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Math Preparedness: How first year civil engineering, construction engineering, and construction management students approach math-based design challenges

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ABSTRACT

First year civil engineering students often take an introductory engineering design course that is meant to orient them to the field, give them opportunities to work in teams, and practice design thinking and problem solving. The introductory design course may introduce students to open-ended, ill-structured design problems that are solved by coupling creativity with foundational skills, such as math, to determine a feasible solution to the problem. One challenge with the first-year design experience is that students come in with different levels of preparedness in these foundational skills. The level of preparation can impact how students approach a problem, which can lead to a number of creative assumptions and solutions. The objective of this study was to investigate how first-year civil engineering, construction engineering, and construction management students with varied levels of math preparedness approach math calculations in a design course. Data was collected from 5 course sections over 3 semesters (n=119 students). Students' math preparedness for all majors ranges from Foundational Math to Ordinary Differential Equations. The design challenge had students work in teams to propose concrete mixes and a canoe design for the American Society of Civil Engineers Concrete Canoe Competition. We analyzed the approaches students took to make calculations of canoe volume. We found students took a variety of approaches and assumptions to their calculations: Volume was calculated either by an area of shapes approach, a prism approach, or via engineering software. Only some groups calculated the volume of a hollow canoe. Calculations did not necessarily reflect the highest level of math preparation by one member of the team. Some complex solutions were performed by students enrolled in Trigonometry and by those in Linear Algebra, while some simple solutions were performed by students in Pre-Calculus. All teams were able to produce a final calculation for the size of their canoe. These findings indicate that civil and construction engineering and construction management students, even with their varied math backgrounds, can come up with creative approaches to solve ill-structured problems based on their existing preparedness.

INTRODUCTION

Students enrolled in collegiate engineering programs often are required to take an entry-level design course. These types of courses expose students to ill-structured complex design problems, where there is not one single method or solution and there is uncertainty about which rules or principles are necessary to use [1]. Research suggests that hands-on design-based project classes also excite engineering students and motivate them to stay in an engineering program [2]. Ill-structured design problems-- as opposed to well-structured problems-- more closely mirror the work engineers perform outside of academia. To solve real-world problems, engineers must gather information that is not readily available, decide on a process, and identify and justify optimal solutions [3].

College students will often enroll in an entry level design course as pre-engineering majors while completing their other degree requirements, notably math courses. Different schools have different requirements of math classes that students must have passed in order to be admitted in the engineering program. Many engineering programs require students to complete Calculus I or II to enter engineering. The precise level of math required as well as the presence of entry requirements is contended in the engineering education community [4]. Proponents of the math entry requirements suggest that performing well in math correlates to performing well in engineering, while opponents of math entry requirements say that it is an unnecessary and unjust barrier [5]. The term “math preparedness” is often used in relation to this concept and throughout this study.

What type of math preparedness is required to be successful as an engineering student? Some studies suggest that students who have successfully completed higher math courses may receive higher grades in their engineering courses when compared to their classmates in less advanced math courses [6]. One study found that students in Calculus II or higher received statistically higher grades on exams and the final engineering class grade compared to students in Calculus I. Another study found that students with higher level math experience have higher degree completion rates [5].

However, unlike the more traditional assignments like exams, lower levels of math might not necessarily correlate to difficulty solving ill-structured design problems. This may be because mathematical thinking is more than just the knowledge base students contain; thinking processes and strategies are also important markers of success [7], [8]. Academic and non-academic experiences help students with solving ill-structured problems. Students perceive that prior personal and work experience contribute to how they solve ill-structured problems [9]. A 2011 study on K-12 students suggests that while using math in engineering design activities may not lead to project success, it does increase students’ interest in math and their understanding of the value of utilizing math [10].

Engineering educators can build excitement around engineering with the implementation of design courses because students can approach ill-structured problems with the math level and skills they currently have—regardless of math course history. Perhaps engaging early-stage engineering students in ill-structured design challenge assignments may be a useful tactic to build student experience in math problem solving.

