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Benchmarking Architectural Engineering Capstones Part 3: Exploring Technical Studies and Integration

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Abstract

Architectural Engineering (AE) programs are poised to be leaders in educating future engineers on best practices and leading industry trends. To the AEC industry's leading providers of critical thinkers, creative solution makers and future leaders, AE programs adopt a myriad of teaching strategies. The core of AE programs revolve around providing a realistic design and construction experience for students that simulates industry, with senior capstone projects commonly being the location for such an experience. Up to now, much has been researched on capstone delivery, but often excluded in this research are AE programs due to the small cohort size, as say compared to mechanical engineering. This paper is the third in a series of AE program benchmarking, where the initial paper looked at general formulations, delivery, and project utilization, duration and location, and assignment formulation. The second paper in the series examined mentoring models, facilities, industry support, and project criteria. The presented work in this paper extends the topics covered in the first two papers by looking at grading mechanics, technical studies within different AE disciplines, how system integration and architecture are handled, the division of work between students, and lastly where AE programs see senior capstone courses trending over the next decade. Results presented here can be utilized by other AE programs to benchmark their practices while also looking for good ideas / strategies to possibly adopt in their program.

Keywords: Architectural Engineering Programs, Senior Capstone Projects, System Integration, Technical Assessment

Introduction

Architectural engineering (AE) undergraduate programs, and more broadly, all engineering programs, provide authentic engineering design experiences through capstone courses [1-3]. When structured properly [4], capstones provide excellent opportunities for assessing student knowledge [5], developing new leaders [6], bridging fundamental knowledge with practical settings [7], showcasing innovative technologies and design approaches [8], and more. Compounding factors for AE capstones exist across the 27 ABET accredited programs in the United States, such as the types of courses offered, the level of industry connection, the size of the program, the duration of the degree, and where the AE program is situated within the college or university, all can impact the capstone experience [1, 9-11]. Given their importance, along with ABET accreditation requirements, capstones require continued reflection and evolution to keep the academic experience relevant and impactful [8,12].

One way to keep capstones relevant is to review/assess what other similar programs are incorporating into their programs in regard to means, methods, and trends [12-13]. A review of published capstone papers has shown limited documented successes and struggles by AE educators as compared to other engineering majors [13-15]. The majority of papers focus on the delivery, assessment, and engagement aspects [14,16]. This paper seeks to expand the earlier studies [14-15] to focus on other core capstone features that can be of benefit for programs to know. This expansion of the study documents grading philosophies and mechanics, single isolated discipline as well as cross-discipline technical studies, how system integration is balanced, the division of work between students, and lastly, where AE programs see senior capstone courses trending over the next decade. Several reflective takeaways to think about when reviewing what a current capstone is doing or could be doing are provided.

Established Survey

A Qualtrics™ questionnaire was sent to the 27 ABET accredited programs in the United States to gather the information presented in this paper. Surveyed individuals were established as those listed on programs' websites as having capstone affiliations, teaching duties, or were in a leadership status within the program. Furthermore, the ASCE-AEI Faculty Academic Council listserv was used to find people as they are a representative body interested in advancing AE programs. If any school had more than one survey taker, that program's responses were averaged. The survey consisted of 25 questions across 4 categories, though answers to all 25 questions were not required as the survey permitted question skipping. Question format included: multiple choice, multiple selection, and short answer questions, sliders, and matrix selection, as well as the opportunity to share additional information (such as syllabi, project information, etc.) with the researchers through a shared drive. Additionally, some data from the earlier study by Solnosky and Phillips [14-15] was collected, yet never reported. As such, the unreported data from that earlier study is provided here in this paper, as applicable, to the central topics of discussion. Of the 27 programs, all were invited to participate and were given one reminder over a 4-week period to complete the survey. At the time of data analysis, 13 out of 27 programs completed new 2024 survey with 19 having completed the 2022 survey (Fig. 1). For comprehensiveness of scope, partial survey responses were included in this paper which gives way to the different sample sizes in different sections.

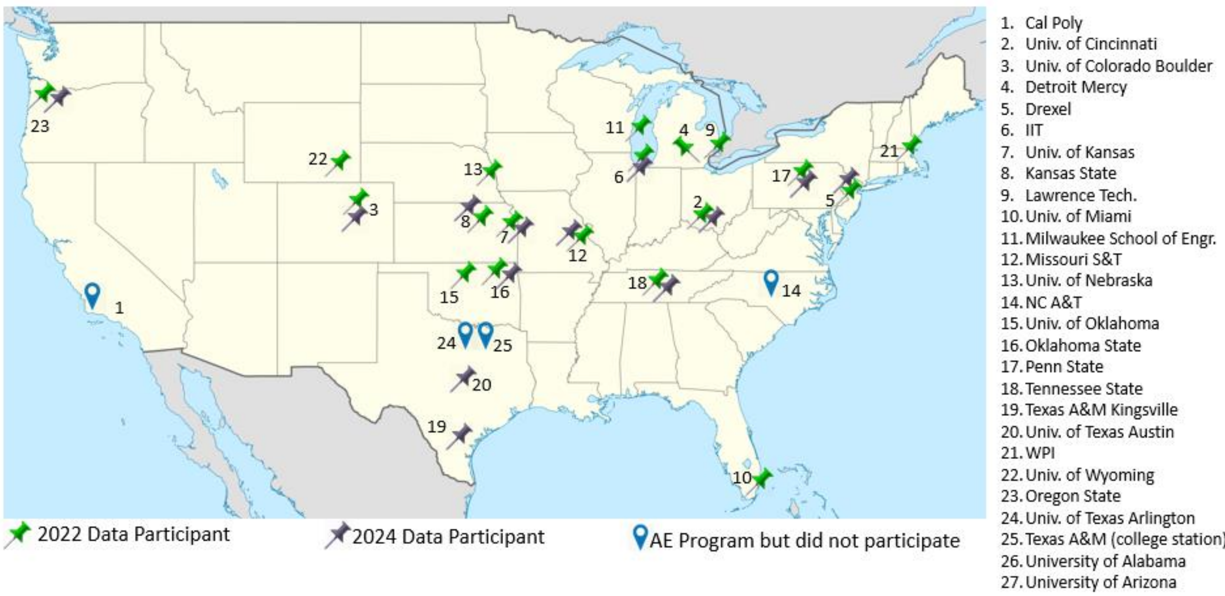
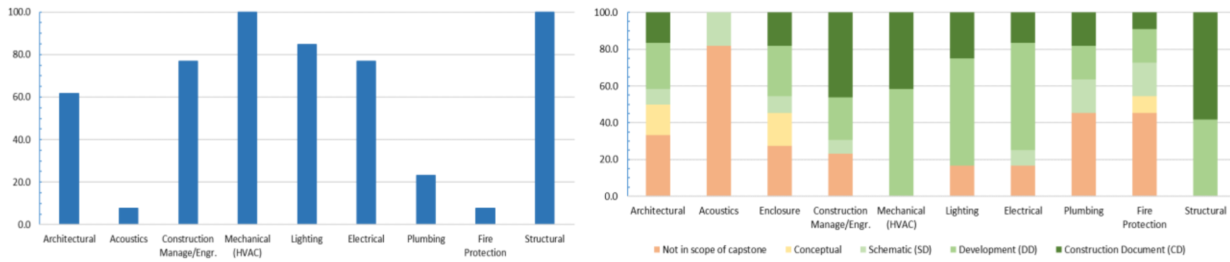


