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Teaching models for Senior Design courses; a Case Study

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Abstract
Over the past five years, multiple teaching configurations have been used at the University of Maine's Mechanical Engineering Senior Capstone two-course sequence in response to faculty turnover and a 40% growth in student numbers. The configurations evolved from a single instructor supported by a lab manager, to two co-instructors jointly overseeing all teams with limited volunteer faculty mentor help, to a single instructor overseeing all teams supported by faculty mentors advising one to two teams in their area of expertise, to three closely coordinated instructors advising only the subset of the teams aligned with their expertise in the form of three different sections.

The single instructor model was not suitable to accommodate the student growth and to provide the diversity of projects needed to satisfy student interests. In order to manage the high number of student teams, an increasing delegation of student advising to support staff took place, combined with a streamlining of the project theme to converge at multiple instances of a single project. Challenges of this system included a progressive weakening from the course learning outcomes, and a lack of project choice for the students. Subsequent changes aimed to develop a model that offers diversity of both expertise and projects, while maintaining a sustainable workload for the participating faculty. Two faculty members jointly supervised all projects, and with the support of additional mentoring faculty, significantly increased the variety of projects. However, advising all teams and coordinating mentoring activities by other faculty members resulted in a very high workload for both instructors. The introduction of a much more systematic assessment and evaluation approach for the course in alignment with ABET further complicated this approach. Sabbatical absences of first one and then the second instructor reverted the process to a single instructor supported by a more extensive team of mentoring support faculty, however it was noticed that more mentors do not automatically reduce the instructor of record's workload. The current approach relies on three instructors that focus on their areas of expertise by having separate course sections. While constant collaboration and calibration of the assessment is necessary, the focused work, while still enabling an ample variety of projects, is proving to be sustainable and effective.

The paper quantifies instructor workload, coordination challenges, student feedback, project diversity, and assessment and evaluation characteristics of the different instructional models based on data collected over the past 6 years, and can help inform the suitability of teaching modality choices.

1. Introduction

Capstone courses represent the culminating experience for engineering students, and as such take on a central role in every engineering curriculum. In addition to introducing a range of learning objectives that vary from institution to institution, they very often constitute a core element of the ABET accreditation effort [1]. They also offer an important bridge to industry, with implications ranging from student hiring, to strengthening departmental bonds with participating industry [2], [3]. Capstone courses are also becoming increasingly multidisciplinary to reflect the nature of the profession, however this progression remains difficult due to differing timing and assessment and evaluation requirements of the different disciplines [4].

The typical learning objectives of capstone span the range of professional skills such as teamwork and communication, as well as technical skills, where students utilize material learned throughout the curriculum to develop an engineering design. An important element of this process is the consideration of industry-near practices and standards, as well as a risk-based analysis and an ethical perspective on the design task. Often the student design is also built and tested, thus closing the loop of the design-build-test sequence. Thomas et al. [5] classify the overarching objectives of the capstone experience as one of integrating and synthesizing precious knowledge, of preparing a transition to working life, to have students reflect on their learning and practice lifelong learning, and to provide closure in the form of a culminating experience.

Capstone courses display a great variety of instructional practices [6], [7] however there is little literature on the effect of these practices [6], [8] on student learning and faculty workload. Faculty workload in a course like capstone can become very high due to the frequent individual interactions needed with the teams [8], [9]. The amount and nature of the instructor-student interactions varies, but always relies on periodic meetings to supervise and mentor student team progress. During these meetings, typically feedback and advice are given on the technical aspects of their project, project management, and teamwork dynamics. It is critical that the instructor be able to support all elements of the interaction, and be a good communicator, and often moderator, in the team process. As such, not only technical expertise in the team-specific project topic is needed, but also exposure to industry and professional project management and teamwork processes is highly beneficial.

The instruction mode of capstone courses may vary greatly due to department goals, faculty teaching style, and student populations. A one-size-fits-all approach is not likely to be successful, but each department can benefit from considering several instructional models for capstone to determine what would best meet their needs. At the University of Maine, changes to faculty and student populations during the period of academic year 2016-17 to 2021-22 led to the department implementing five distinct instructional modes defining how student teams interacted with faculty. In this paper we first describe each of the modes and the reasoning that triggered the implementation of that mode. We provide information for each mode related to six important metrics that a department may consider when implementing a capstone model: scalability, project diversity [9], student satisfaction, cost, consistency of the assessment process [9], and faculty workload. The relative performance of the five modes across these metrics are compared in the discussion. Recommendations and conclusions are then made. The information and recommendations provided will allow programs to help determine the most appropriate capstone model when faced with student growth or changes in faculty resources. As noted above, it is not likely that a single model is best for all situations.