The research question posed in this study was: How do civil engineering, construction engineering, and construction management students in an entry-level design course with varying math backgrounds (ranging from Foundational Math and College Algebra up to Ordinary Differential Equations) approach math calculations in ill-structured design problems?

METHODS

Course and program background

This study was conducted in an introductory Civil Engineering Design course at the University of New Mexico (UNM), an R1 Hispanic Serving Institution in the Southwestern United States. This 3-credit course is offered every semester in the Department of Civil, Construction and Environmental Engineering (CCEE) and is a requirement for pre-civil engineering, pre-construction engineering, and pre-construction management students to enter their respective majors.

The University of New Mexico's CCEE program is unique in that it mixes civil/construction engineering and construction management students. These students take several courses together, including but not limited to this Introduction to Civil Engineering Design course, and final senior capstone design. Many students take this course during their first or second semester at the University, alongside other technical required courses such as mathematics to complete their pre-engineering or management degree requirements. Engineering students must complete Calculus II and management students must complete Applications of Calculus to be officially admitted into the major. Students enroll in a math course based on the results of a placement exam taken during first-year student orientation or their SAT/ACT score.

Concrete canoe ill-structured design challenge featured in the course

We developed an ill-structured engineering design challenge connected to the annual American Society of Civil Engineers Concrete Canoe competition [11]. The objective of the challenge was to design a bid package, including a proposal, letter of intent, project schedule, and cost estimate to make the concrete mix for the University's ASCE concrete canoe team [12]. A key component of the design challenge was to sketch a proposed canoe design and calculate the canoe volume in order to determine the amount and cost of materials needed. Students are informed that there is no one correct way to calculate volume; they can approach this by any means and should provide details of their approach in their deliverable report.

The concrete canoe design challenge is ill-structured because within the constraints of the problem, the dimensions and shape of the canoe are undefined and must be determined by the student. As there is no established volume method provided by the instructors, students must come up with their own method to solve the problem. There is no single correct solution to the volume problem and can be made as simple or complex as the students choose. Without using a drawing software, the actual calculation is uncertain, but students can justify their assumptions and methods for calculation.

Data collection
Data was collected over three semesters (Fall 2023, Spring 2024, Fall 2024) from 119 students who provided informed consent, and 45 teams of 3-4 students where at least one student on the team provided informed consent.

We gathered data from the following: i) team deliverable reports detailing canoe design and volume calculations, and ii) individual students concurrent math enrollment.

Math Enrollment
Concurrent math enrollment data was collected from the University's internal degree roadmap portal for all students who provided informed consent.

Team Deliverable Reports
Deliverables were analyzed from 23 groups in Fall 2023, 6 groups in Spring 2024, and 16 groups in Fall 2024. Students submitted 5 deliverables over the course of the design challenge: Background research and canoe mix design proposal, Results from lab where different concrete mixes were tested, Stakeholder and customer analysis, Bid Package, and Final Presentation. Across the deliverables, the research team collected data from report sections that specified roles and responsibilities of each group member, showed hand- or computer- drawings of canoes, and described math calculations performed to obtain canoe volume, choices they made regarding the canoe design, and any challenges faced during the design process.

Data analysis

Coding analysis
The research team analyzed team deliverable reports and developed a coding scheme to categorize the approach to volume calculations.

Code categories	**Category options**
What mathematical method did the team use to approach canoe volume calculation?	Calculated volume of a prism Calculate area of each side wall piece Used engineering software to sketch canoe and calculate volume
If prism approach, what type of prism?	Rectangular, Triangular, Trapezoidal, Cylindrical, Ellipsoid, Mixed (multiple shapes)
Was the canoe hollow?	Yes, No
Did the students add a correction factor?	Yes, No
Were there mathematical errors in the calculation?	Yes, No

