Um, with our second design in our final iteration of this nozzle we went with a one inlet at the center of the plate, and then we had outflows at each of the corners, um, to help spread the water out more evenly across the plate and also hit it, the plate where it's the hottest when it comes to electronic cooling."

Results

Using the two methods described, each design pitch was analyzed. Following is a sample of the coding done using Methods One and Two.

Table 3: Sample of coding using Methods One and Two.

Passage	***Method One Ranking (1-3)***	***Method Two Ranking (0-4)***	***Notes***
All right. So, uh, our project was to design a liquid cooling unit for a CPU that could outperform some of the face, um, the stock fans that we have on the market	n/a	1	Project scope information

And to also find, um, one of our goals is to find a way to make things cheaper for liquid cooling units	n/a	1	Project scope discussion
So with this, we decided to go with, um, copper plates for these designs, and then a 3D printed, uh, plastic nozzle.	2	3	Missing details.
Um, in our first design, we went with a, uh, two inlet, uh, two outlets for the plate	2	3	Why? Not explained.
So each of the corners had, um, a nozzle hole thread into it for the flow to go through. And, uh, the flow would go across the plate to the others where it would be exfilled and taken out of the unit.	2	3	Advantages?
Um, with our second design in our final iteration of this nozzle we went with a one inlet at the center of the plate, and then we had outflows at each of the corners, um, to help spread the water out more evenly across the plate and also hit it, the plate where it's the hottest when it comes to electronic cooling.	3	4	Delivers water to where plate is hottest.
Do you wanna talk about the uh…	n/a	0	Introduction of team members
So when we're doing the test and then the simulations on it, we find that the CPU most heated at the center, so we incorporate the nozzle at the center. (word unclear).	3	4	Design backed by simulations.
We designed some different copper plates with it. And, uh, so that, uh, the reason why we picked copper is because typically in the market, you either use copper or aluminum, but then copper has a better thermal conductivity of it. And then aluminum is lighter than copper so it's even harder to machine it. But we actually machined the copper, we still got the deburrs, we can imagine how hard it would be to actually machine with aluminum.	3	4	Advantages of copper detailed.

The numerically coded data were also entered into and analyzed using Microsoft Excel to perform the statistical analysis and plotting as described below.

Disciplinary Diversity of the Teams. For the 45 teams analyzed in this study, the mean disciplinary diversity score was 0.74, with a median of 0.91 and a mode of 1.04. The sample standard deviation of the data was 0.40. Figure 1 is a histogram of this data.

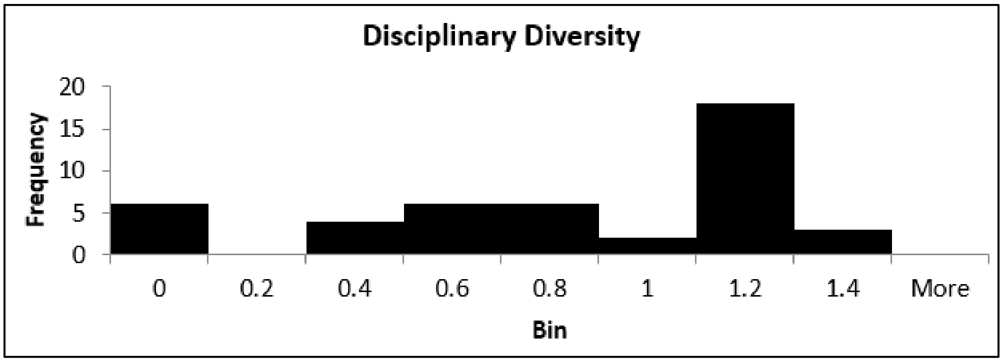
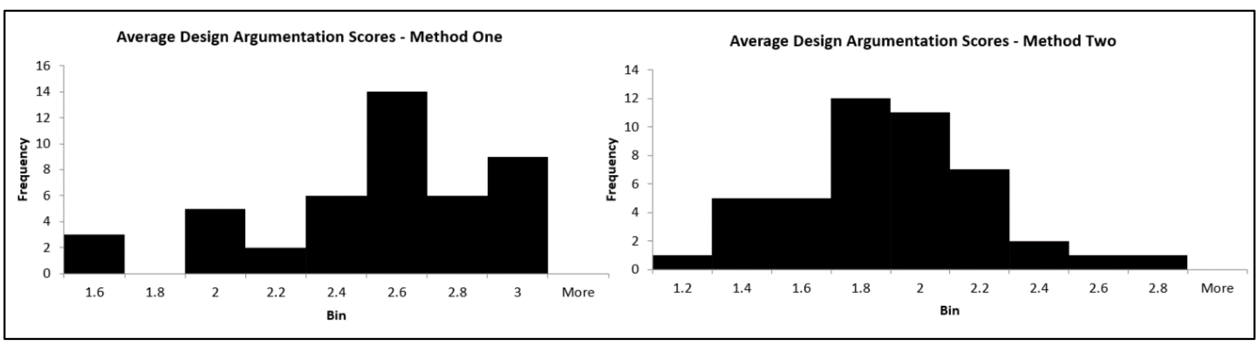