1.1. Capstone at the University of Maine (UMaine)

The UMaine Mechanical Engineering Capstone is a full year, two-semester course sequence. During the fall semester, student teams follow a rigorous process to design and simulate their project, and in the spring semester they build their project and test the performance, comparing it to the predictions computed in the fall [10]. This sequence is split into four major phases; conceptual design, detailed design, manufacturing, and testing. The design phases are accompanied with the respective deliverables, consisting of a mix of individual assignments and team assignments. While the individual assignments aim to explore student progress (and challenges) within the teamwork setting, the team assignments reflect project progress, including all ABET specific elements of the culminating design experience [1]. These deliverables include team presentations, major reports for each phase, as well as CAD packages, websites, and also require a continuous peer assessment process to allocate merit within each team [11]. Instructor meetings typically happen weekly, with ongoing communication throughout. Over the winter break, the instructor team compiles the materials list for the builds, with purchasing being executed by departmental staff. The capstone experience relies on departmental funding, however externally funded projects are included which, in addition to lowering the cost burden for the department, improve project diversity and often provide exceptionally relevant experience for students [10].

1.2. Evolution of instruction models at UMaine

From 2016-17 to 2017-18 there was a substantial change in the UMaine Mechanical Engineering Capstone. A new performance indicator based ABET assessment and evaluation system was introduced in the department, resulting in a high number of performance indicators requiring assessment in the capstone sequence [10]. This triggered the development of a new course-level assessment system that introduced more deliverables. As such, the workload of the supervising faculty increased beyond the already high load, even in light of a smaller senior class. In addition, there was a desire to offer a greater project selection to the students, to better align the capstone experience with their individual interests. In following years, as shown in Figure 1, a variety of motivations based on lessons learned and student feedback were used to develop and implement the additional models:

- 2016-17 and prior: Single instructor model (SI)
- 2017-18 Multi-instructor configuration where all instructors jointly oversee each team (MI-J)
    - Motivation: Decrease workload and increase project variety
- 2018-19 and 2019-2020 Collaborating single or multi-instructor model with support from volunteer faculty (VF)
    - Motivation: Decrease workload and increase project variety
- 2020-21 Single principal instructor model with assigned collaborative faculty (AF)
    - Motivation: Maintain project variety and reduce faculty workload while short-staffed lead instructors
- 2021-22 Multi-instructor model with split responsibilities (MI-S)
    - Motivation: address workload and project management difficulties of previous models

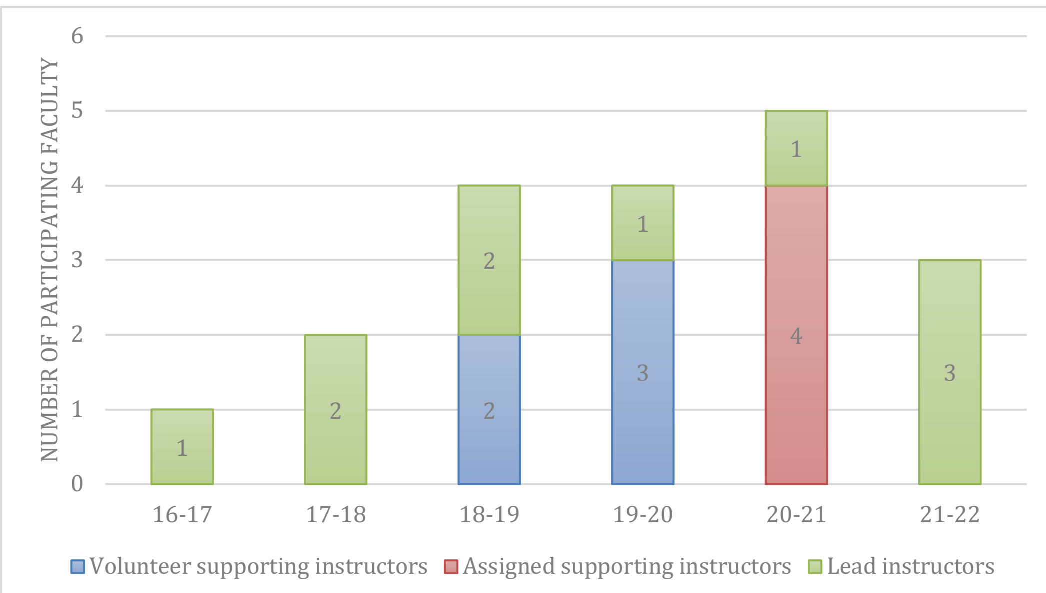

Figure 1. Distribution of lead and supporting faculty 2016-2022.

While these modalities are not universal or exhaustive, this case study offers insight into the motivation, advantages and disadvantages of each approach.