Figure 1: ABET Accredited Architectural Engineering Programs in the United States

Capstone Disciplines: Depth, Breadth, and Design Scope Coverage

According to ABET's AE program criteria, students are required to achieve a synthesis level of knowledge in one of the four traditional AE disciplines (HVAC, Lighting/Electrical, Construction, or Structural), with appropriate levels of application and comprehension of the remaining three disciplines [9,17]. As such, capstones tend to cover a wide perspective of the building project scope [14,16,18]. In aligning with ABET, the four traditional AE disciplines are the most represented in the topical scope covered by AE program capstones ranging from 77% to 100% (Fig. 2a). A little surprising is that lighting is more prominent over electrical (85% vs 77%) and that acoustics and fire protection are tied for lowest. Looking at AE program websites, and prior studies [13-15], the 61.5% architecture inclusion is reasonable as for some, capstone serves as a design studio while for other programs, they want to uniquely position the capstone to not be architecture centered. In keeping with these disciplines, programs were asked to what level of completeness students are typically expected to have their design completed (Fig. 2b). The scale used aligned with how practicing design firms typically organize their design stages (i.e. SD, DD, CD, etc.). As expected, there is a strong relationship to Fig. 2a and Fig. 2b in scope not covered by a capstone. Additionally, three of the four traditional disciplines are where students develop their designs furthest to completion, with electrical design being lowest and equal to plumbing. An unexpected result was how many take their designs to a construction document (CD) level of completeness (Fig. 2b). This could be partially due to a team's ability to go to that level of refinement, or perhaps certain key parts of a discipline's system(s) are developed to that extent while other parts are not. For example, a team may design a single structural connection but not all of them in the building. To provide some literature context, most capstones have students target a level of completeness of their project somewhere between SD and DD [18-19].

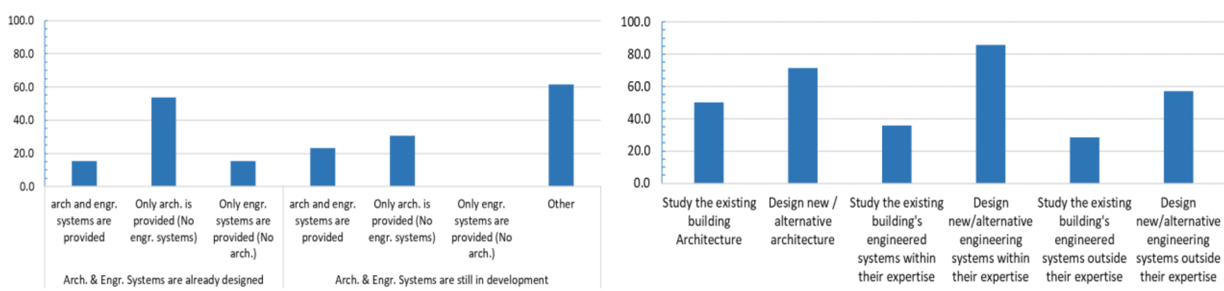


a) covered within the capstone b) completeness of student work

Figure 2: Building Design and Construction Disciplines

Knowing AE capstone typical discipline context (Fig 2a), students have potential opportunities to isolate their work to a single discipline or cross discipline work. Some AE programs allow students to specialize or focus on a specific discipline while others are more general in their requirements [1,13]. Our survey captured how much depth vs breadth work each student conducts within a capstone. Here, depth is considered students working within their specialization while breadth is considered students working outside of their specialization. Responses currently show that 7.7% (n=1) of AE programs have students only work in their discipline depths whereas 92.3% have them do some level of breadth work. In terms of how much breadth, all 100% (of the 92.3%) indicated simple calculations and studies to support the broader team goal whereas no program required an equally balanced depth vs breadth set of calculations per student.

To have a project that can support teamwork [20], as well as allow for multi-disciplinary design studies, the proper project needs to be selected. As indicated by our earlier study [citation added later], project traits, characteristics, and size, are often unique for each program, but there is a general agreement on complexity. One aspect of this survey asked if fully designed systems were provided to students as part of the capstone project. (Fig. 3a). By far the most common method employed was to provide a fully designed real building project but to only provide the architectural design and not the engineering solutions (54%) (Fig. 3a). It is clear from Fig. 3a while other methods are utilized, they are not common occurrences across programs; this does not indicate the other methods are bad, just that they are not popular. Some programs did indicate other options for providing project details, including varying levels of completion and existing vs. new design according to discipline, only providing owner project brief requirements and requiring the student to design both architecture and engineering, and letting students decide on if it's fully designed or still being designed once they know the scope of a possible project.



a) Scope/Type of Projects Given b) Studying vs Designing Existing and New

Figure 3: Architecture vs Engineering Scope and Utilization of a Building Project

Another aspect of the survey asked to what extent of completeness are the projects given to the students at the start of the capstone complete in their design. Results showed a clear grouping of two themes: 1) studying existing designs or 2) developing new designs (Fig. 3b). Only 28% to 50% of programs perform some level of studying existing industry created designs. One perception of this can be that students learn from designing solutions to new projects in the capstone course, while a counter argument can be that students can learn from studying why and how actual designers have reached their final solution on projects. Of those that study existing designs, 100% of these programs indicated they develop new designs after studying the existing. Similar to other recorded trends (Fig. 2), architectural studies scored less common than engineering; yet, designing new architecture was higher than just reviewing existing (50 vs 71%). Central depth focus studies were maintained in this data subset as students who study systems outside of specialization scored 28.6% lower than within a discipline. This can be tied back to Fig. 2 where there is a direct correlation between disciplines and how much breadth vs. depth work is done.

Given how large a building can be, and depending on if a capstone has individual students, small teams, or large teams, the scale/portion of the project being studied needs to be determined by faculty. Respondents indicated that for their typical project in a given year, 84.5% of programs utilize the entire building while 31% may utilize a wing or zone of the building, depending on its size and shape (Fig. 4). Some programs (23%) acknowledged that this is partially dependent on the discipline. For example, structural students typically study the entire building but may focus efforts on the more typical bays if the project is too large whereas; lighting and mechanical systems design might focus on a few different spaces within the building mostly to avoid tedious repetitious work.