RESULTS

Math enrollment while taking Introduction to Civil Engineering Design

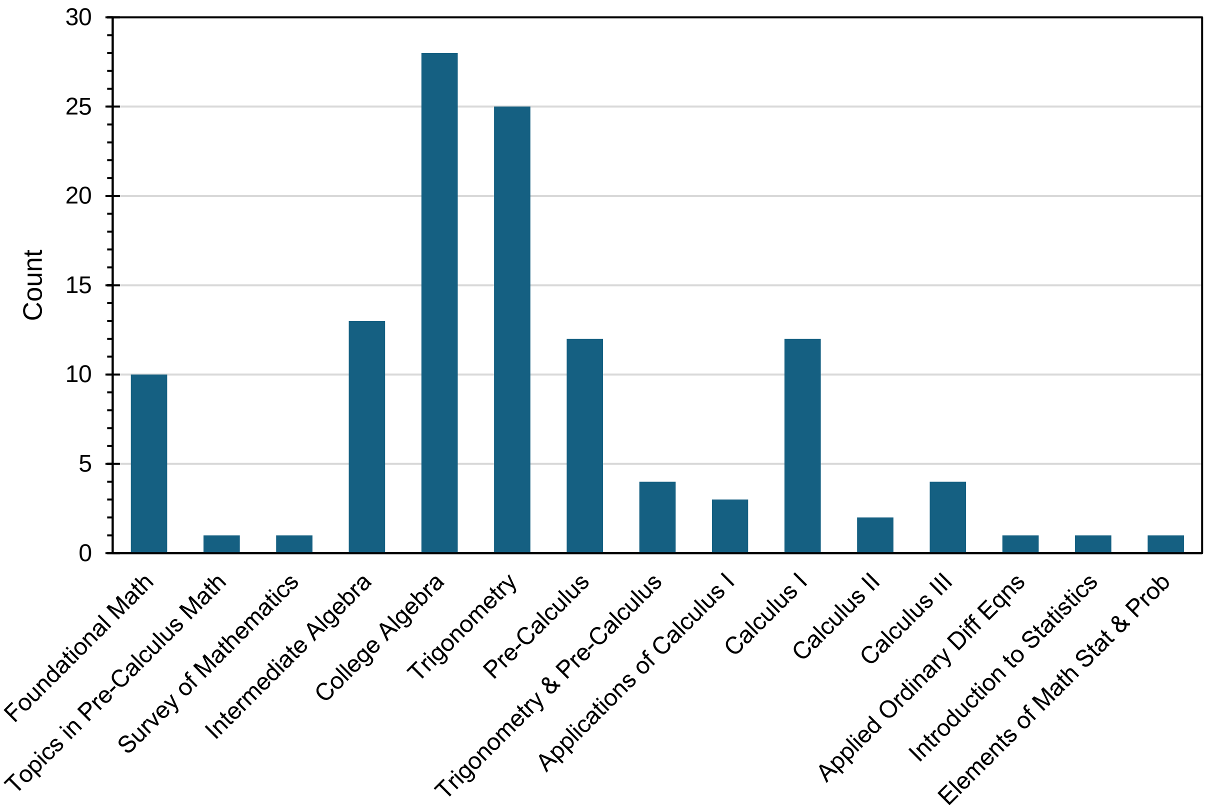

Figure 1: *Math enrollment of students while taking Introduction to Civil Engineering Design*

Figure 1 shows current math enrollment of individual students taking the Introduction to Civil Engineering Design course. The figure reflects individual course enrollments, and students may be enrolled in more than one math class during the semester. The majority of students were enrolled in College Algebra (n=28), followed by Trigonometry (n=25). A similar number of students were enrolled in Intermediate Algebra (n=13), Pre-Calculus (n=12), Calculus I (n=12), and Foundational Math (n=10). The requirement to move from "pre-major" to "major" status for Civil and Construction Engineering is to pass Calculus II, and for Construction Management to pass Applications of Calculus. Among students currently enrolled in our course, 80% (n=94) are 1-5 classes behind in the sequence before either Applications of Calculus or Calculus I (students enrolled in Pre-Calculus have 1 class left to complete, while students enrolled in Foundational Math have 5 classes left to complete).