Figure 1: Histogram of Disciplinary Diversity Scores

This histogram is left skewed, indicating that the bulk of the teams had a significant amount of interdisciplinarity, which is to be expected based on the parameters of the team makeups for this project. The histogram also shows that there is a significant range of data which allows for the analysis to cover both low and high amounts of disciplinary diversities in the teams to discover relationships and trends in the data.

Descriptive Statistics Representing Argumentation Scores.

Method One: For the 45 teams considered in this study using Method One (which entails coding only those passages directly related to design argumentation), a total of 391 passages were coded with a mean of 8.69 passages per presentation and ranged from 2 to 15 passages per presentation. The mean of the Average Design Argumentation scores was 2.45 with a median of 2.50 and a mode of 1.04. The sample standard deviation for this data was 0.40. Figure 2 is a histogram of this data.



Figures 2 and 3: Histograms of Average Design Argumentation Scores Using Method One and Method Two, Respectively.

This histogram is slightly left skewed, indicating that the bulk of the teams had a moderate amount of higher disciplinary argumentation scores. This is expected since only relevant design pitch passages were scored.

Method Two: For the 45 teams considered in this study using Method Two, a total of 1076 passages were coded with a mean of 23.91 passages per presentation and ranged from 9 to 37 passages per presentation. The mean of the Average Design Argumentation scores was 1.81, with a median of 1.79 and a mode of 1.65. The sample standard deviation for this data was 0.33. Figure 3 is a histogram of this data.

This histogram shows a more normal distribution than the previous histogram, indicating that the non-design pitch statements in the presentations produce a smoother distribution of scores throughout the range of the data.

Summary: Table 4 below summarizes the data presented above.

Table 4: Summary of Methods One and Two data

Metric	**Method One**	**Method Two**
Team Disciplinary Diversity:		
Mean (SD)	0.74 (0.40)	0.74 (0.40)
Median	0.91	0.91
Mode	1.04	1.04
Passages Coded		
Total	391	1076
Mean Passages/Group	8.69	23.91
Range	2 - 15	9 - 37
Average Design Argumentation		
Mean (SD)	2.45 (0.40)	1.81 (0.33)
Median	2.50	1.79
Mode	1.04	1.65

Comparison of Methods: Since Method Two involves quantifying all the passages in the presentation, rather than just those that pertained to technical details, it is expected that Method One's average design argumentation scores would generally be greater than Method Two's average scores. However, for a few teams, Method 2 resulted in a similar or slightly lower score, which indicates that these teams not only had very few technical details, but the technicality of the overall presentation was not high. Figure 4 below is a plot of these average scores for each team presentation analyzed and figure 5 compares the average design argumentation scores for each team using the two analysis methods.

For both methods, the data was entered into a Microsoft Excel spreadsheet and plotted. For figure 5, a best-fit line was also calculated using Microsoft Excel and an equation for this line (along with a correlation coefficient) was determined, as shown on the graphs.