1.2.1. Single instructor (SI) model (2016-17 and prior years)

- Number of lead instructors: 1
- Supporting faculty
    - Volunteer instructors: none
    - Assigned faculty: none
- Number of students: 94
- Number of student teams: 24

Prior to 2016, a single faculty member oversaw the capstone experience. Since the beginning of the decade the Mechanical Engineering Department has seen strong student growth. This model, while initially serving about 50 students, incrementally increased to 94 students in 2016, reaching the limit of what was feasible with a single instructor.

The very high workload of the single instructor combined with only a single person's area of expertise required a streamlining (unifying) of the capstone projects. In 2016-17, 60% of the students in the class conducted the same project; there were 15 autonomous land drone teams (Figure 2). This standardized project consisted of an internal competition of autonomous all-terrain land vehicles and, while incorporating all essential elements of a culminating design experience, severely limited available project choices for students. An advantage of this development was the standardization of components (all teams were required to utilize a gasoline engine as power source, that then either directly drove the drone, actuated a hydraulic pump, or an alternator to electrically drive the vehicle).

Figure 2. 2016-2017 Capstone land drone team (one team from 15 conducted that year).

The increasing workload on a single instructor and course streamlining to cope with the growth, also led to fewer and easier to assess deliverables. Written reports, which require significant reading time and technical knowledge to assess, were reduced (or "farmed out" to supporting technical writing courses) in favor of CAD print packages, which can be evaluated quickly according to a straightforward rubric. Immediate needs of teams took priority in the form of undocumented progress meetings with individual teams, but little time was left on a regular basis to evaluate with periodic assignments. This made it difficult to fairly evaluate teams, and extremely difficult to evaluate individual students.

Lastly, the lack of deliverables also greatly hindered the assessment of ABET student outcomes in this important curricular element. This edition of capstone marked the introduction of a new

ABET assessment system in the Department by introducing a new, more extensive set of requirements, that would be reflected in student deliverables in following years. The new system introduced Performance Indicators (PI's) that are mapped to the individual Student Learning Outcomes (SLO's). These PI's significantly improve the assessment of the SLO's by increasing the number of assessment points used. Capstone plays a central role in the assessment of the PI's with 16 out of 34 PI's being assessed entirely or partially in the capstone sequence. This required a complete re-organization of the deliverables to align with the necessary ABET PI assessment, including the development of appropriate assessment procedures that address individual student performance in a team environment [10], [11].

A summary of the observations of this mode is presented in Table 1.

Table 1. Single Instructor teaching modality observations.

Scalability	Not scalable - the student growth over the period severely limited effectiveness of this model
Project diversity	Very low - streamlined to a single project with few exceptions
Student satisfaction	Moderate - students were unsatisfied with the seemingly arbitrary grading and the lack of options
Cost	Moderate - projects allowed streamlining, but unified project had a relatively high complexity
Consistency of assessment	Consistent, however highly subjective due to limited deliverables
Faculty workload	Very high

Thus, the motivation for change emerging from this year was primarily an increase in the variety of projects to improve student satisfaction, and to provide an adequate staffing solution to cater to the increased assessment demand as well as mitigating the very high workload of the prior single instructor model.

1.2.2. Joint multi-instructor (MI-J) model (2017-18)

- Number of lead instructors: 2
- Supporting faculty
  - Volunteer instructors: 2
  - Assigned faculty: none
- Number of students: 74
- Number of student teams: 16

Under this model, two instructors were assigned to the course, and jointly supervised all the teams. Rather than a model of split responsibilities and each instructor only being responsible for half the students, the instructors chose to jointly supervise all students. This model was chosen to better and more consistently be able to implement the new assessment framework with the expanded deliverables, while also providing multiple faculty perspectives to the students, thus enriching their experience.

This model was initiated to support a broader expertise background and enable a greater diversity of projects. In addition, an increased effort was made to link capstone teams with external "clients" to increase the industry-near elements of the experience. Several external clients were recruited, and in particular the increasing interest in aerospace engineering was incorporated by conducting a series of externally funded Uncrewed Aerial Vehicle (UAV) projects, ranging from remote sensing platforms, to lighter-than-air vehicles (Figure 3).

Figure 3. 2017-2018 capstone teams developing hybrid UAVs in collaboration with researchers from the School of Forest Resources.

The joint supervision approach was utilized to expose students to multiple viewpoints and management styles and was generally well received. A disadvantage of the joint assessment is that effectively the workload of each instructor is the same as that of a single instructor. However, the dynamic that emerged from the very constructive collaboration of the instructor team yielded a significant improvement in the supporting course materials and processes. In addition, this modality provides ample flexibility if one instructor is not available, as both are familiar with all teams and course materials. Thus, overall both student satisfaction as well as assessment quality increased, however instructor workload remained very high. In addition, the method does not scale well. A summary of the observations of this mode is presented in Table 2.