Math approach to calculating canoe volume

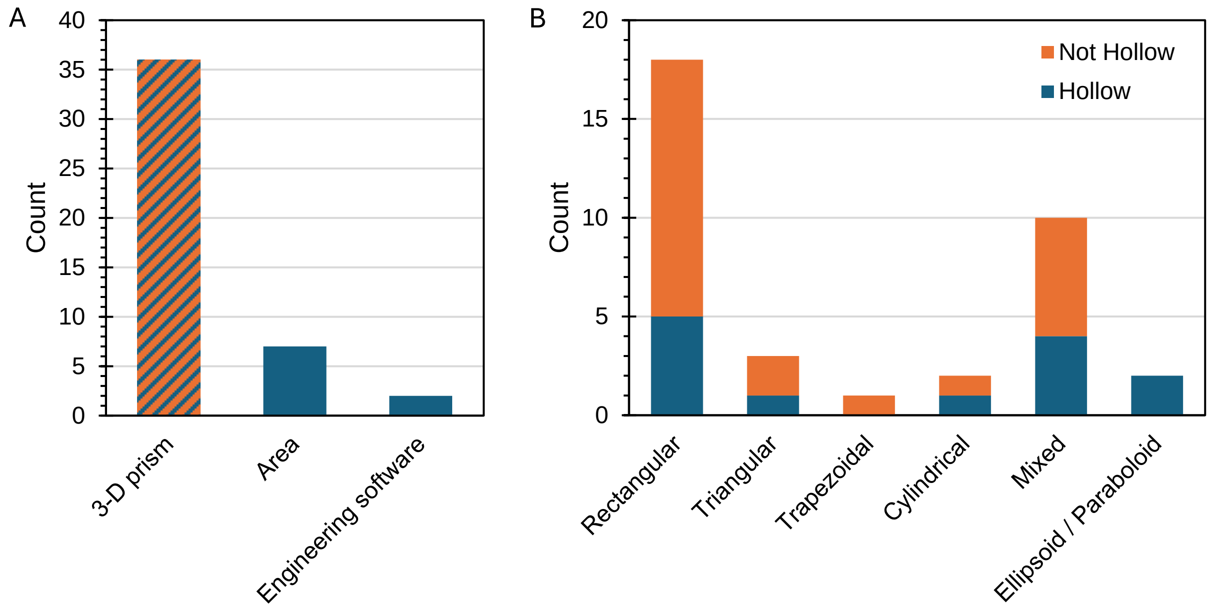

Figure 2: *a) Method of math approach teams took to solve for the volume of a canoe; b) Type of 3-D prism used to calculate volume of the canoe. Orange indicates that the canoe was not hollow, while blue indicates that the canoe was hollow. Orange and blue stripes therefore indicates a mix of approaches that are detailed in Figure 2b.*

Student groups approached calculating the volume of a canoe by one of three methods: 3-D prism, area, or via engineering software (**Figure 2a**). The 3-D prism method was the most popular approach (n=36), wherein students assumed the canoe took the shape of a 3-D prism and calculated the volume using a prism-volume approach. **Figure 2b** shows the majority of 3-D prisms were rectangular (n=18), where students calculate volume by multiplying the length, width and height of their canoe. In a triangular prism approach (n=3), students either calculated the volume of one triangular prism, or assumed the canoe was two triangular prisms placed back-to-back. The trapezoidal, cylindrical, and ellipsoid/paraboloid prism approaches calculated canoe volume using equations for the respective shape. In the mixed prism approach, multiple shapes were combined (e.g., 1 rectangular prism and two triangular prisms). Among the 36 groups who used the prism method, only 13 teams calculated the volume of a hollowed-out canoe. The most common approach to hollow the canoe was to subtract the volume of a smaller interior prism, leaving a canoe with sidewalls that were several inches thick.