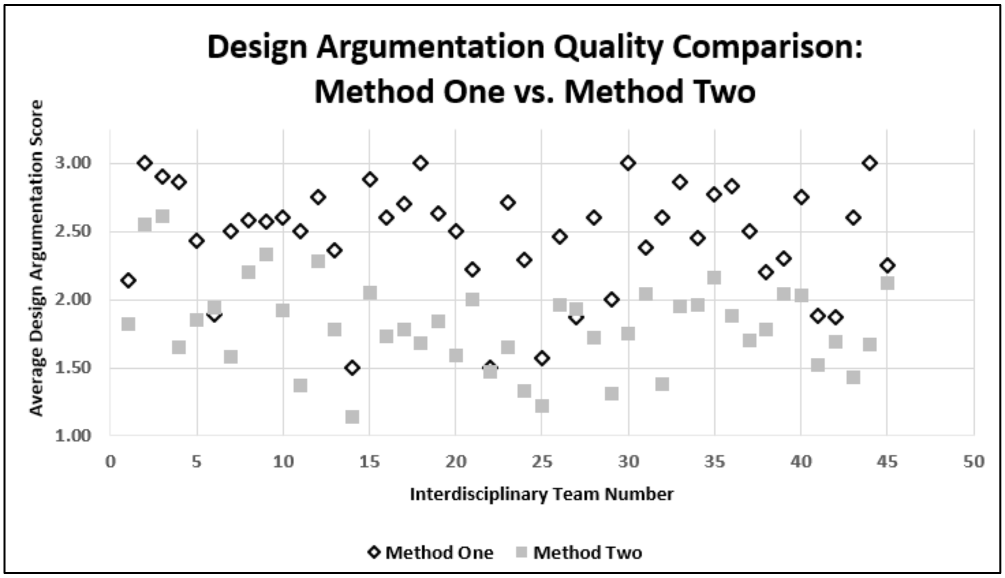


Figure 4: Plot of Average Design Argumentation Score of Methods One and Two vs. Interdisciplinary Team Number

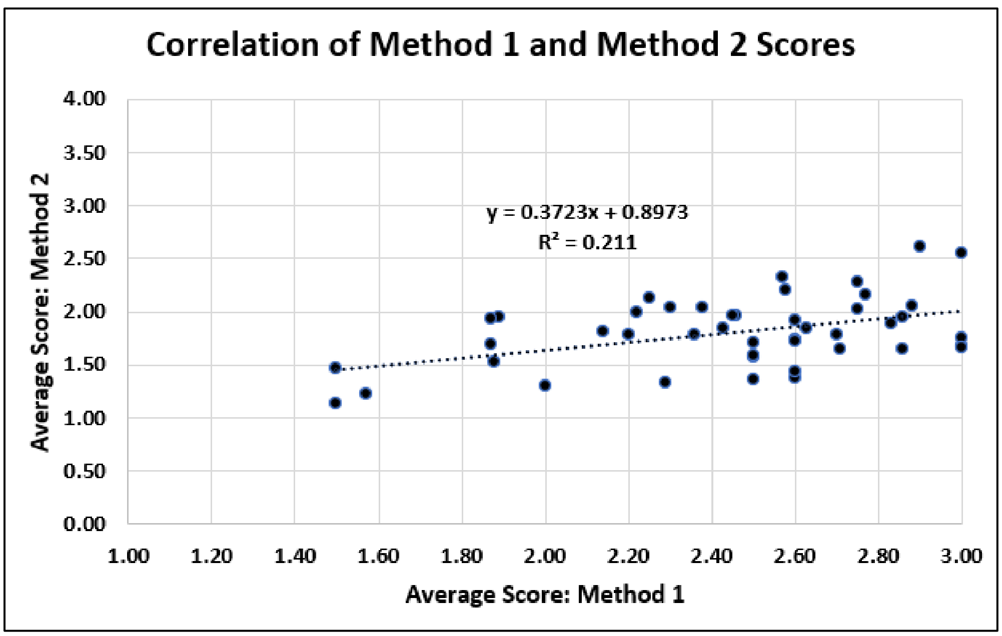


Figure 5: Plot of Average Design Argumentation Scores of Methods One and Two

Figure 4 shows that the average design argumentation score is generally higher for each team using Method One except for some low scoring teams. This is to be expected as only the relevant design argumentation passages were analyzed using Method One and the non-relevant passages were ignored, increasing the overall average value. Figure 5 indicates that there is a weak positive trend between design argumentation scores using the two methods. Therefore, it can be concluded that the trend is for higher average scores using Method One analysis, although it is not statistically significant.