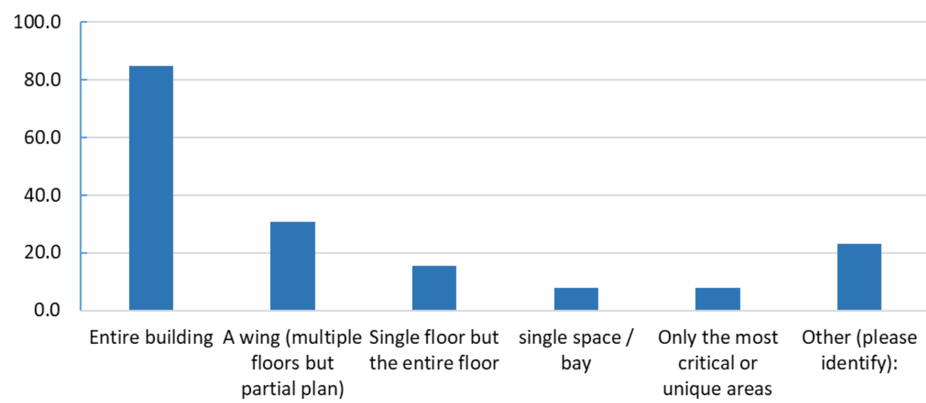


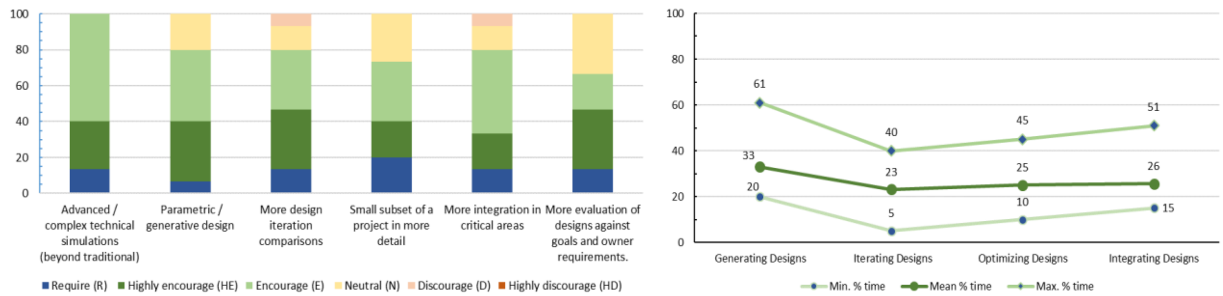
Figure 4: Scale of a Building Project Studied

Design Cycles, Iterations and Types of Design

Moving from broader discipline studies found in AE capstones, the survey also examined more deeply into the design side of what students work on, how much work they perform, and the expected level of completeness of that work. Various capstone literature has shown that technical studies can vary in terms of complexity, comprehensiveness, and scope from project to project or even from instructor to instructor [16,19,21]. Knowing general trends can help AE programs keep a reference on what other programs are doing and the level of completeness to strive for as modifications are made to their own programs.

Given that design across AE discipline topics can vary in terms of duration, complexity, and even approach, two questions were asked on what types of design strategies are adopted. The first was to define how students design (Fig. 5a) while the second was to determine how much time was spent on the varying stages of design (Fig. 5b). All six design options had some level of requirement; yet, they were all under 20%. Additionally, for the ranges of highly encourage to encourage, students adopting multiple design approaches was fairly consistent (range: 53% to 67%), with only having students do some advanced technical study being greater (86% HE and E). From the data, only two methods of design had discouraging results: 1) more iterations comparisons (6.7%) and 2) more integration in critical areas (6.7%). Given their low percentage, these are not “out-of-normal” expectations. Supported by open-ended responses, AE programs regularly encourage multiple approaches for students to take but do not heavily mandate which; instead, students pick applicable methods for what they are trying to accomplish.

On the topic of how much time is spent on different types of design, Fig. 5b shows that there is a considerable range of effort. While min. and max. ranges are broad, the means are consistent. Most teams seem to spend the most time either generating design ideas and solutions (M= 33%, Max: 61%) or integrating their solutions with other students (M= 26%, Max: 51%). Time spent optimizing design performance was lower than expected as often that is where the more discipline specific work can focus efforts towards showcasing their depth skills. The results for integration were not surprising given how many programs adopt competitions where integration is central to that competition [14]. For the time component, programs either kept student on track to be fairly uniform in their work or they had high early effort or late effort, but no program had larger generating %s or large integrating %s.



a) Encouragement on type of design to leverage b) Percentage of time spent on design stages

Figure 5: Types of Design and Time Spent Doing the Design

When designing technical solutions, a variety of approaches are possible. A question asked by this survey related to the types of calculation techniques students are required / encouraged to do considering different levels of complexity. Fig. 6 provides the survey results on the level of calculations from approximation by hand up to and including full 3D model simulations. Each type of calculation recorded includes the five stages of design reported earlier in Fig. 5. From Fig 5’s data, it’s good to see that every stage/type of design has some level of correlated calculations being performed. This solidifies that technical application is included in all stages of design. Looking at the graph trends more closely (Fig. 6), it can be seen that quick hand calculations, spot checks and approximations are expected by faculty in earlier stages of design and design coordination, while optimization is saved for more computational approaches with some software validity checks. These make sense given the scope of AE projects (Fig. 4) tends to be the full building, as it is neither practical nor the most beneficial situation for students to perform all calculations by hand, though this condition does reinforce the need for students to check their computational work by hand during the design process.

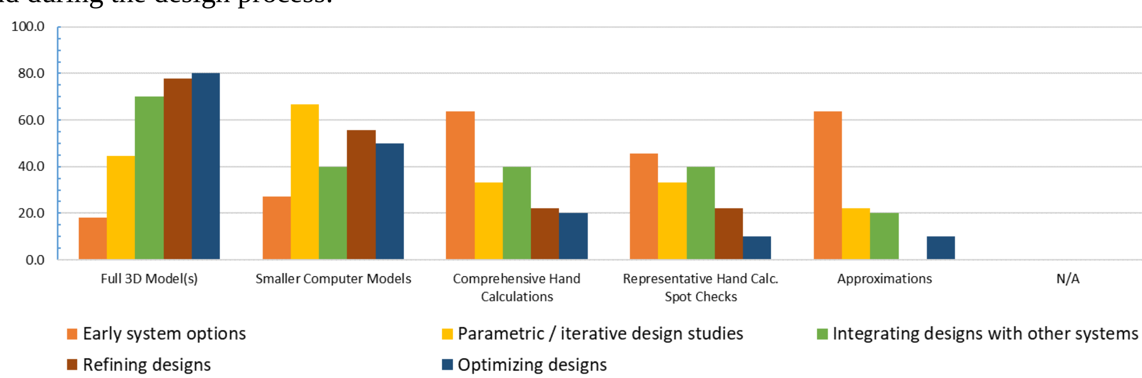


Figure 6: Calculation type vs when they are utilized / leveraged in design stages