Groups who utilized the area method (n=7) did so because it enabled them to piece together the volume of only the side walls and let the canoe interior remain hollow. These groups broke the canoe walls into several shapes (e.g., rectangles, triangles), calculated the area of each shape, multiplied the area by a side-wall thickness to obtain the shape's volume, and subsequently summed the volumes of all the shapes.

Two teams had group members who were familiar with engineering software (e.g., AutoCAD). These groups drew their canoes in the software, and had the software calculate canoe volume. Hand-written calculations were not provided to supplement the computer-aided calculations.

Only in the Fall 2024 semester, 3 groups added a correction factor to their volume calculation. These groups (1 area method, 1 hollow rectangular prism, 1 not-hollow cylindrical prism) added statements such as:

- *Subtract 33% from calculated volume as a correction factor (hollow rectangular prism)*
- *Add 15% to final calculation to make sure enough material is accounted for (area)*
- *Correction factor of 0.8 (not-hollow cylindrical prism)*

Students appeared to apply correction factors that either added or subtracted from their original canoe volume to account for the roughness of their volume calculation.

Table 1 shows example case studies of each mathematical approach that we coded, alongside the highest and lowest math enrollment among students of the team. In some cases, teams specified which student performed the calculation. Case study groups were selected to show the diversity of approaches that were taken to solve the ill-structured problem, alongside the diversity of math preparedness among groups and across the class.

Table 1: *Case studies of mathematical approaches and associated math levels of students on teams.*

Case Study Group	**Math Approach Coding**	**Highest level math in group**	**Lowest level math in group**	**Math level of person responsible for calculation**
1 Area	*Method:* Area *Math errors*: no	Calculus III	College Algebra	Trigonometry
2 Area	*Method:* Area *Correction factor:* yes *Math errors*: no	Linear Algebra	Intermediate Algebra	Linear Algebra
3 Simple Prism	*Method:* Prism Rectangular Prism *Hollow:* no *Correction factor:* no *Math errors:* no	Trigonometry	Intermediate Algebra	Intermediate Algebra
4 Simple Prism	*Method:* Prism Rectangular Prism *Hollow:* no *Correction Factor:* no *Math errors:* no	Pre-Calculus	College Algebra	Pre-Calculus
5 Hollow Prism	*Method:* Prism Rectangular Prism *Hollow:* yes *Correction Factor:* no *Math errors:* no	Differential Equations	Foundational Math	Not indicated

6 Complex Prism	*Method:* Prism Triangular Prism *Hollow:* yes *Correction Factor:* no *Math errors:* no	Pre-Calculus	Intermediate Algebra	Trigonometry
7 Software	*Method*: software	Calculus I	College Algebra	Not indicated

DISCUSSION

This paper aimed to study how entry-level civil/construction engineering and construction management students with varying math backgrounds approached ill-structured math-based design challenges.

Methods of approaching ill-structured problems

Early-level math courses such as Foundational Math, Algebra, Trigonometry, and Pre-Calculus all teach useful skills that can be applied in higher level Calculus courses and engineering major courses. A key challenge is that problems in traditional math courses are well-structured, with a single correct method and answer that must be properly followed to be successful in the course. This teaches students to only have a linear approach, where constraints are well defined, problems exist within a narrow space, and they do not have to look far beyond course materials for additional resources to solve the problem.

Making the leap from these well-structured courses to solving ill-structured design problems may be a challenging barrier but also an opportunity to promote early success in an engineering program. Switching student mindset from solving well-structured to ill-structured problems requires instructors to create problems that still have students use their foundational tools, but allow for creativity in the approach of how simple or complex the student chooses to make the solution. When faced with solving an ill-structured problem, early-stage undergraduate students can react to ambiguity by eliminating, acknowledging, accepting, or embracing it [3]. We found that a large number of groups (n=23) eliminated ambiguity by calculating canoe volume simply as LxWxH without hollowing out the canoe (e.g., Case study groups #3 and #4). Often, one person did the calculation, and teammates did not check or verify the answer. A more advanced level of solving an ill-structured problem is to acknowledge that it is not well-structured, and learning that assumptions may need to be made in order to navigate the problem-solving process. Several groups initially struggled with how to begin, as there was not a "given equation" to use to solve the problem. Moving through the challenge, we saw that several groups (n=36) tried different shapes of prisms (e.g., triangular, trapezoidal), or used a simple area approach to solve for volume (e.g., case study groups #1, 6).