Figure 5 also indicates some other trends in the data. Specifically, teams that scored identically under the system of scoring in Method One had a range of scores using the Method Two scoring system. For example, Method Two scores ranged from 2.56 to 1.67 for the three teams that scored a perfect 3.00 using Method One. This indicates that teams varied in the amount of non-essential statements delivered in their presentations, i.e., some teams were more efficient in their communication than others. Additionally, as the Method One scores increased, the range of Method Two scores for a particular Method One score increased. For example, the range of Method Two scores for teams with a Method One score of 1.50 was 0.33, while the range of Method Two scores for teams with a Method One score of 3 was 0.89. This indicates that when teams were better at arguing for their design in their design argumentation section of their presentation the teams were more likely to have a wide variety of usefulness in the remainder of their presentations. This could indicate that even when instruction is effective in producing teams with a high degree of design argumentation, more instruction is needed in focusing design argumentation.

<u>Correlations between Disciplinary Diversity and Argumentation Effectiveness</u>

After coding was completed, the average score for each presentation was calculated and analyzed in relation to the teams' disciplinary diversity. Graphs of Disciplinary Diversity vs. Average Design Argumentation Score were produced for each analysis method (see Figures 6 and 7).

For both methods, the data was entered into a Microsoft Excel spreadsheet and plotted. These graphs both show a wide spread of data with no apparent pattern. A best-fit line was calculated using Microsoft Excel and an equation for this line was determined, as shown on the graphs.

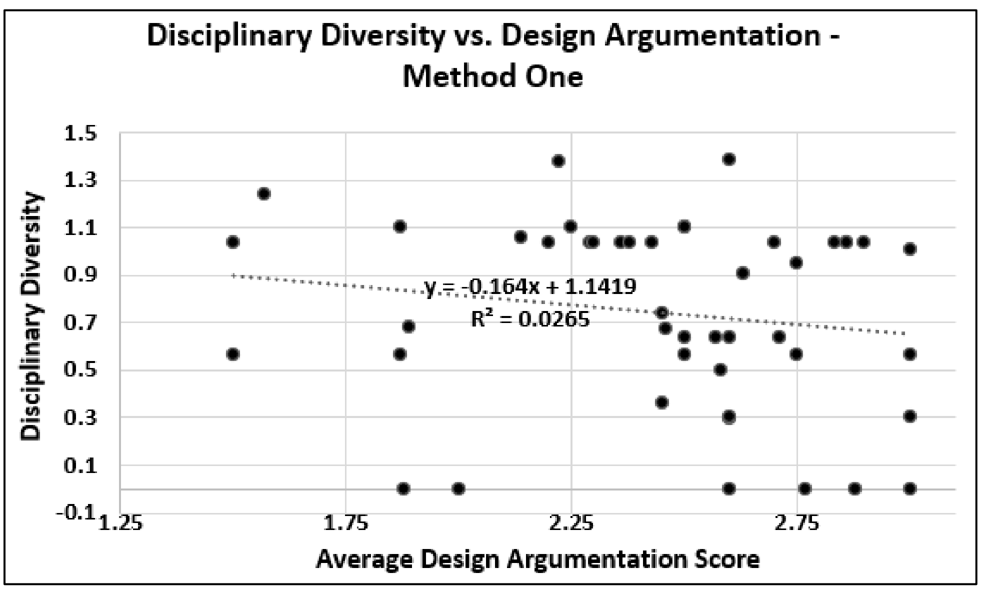


Figure 6: Correlation between Disciplinary Diversity of Design Teams and Average Design Argumentation Score using Analysis Method One.