Given the data earlier in Fig. 3, most programs have students design from only architectural drawings. Knowing this, two questions that capstone educators may have when formulating assignments or processes are: 1) how do students select their possible systems and 2) how many iterations or options do students carry along in the design process. These two issues can vary the volume of work for a team, the comprehensiveness of technical work that students can achieve, and also how encompassing they are in picking the "best" solution. In answering the first part of how students pick systems, the data indicates that no program gives a free choice without justification. After that there is a fairly equal balance of letting students choose but require justification (@38.5%) vs making students study multiple configurations and types (@46.2%). These two could be merged into free choice but require a certain distinct set of options to ensure comprehensiveness. Justification could include: research and/or preliminary calculations/comparisons to back up decisions. None of the programs exclusively stipulate for which options students must designed. This practice aligns well with building professional skills on knowing when and how to pick a system. Adding clarity to this when there are teams, respondents indicated how the design is shared amongst team members. 31% have each student generate some designs that are then narrowed, and work is shared, while 54% have a requirement that all members in that discipline must split duties but have contributions to all sets of design. Some programs (69%) indicate they have assigned or students self-assign specific tasks of which 38% rarely conduct across member input or review while the other 31% has a substantial across member reviews.

How many iterations or sets of designs should be performed for a project, or more frequently, a system is the second question that is often asked by students, and to an extent by faculty when developing new assignments. Fig. 7 provides insight into what AE programs regularly recommend. Early in the project, 53.8% indicated they typically have students work on either 1-2 or 3-4 alternatives. These ranges are fairly consistent across key Fig. 2 disciplines. That said, 38.5% vary this by discipline due to the complexity of the discipline and system. Now, as students move along in their design and begin to iterate, 8.3% (n=1) of programs don't require iteration, while the majority (67%) require 1-2 or 3-4 iterations to showcase that the designs are improving in their performance and/or are becoming more aligned with owner/team goals. This data is closely aligned with the number of multi-disciplinary integration reviews that teams perform. The data suggests that teams spend time purposefully refining their solutions after each review and advance its overall targeted performance. At the end of the capstone, 92% (n=12) of respondents indicated that teams have either a final solution or a final solution with a backup best alternative, leaving the final decision to another to make (i.e. such as presenting options to a client for approval).

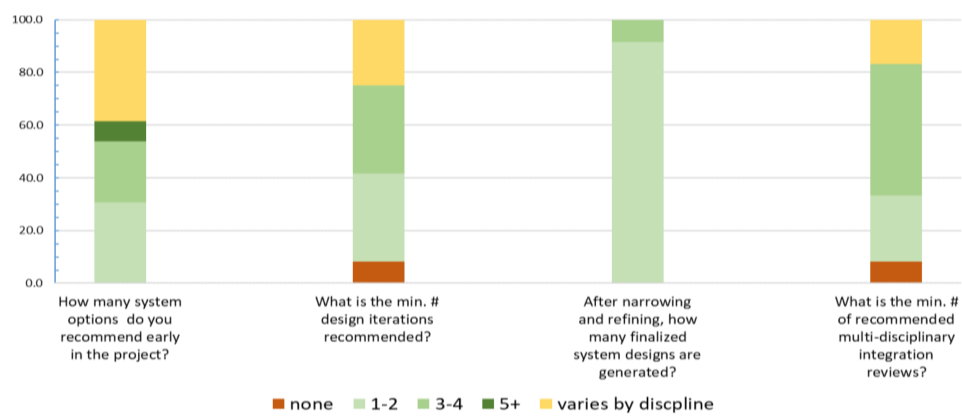


Figure 7: Student conducted number of studies, iterations, integrations and final solutions.

Adding to the topic of calculation types and iterations, programs were asked approximately how much time a typical student/team spends (% relative to the entire course) on four types of calculations within common technical design. Results in Fig. 8 show that the recorded min., max. and meantime correlate well to the prior data in Figs. 6 and 7. Given how much technical emphasis has come across the survey data, the 15% to 50% of time spent optimizing design is reasonable with a mean of 30%. If we think about a 3-credit class with 9 hrs of work a week as typical and a 15-week semester, this will correlate to ~40 hours per student on optimizing vs 20 hours of preliminary hand iterations. Key here is balancing this level of calculation usage with an appropriate level of assessment and technical review. The same type of assessment cannot be used in larger modeling with optimization compared to iterations by hand. Interesting is that in Fig. 5b integrating is the largest % of time spent as design yet here in Fig. 8, integration is second for time spent performing technical calculations. This provides insight into the idea that integration is not simply technical but encompasses a broader definition to AE programs.

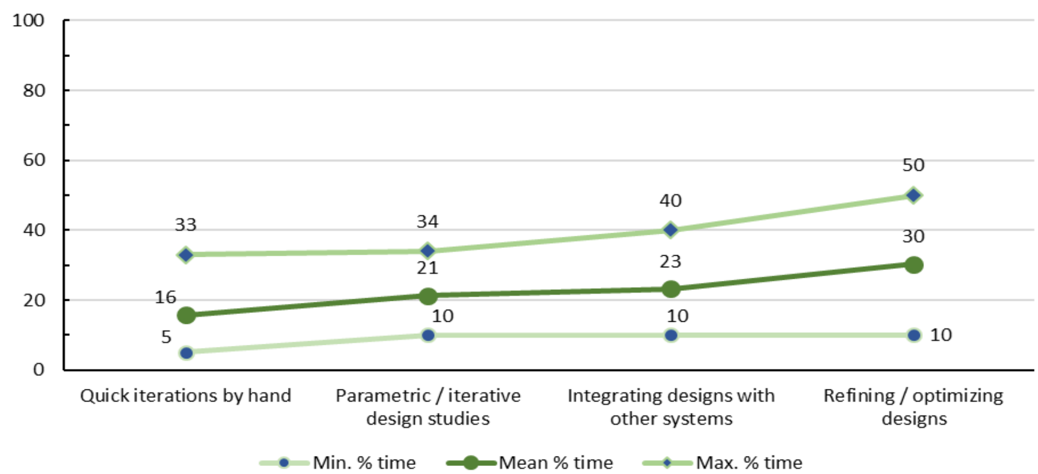


Figure 8: Percentage of time spent on various types of calculations within design.