Advanced students can accept and embrace the ill-structured challenge and move beyond the constraints it poses to leverage creative solutions. This entails troubleshooting, iterating on an existing solution, and accepting ambiguity as inherent to ill-structured problems solving. For instance, one team initially used a mixed prism approach in their first design deliverable, then iterated in following deliverables to using an area approach as they found it to be a more accurate representation of the total volume calculation. Other teams paused throughout class to ask the instructional team whether their calculated value was "too high." Three teams acknowledged that their solution was likely not accurate given the assumptions they needed to make, and therefore added correction factors to compensate for the estimated nature of their volume calculation.

How teams work to solve ill-structured problems

How teams chose to approach the design problem varied widely across the course. In several instances, one student took the lead on calculations, while others peer-reviewed their calculations. This led to the level of complexity of problem solving to be determined by only one student within a team of 3-4 members (or 25% of the students in the course). On the other hand, some teams worked collaboratively throughout the design process. Uniquely, one team in particular had one member taking Trigonometry and Pre-Calculus, one in Calculus II, one who had passed Calculus I and one who had passed Applications of Calculus. Their solution, which integrated ideas from all four team members, was a mixed prism combining many shapes including trapezoids and triangles, but the canoe was not hollow.

Skills gained by approaching ill-structured problems

Table 1 shows that we have some students in higher math levels who are approaching problems with more complexity (e.g., Case study group #2). However, it also shows that students in earlier level math are attempting the same problem and coming up with their own versions of solution. Occasionally, this is done by simplifying the problem (group #3). Some simple solutions (not hollow rectangular prism) are done by students in Pre-Calculus (group #4) while some of the most complex solutions (complex prisms and area method) are done by students in both lower (trigonometry, group #6) and upper level (linear algebra, group #2) math classes.

All the students in this course, regardless of their math background, are gaining skills by completing the design challenge to the best of their ability. Students of all levels are working in a team, solving open-ended problems, experiencing hands-on laboratory science, and learning that there is more than one way to approach a problem and that those methods may not be given to you. All of these skills are important to being a practicing engineer. Everyone in the class approached ill-structured problems; the result of their math methods is not necessarily indicative of the highest math knowledge. Having entry-level students solve exciting, complex design problems through an engineering perspective can perhaps even encourage them to stay in the major and complete all the math requirements.

Limitations

While this study provides insights into how early-stage undergraduates approach math in design challenges, it is limited to data from a relatively small sample size. Data was collected from 119 students and 45 groups. Students all attended the same university which represents a unique student body. The University of New Mexico is a Hispanic-serving, first generation forward university where half of the students are first-generation college students. Enrollment demographics reflect that of the state, but it may not be reflected at other large, R1 flagship universities.

Additionally, data on individual student math preparedness was determined by the math class students were enrolled in at the time of taking the engineering design challenge course. This may not necessarily reflect their math knowledge because student math course enrollment is determined by a math placement test at new student orientation. For example, students may have taken Calculus in high school but were placed in Pre-Calculus based on placement exam performance.

CONCLUSION

Math preparedness is often used as a gatekeeping approach in engineering programs, with the assumption that students not well prepared in math will not be able to solve complex problems and challenges posed within the discipline. We find that early-stage undergraduate students in our Engineering and Construction Management programs are still early in their math course sequence, with the majority enrolled in College Algebra. Yet, many students are able to work in teams to come up with a range of simple to complex solutions to math-based design problems. This exposure to ill-structured challenges has the potential to encourage students to continue on their math progress and remain within the major, as it shows them how they can still apply early math tools within an engineering context.

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