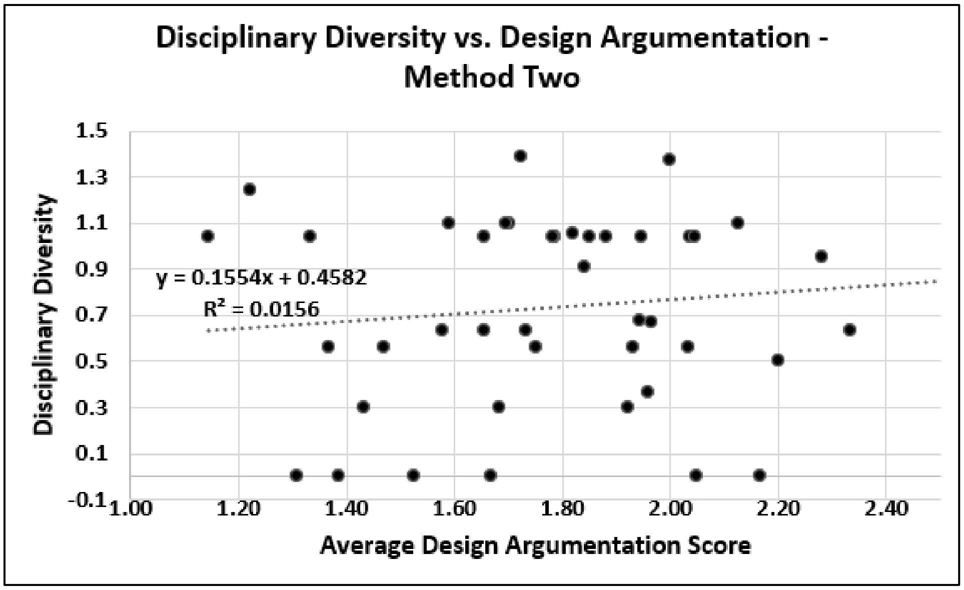


Figure 7: Correlation between Disciplinary Diversity of Design Teams and Average Design Argumentation Score using Analysis Method Two.

In both cases, the correlation coefficient for these best-fit lines is very low (0.2088 for Method One and 0.0735 for Method Two) and no strong correlation between Disciplinary Diversity and Average Design Argumentation Score can be drawn from this data. Therefore, for this data set, the ability of the design team to effectively argue their design solution is independent of the disciplinary diversity of the team.

Discussion and Conclusions

The goal of this research was to investigate the relationship between disciplinary diversity and effectiveness of design argumentation to determine if disciplinary diversity can be disregarded as a significant factor when analyzing engineering design teams' argumentation skills. As Krishnakumar et al.'s research on this data set determined that interdisciplinarity of a design team did not relate to the outcomes of the engineering projects or the quality of the design pitch as determined by sponsor satisfaction [41], our results also showed no statistically significant correlation between disciplinary distance and design argumentation effectiveness. The rubric-based method used for coding and scoring of the presentations in this study should also aid future researchers in performing similar analyses. Rubrics allow for fairer scoring of design presentations, increasing the objectivity of the reviewer [57-60]. Two different rubrics and methods of scoring were utilized to analyze the presentations. It was found that the different methods of scoring did not have any overall effect on the conclusions of the study.

From this study, we can recommend that disciplinary diversity does not play a significant role in how well design teams communicated their technical pitch, at least using the type of categorizing and analysis schema presented here. Therefore, methods to capture and assess quality of interdisciplinary communication patterns of engineering design teams may require a more nuanced research analysis schema.

This study was limited to forty-five senior engineering capstone presentations at one university. Additional research is needed to increase confidence when applying these conclusions to non-engineering design teams or design teams from other universities. Additionally, only audio transcripts are available, so any other communication by the design team, including gestures and demonstrations of design solution prototypes, could not be analyzed. Future work could analyze larger data sets in different settings and incorporate these visual aspects of design communication to obtain a more complete picture of influencing factors.

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