Discipline Technical Studies

To strengthen the survey's data collection, several open-ended questions were included asking programs what technical studies were typically conducted by students and how the scope varied by discipline to capture richer contexts. Additional trending technical topic questions found in other literature were also asked to identify how they relate to AE programs.

One follow-up question on what other building studies are performed and how they are recommended to students was asked. Fig. 9 shows that building enclosure was the most required to always recommend being studied (combine 74%). Counter to that, the largest avoid studying is security design and landscape architecture (33% and 40%). "Lesser" building systems that are not a major teaching area in AE showed as only having students study them for specific scenarios where they are critical to that project type (11.5% to 46%). These systems include fire protection, plumbing, power generation, and building operations and maintenance. While not asked, these systems require expertise that some faculty may not have, which could have led to these lower numbers.

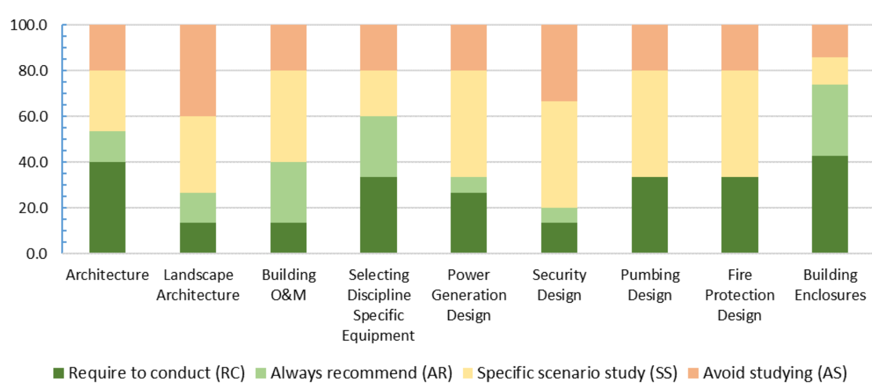


Figure 9: Technical studies and system designs to complete in capstone.

Adding to the discussion of discipline specific technical studies, programs indicated in open-ended questions that teams study the traditional aspects of technical disciplines. These include gravity, lateral and foundation systems for structural; heating, cool and natural ventilation means for HVAC; power distribution and energy systems for electrical with some programs having basic lighting design while others go into more depth as well as conduct daylighting studies. AE programs that offer the construction discipline center capstone activities on cost, schedule, site logistics, delivery and sequencing of the project. Programs that don't offer construction did indicate that other disciplines are commonly asked or required to perform some cost estimating, but at a much more conceptual level.

In seeking specific clarity on documented "trending" literature technical studies that span disciplines, a question was asked on how they approach them as part of their course (Fig. 10). Only 6 of the 10 studies were documented as required (as indicated by blue) with document creation (i.e. design working drawings) being the largest (60%), with advanced sustainability studies and architectural performance tied at the next highest with 26.7%. Discouraged or highly discouraged was limitedly recorded with acoustics having the highest combine value at 20%. In review, it appears faculty across AE programs are incorporating more sustainable and energy efficient design studies across disciplines with the inclusion of life cycle analysis and payback type studies to provide "proof" that designs are working. This trend aligns well with industry's push in the same direction.

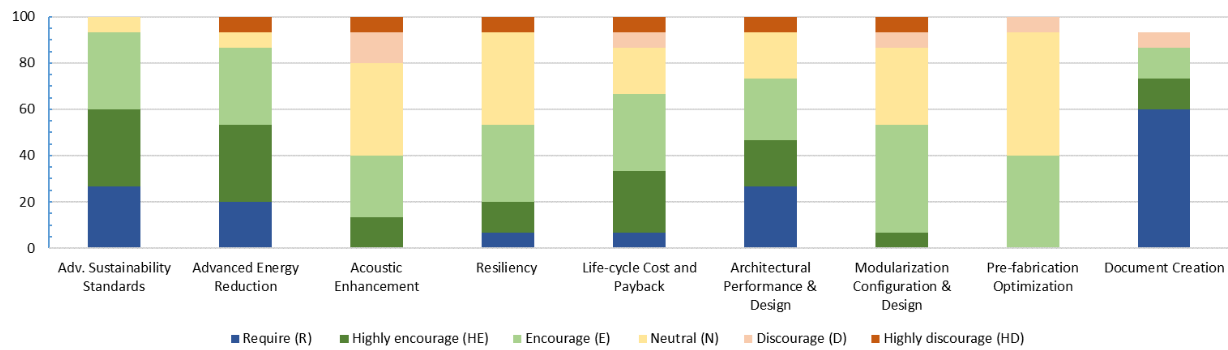


Figure 10: Trending AE Topics and how they are encouraged, discouraged or required in capstones.

While programs did provide some core discipline technical scope, and with Fig. 10's insights into the more up and coming side of technical known, gaps still remain. Knowing what faculty don't recommend is equally important. Table 1 provides a grouped listing of items that students are typically advised to not undertake from the perspective of the faculty. Two respondents specifically mentioned their lists are more of a recommendation, as they want students to focus on studies that are impactful, but are open to students exploring these areas to learn about the topic. Items listed in Table 1 often are advised as such due to a program's scope of coverage or that the items listed center on issues not normally critical to learning the bigger picture of design that often is the core scope of the capstone. One might consider the cost estimating in Table 1 to be a surprise, but it was given the context that the school does not have construction in their AE degree and thus keeps that requirement to a minimum. One school did indicate that as long as they can "finish" the designs required and are confident they can proceed, but that students may be advised it's not the best use of their time.

Table 1: Studies Faculty Recommend to Students to Avoid doing in Capstone.

General Categories	Specific Technical Task Categories	Discipline Specific Categories
• Non-critical systems • Students cannot just have software do everything it must be justified • Anything that is not "engineering" • Doing items that have limited benefit just to say they did it • Going too in-depth in calculations too early in design and system selection • Designing every room that is similar (not grouping designs)	• Arc Flash • Complex structural models that are not necessary • Temporary construction design details • Construction contracts • Complex energy models that end up not working and too much time is wasted	• Advanced structural design that is “in the weeds” within design specifications • Geotechnical work • Cost estimating • Acoustics • Excessive time on architectural studies • Over-modeling in Revit for limited return on investment • IT and telecommunication system design

To support multi-disciplinary design and what is best for the project/owner, systems’ integration becomes important for teams to proactively conduct. This area of education and assessment is often difficult to teach/assess [22-23]. To better understand how programs approach this, participants were asked to summarize how their student teams accomplish integration in the capstone. From the data, six general approaches were determined (bulleted below). These six were in most cases not mandated by instructors but found to often work or resulted in students finding out when something didn’t work. Of the six, four were mentioned by multiple programs and were not isolated to a single school. They include:

- Tie/paired/coupled systems (ex: MEP) need to be checked at each major milestone submittal for coordination and performance harmony with a portion of the grade being impacted.
- Without prompting, teams tend to focus on the physical integration of systems by relying on modeling to coordinate space and often skip the system performance where the goal is to continue to reduce problems.
- No set requirements are mandated other than having to address design review questions (for a grade) which starts forcing conversations in their groups to discuss these comparisons. Review questions can be: what is the trade off in performance between X and Y; what is the impact X has on this other system, is there room for X and Y in that space, etc.
- Integration is partially done through decision-making comparisons back to the goals/program criteria for the project where objective evidence is needed to support the “why”.
- Integration is pushed to be done more in the schematic stage where more impacts are fixable before too much student time is lost and less later on making it look integrated.
- Students address all interdependency connections while evaluating design alternatives for their respective designs by going beyond what is best for a single discipline.

Interestingly, a theme across integration seemed to exist between physical system integration vs technical performance integration. Physical integration is where teams look at designs and ensure they are not clashing physically and have adequate room and efficient relationships that make their designs work. Technical performance integration, however, investigates how systems contribute to the larger project goal of meeting owner target metrics and design standards (e.x. energy reduction, sustainability, lifecycle cost, etc.).

Given the trends discussed previously, perhaps one of the most impactful questions that others may be interested in for their adoption is: *how do students get a choice within their discipline depth studies?* Results to this question state that 23.1% of programs give students a free choice if that choice has a technical rigor and is reasonable for the project. Also, 30.8% give a free choice but all members of the team need to agree upon the choice. Often these two are tied to one another given the formation of typical teams. Lastly, 23.1% of AE programs provide mandates on what types of studies to perform. This approach comes from ensuring students meet certain learning objectives and capstone needs to capture technical work not covered in prior courses. Any approach mentioned is valid, but it does change the dynamic of the capstone in how design decisions are made, and critical professional thinking skills are tested.

Grading of the Capstone Deliverables

Grading of student work in a capstone course can often be problematic [24-26] due to the open-ended nature of capstone design with no one clear solution. Compounding grading is the factor of interdisciplinary teams often being involved in AE capstones [27-28]. Industry involvement, different discipline requirements, and potentially multiple different projects within a course lead to challenges in cohesive and consistent formative and summative evaluations both with and without rubrics [29]. With a plethora of grading schemes possible in conjunction with literature documented challenges, AE programs were surveyed in several key grading aspects to see if trends exist. Across literature, four types of student generated work are commonly listed, they are [18, 30]: technical work, written work, presentations, and general team behavior. According to the survey respondents, 93% of AE programs grade technical work, written work, and presentations, while 73% also grade general team behavior. The reason for not having 100% in a category is due to some programs only grade one or two of the categories and not all four; in fact, only 66% of AE programs evaluate all four categories. Knowing this, we can refine how these categories are evaluated further.

Across the four work categories, success can take on different meanings to capstone stakeholders. Each program was asked how they evaluate success for six commonly documented attributes of the capstone. Respondents were allowed to check if these six are primary, secondary, or were not considered, with results of the survey shown in Fig. 11. Quality of the end solution, execution of the design process, and apply proper knowledge each scored the highest at 93% as primary considerations. Technical correctness was close at 87% as a primary consideration. Only one category had a high secondary ranking, and this was adhering to a feasible process (46.7% secondary), with 13% of the programs not even evaluating this category. These results reveal an emphasis more so on correctness rather than the path taken by students to the answer. This could be either good or challenging when trying to establish problem solving and critical thinking skills [31].

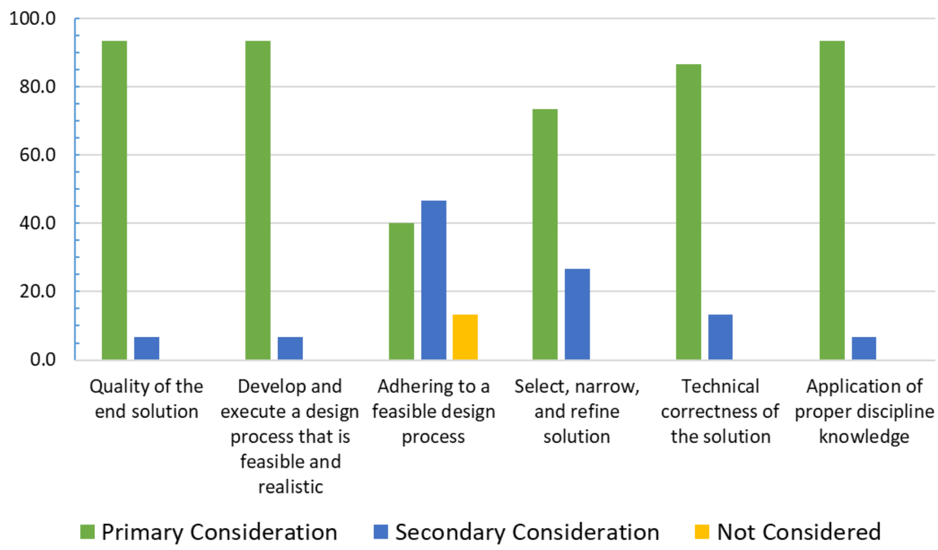
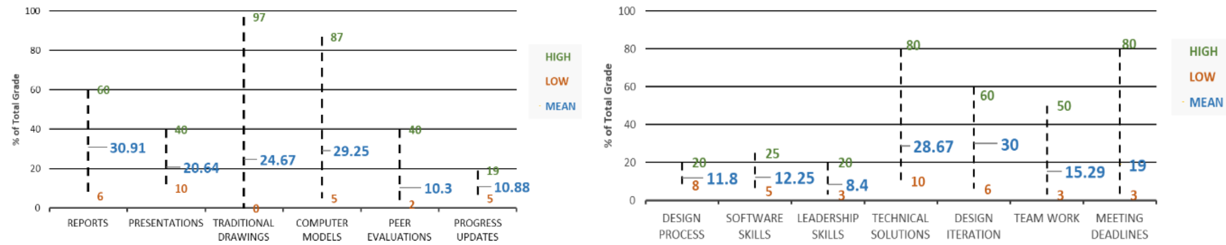


Figure 11: Level of Grading Consideration for different aspects of what students generate / perform.

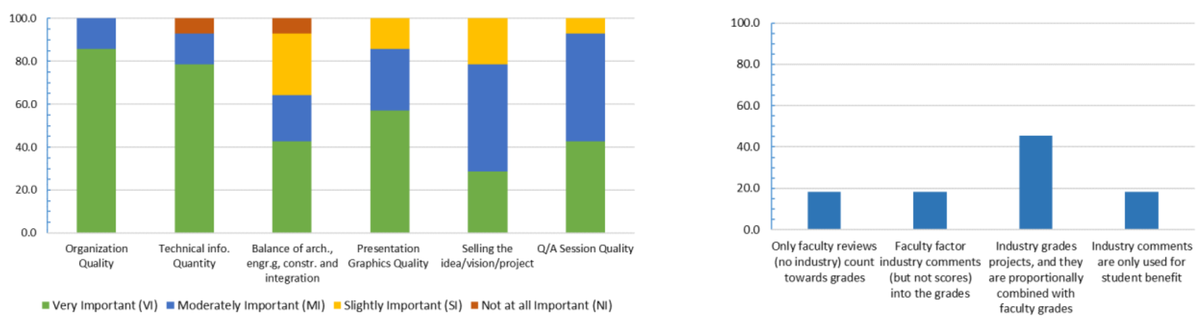
Students can generate many different types of results and documentation. Fig. 12 gives an overview of survey responses indicating the percentage of the final grade for which each produced student work falls. It became obvious in the individual school data that these numbers are skewed due to programs including grading for some but not all topics. However, it is worth noting that some of the topics have higher mean values as part of the final course grade (Fig. 12). Reports, design iterations, computer models, and technical solutions on average accounted for 20-30% of the course grade, with peer evaluations and leadership skills landing near 10%.



a) Grade distribution grouped on items b) grade distribution grouped by skills

Figure 12: Capstone final grading breakdown

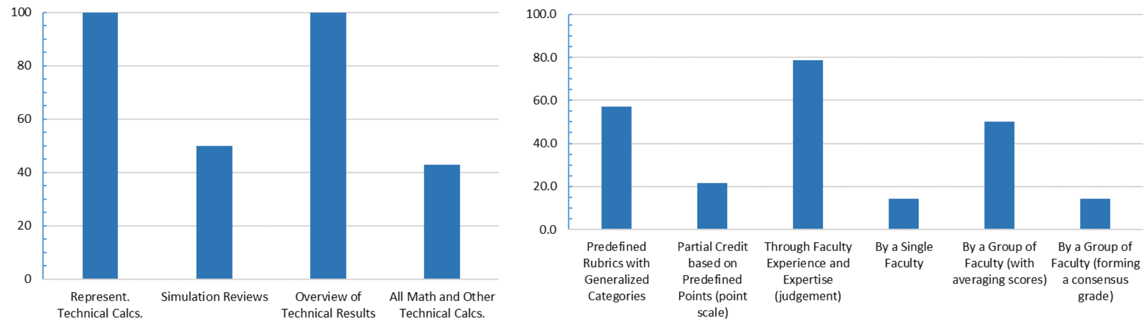
Breaking down student presentation grading, Fig. 13 provides data on an importance scale of what makes for a good presentation. Quality of organization and technical information are very important at 85.7% and 78.6% of programs. The least very important ranking came from the ability of a student/team to sell their ideas while presenting. Q/A sessions of most presentations had the most balance between very important and moderately important (43-50%). In Fig. 13a the data indicates that students should balance their presentations to encompass an array of objectives. Many times, industry and outside mentors/stakeholders are involved in capstones [10,15], particularly at presentation review stages. As a result, some programs have this group involved in the process of assessment (Fig. 13b). In looking at how industry comments and opinions are considered as part of grading, 45% of AE programs have industry participants grade the projects and their scores are proportionally combined with faculty grades (Fig. 13b). The other mechanisms of only faculty grading or only students seeing industry comments are lower at 18%. This makes sense to standardize their feedback but not overly rely on industry as the sole mechanism.



a) Importance or presentation attributes in grading b) Industry vs faculty evaluations

Figure 13: Assessment statistics on student presentations

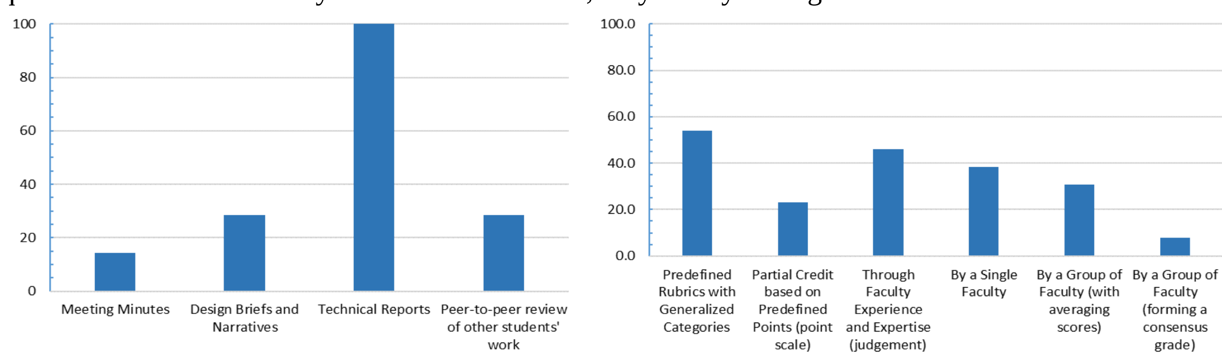
As indicated earlier, technical calculations are critical to AE programs to assess. All programs grade the overall technical results along with selectively picking representative key technical calculations to ensure accuracy (Fig. 14a). 50% of programs will review students' simulation results that have been generated. This response rate can be considered low given how much time some capstones place on software utilization within the course. How these technical aspects are graded are equally varied (Fig. 14b). The most utilized grading mechanism is through faculty experience and expertise to establish the quality and corresponding grade (78%). Generalized rubrics are more popular over partial credit point scale models (57% vs 21%). Surprisingly, the least common is assessment performed by a single faculty member (14%). Instead, it is more common for a group of faculty to grade (64%) with the most common group approach being to average the scoring. According to some capstone literature [16,19], these trends do not align to more civil and mechanical focused capstones.



a) Technical items that are assessed b) Methods to assess technical

Figure 14: Assessment of Technical Work

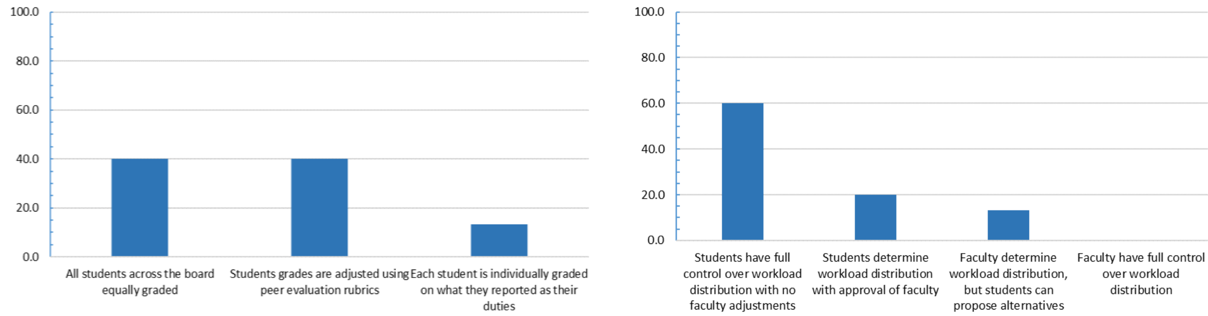
Next in grading is a students' writing ability. According to the survey, four types of assignments are leveraged by programs (Fig 15a): meeting minutes (@14%), short design narratives (28%), technical reports (100%) and lastly, students providing peer-to-peer review summaries (28%). The documented low results for meeting minutes are not a surprise as these are often not required and/or are lumped into a larger professional skillset assessment [32]. Digging deeper into technical reports, Fig. 15b showcases the usage frequency of different grading methods. Unlike presentations, reports have the highest use of pre-defined generalized rubrics (54%), followed by faculty experience and expertise (46%). These are common in literature as writing tends to be broader and requires a qualitative approach to assessment. From the respondents, 67% utilize only the final versions while the other 33% leverage both intermediate and final reports. This breakdown is interesting as it does not follow a typical English course approach to writing iteration and reflection for criticism and improvement. That said, more detail cannot be established as the questions did not ask if they were reviewed or not, only if they were graded.



a) Writing items that are assessed b) Methods to assess writing

Figure 15: Assessment of Written Work

How AE faculty/advisors handle the team aspect of grading was the last component in the survey on assessment. This is particularly pertinent when more than one discipline student is on a team (ex: say two structural). From Solnosky and Phillips [14], most AE programs are team-based formulations. In general, faculty generally treat all team members equally (40%) for grading common items (share the same grade) when two or more students are in the same discipline (Fig. 16a). The other equally popular approach is to treat them the same but utilize peer evaluation rubrics to then adjust individual student grades. Only 20% of the respondents individually evaluate each student's specific contributions. Complementing this data, Fig. 16b shows how faculty have considered the workload distribution across students on the team. For most programs (60%), not interfering with how teams break down student self-generated workloads is the preferred approach. If issues arise here, it is handled more so in the grading over the distribution. 33% of programs have some aspect of faculty control over workload, whether it is a negotiation process, an approval process, and/or an iterative method of balancing expectations.



a) Assessment of 2+ same students on a team b) Method of workload sharing on teams

Figure 16: Statistics on how to share responsibilities and grade for multiple of the same discipline.

Current Challenges and Future Potential of AE Capstones

To round out this paper (and the broader study on AE capstones), this survey asked faculty to document their biggest challenges in their current AE capstone delivery. Additionally, programs responded to what trends in the AEC industry (or elsewhere) educators should be considering for future capstone enhancements over the next 10 years. Table 2 provides a key set of these summaries. From a challenge perspective, three discreet trends emerged. One is the students' work ethic and commitment to the course given how late it is in their degree along with motivation to do well right before graduation. The second is in the larger and earlier stages of design that often are not taught in many technical courses. Lastly, some continue to struggle to provide an industry connection through mentorship.

Table 2: Challenges and Future Topics for Capstone Educators to Consider

Current Challenges to Remedy	Future Potential for AE Capstones
• Student unwillingness to commit adequate time to the Capstone course. • A longer capstone where more can be accomplished (currently one semester). • Getting students to be better at preliminarily layout of systems and not waste time. • Lack of "looking at the big picture" and how their actions influence other systems. Only want to focus on "what they will do after graduation". • Finding practitioners to mentor. • Students have difficulty transitioning from lecture format courses to hands on applied design studio with significant self-time management. • Integration of systems design beyond what students want to do of just clash detection. • Faculty to student ratio particularly with multi-disciplinary teams and having knowledge people around to answer questions or having the right balance of disciplines.	• Continue to push for more integrated designs & overlapping/connected discipline experiences. • Impact of AI on design and engineering and how to leverage it in capstone. • Continue to push for more BIM, AR, and VR adoption. • Better guidance and adoption of life cycle assessment, deeper sustainability studies, net zero design and occupant wellbeing. • More electrification and more generative and parametric studies. • Leveraging of remote tools to encourage mentor participation and meaningful engagement. • Continue to work more on critical thinking and problem-solving skill development over routine calculations.

Moving to future trends, Table 2 provides a summary of three areas of continued work. First is work towards the continuous advancement of integrating more modern technology and digital design for students to leverage. Second was the acknowledgement of more topics adoption/scoping that are emerging in industry. Here they are acknowledged such that students should be investigating them, so they are set up for early success. Lastly, continued guidance of the teams is encouraged to better their critical thinking and problem-solving skills around integrated design.

Conclusions and Takeaways

For nearly all programs, AE capstone courses are the culmination of AE curriculums that expose students to situations similar to what they will encounter upon entering the profession. Capstones further lead students towards integrating practical skills with fundamental concepts in ways which for most other courses are not possible. The information presented in this paper on the structure of capstone courses showcase that many of the AE programs have a united vision for a rigorous capstone, yet each provide its unique balance and approach. Across assessment, technical skill development, and capstone scope, several key takeaways can be summarized from the work presented. These include:

- Students are often given free, yet justified required choices on which studies and how much of the building to investigate but they are commonly tied to project size and complexity.
- Don't force the entire building scale on a team, instead investigate different sizes and proportions of the building relative to a particular discipline. Consider the amount of work when segmenting.
- Earlier parametric studies can provide opportunities for deeper integration and better performance if students are willing to spend the time doing these. That said, faculty/mentor insight is likely required given prior exposure to this type of work.
- Center AE capstones on the 4 core AE disciplines but consider bringing in building enclosures and other disciplines that complement the project if the team size and strength is there for the extra workload.
- Faculty review of student-scoped work is needed to ensure proper learning while at the same time they need to advise students that the proposed work must be completed just like a professional office that agrees to a project's contract.
- Students are encouraged to leverage software to be able to maximize the learning experience of designing larger building systems, but they need to be cautious and provide meaningful validation spot checks of their results.
- There is a continuous meta-cognition by the faculty to keep improving how students integrate. This is an area that needs to be pushed by the faculty as students want to only look at the physical integration and not the performance integration.

Results in this publication allow all AE programs to understand more fully what is currently happening in AE education and can allow for increased educational opportunities in their own program. Furthermore, these takeaways provide a starting point for other programs to have a self-reflective exercise to see if their capstone does or does not meet the documented trends. Depending on the answer, the data presented earlier can provide starting discussion points for a department on where to possibly shift towards or consider programmatic modifications.

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