Table 2. Joint multi-instructor teaching modality observations.

Scalability	Not scalable – the student growth over the period severely limited effectiveness of this model
Project diversity	Moderate – the expertise fields of two faculty augmented the project variety
Student satisfaction	High – better options, although higher requirement on deliverables
Cost	Moderate – more instructor supervision allowed cost savings
Consistency of assessment	Consistent with close coordination between instructors
Faculty workload	High to very high

The motivation for the next iteration of capstone was primarily to alleviate the very high workload of both the lead instructors, and to provide more project-specific expertise to support the diversity of projects. While there was consensus that jointly advising all teams is beneficial, there was also student feedback that multiple viewpoints could be conflicting.

1.2.3. Joint multi-instructor (2018-2019) or single-instructor (2019-2020) with collaborating volunteer faculty (VF) model

- Number of lead instructors: 2 (2018-2019) and 1 (2019-2020)
- Supporting faculty
  - Volunteer instructors: 2 (2018-2019) and 3 (2019-2020)
  - Assigned faculty: none
- Number of students: 86 (2018-2019) and 81 (2019-2020)
- Number of student teams: 18 (2018-2019) and 14 (2019-2020)

In order to alleviate the high workload demands while still maintaining the exposure of students to multiple management styles and increase and better support the project diversity and associated specific technical know-how, a number of volunteer faculty were enlisted to support teams in their area of expertise. The overall guidance of the teams still relied jointly on the lead instructor(s); however, the hope was to delegate the technical advising to the collaborating volunteer faculty, with the lead instructor(s) jointly retaining the assessment and evaluation of the course. The lead Instructors also attended all scheduled group meetings.

Figure 4. Capstone student during the 2018-019 AY working on hydrofoiling multihull vessels.

The additional expertise supported the project variety and student satisfaction; however, in the collaborating faculty advised groups, the separation of technical advising and assessment and evaluation caused some confusion. This was aggravated by the necessary familiarization of the collaborating faculty with the complex individual and team grade as well as the peer evaluation process. From a faculty workload perspective, this model does not alleviate the very high workload of the lead instructors, as they continue to oversee all the teams. In addition, the training of the volunteer collaborating faculty further increased the workload, in particular due to the understandable lower level of prioritization of the volunteer faculty members.

A summary of the observations of this mode is presented in Table 3.

Table 3. Joint multi-instructor teaching modality with collaborating volunteer faculty observations.

Scalability	Limited scalability without full delegation of team responsibility to collaborating volunteer faculty
Project diversity	Good
Student satisfaction	Medium–- better options, although higher requirement on deliverables; some confusion due to the separation of technical and course advising
Cost	Medium–- more instructor supervision allowed cost savings
Consistency of assessment	Consistent with close coordination between instructors
Faculty workload	Very high–- both for the primary instructor and the support faculty due to training efforts and coordination among a large team

A similar multiple-instructor, volunteer faculty model was adopted again in the 2019-2020 AY. However, a sabbatical of one instructor reduced the team to a single instructor for the spring semester of the 2019-2020 AY. That semester represented the build and test phase, and finalizing the cohort with the single remaining instructor with strong support from the lab manager was deemed feasible, especially with now better-trained volunteer collaborators. The single instructor initially carried a large administrative and grading burden, which was only possible through the elimination of other teaching and service duties. However, the semester was cut short due to the COVID pandemic, and thus few additional insights were gained. Without the ability to have in-person meetings to complete the fabrication and testing phase of the course, most projects were left unfinished and only half of the semester graded deliverables were submitted by students and evaluated. Under these circumstances, it was difficult to fairly assess student satisfaction with the arrangement in addition to the instructor workload level.

1.2.4. Single principal instructor with assigned supporting faculty (AF) model (2020-2021)

- Number of lead instructors: 1
- Supporting faculty
    - Volunteer instructors: none
    - Assigned faculty: 4
- Number of students: 73
- Number of student teams: 14

The 2020-21 AY was approached in the single instructor (now the other lead instructor was on sabbatical) with assigned supporting faculty mode. The motivation to formally assign faculty team mentors originated from the previous mixed success of faculty participation on a volunteer basis. Also, the cohort numbered 75 students, making it difficult for a single instructor to oversee all teams. As such, the responsibility of individual teams was delegated to the assigned supporting faculty mentors (some with capstone experience and some without). The lead instructor managed 9 student teams, and the supporting faculty (4 faculty) were paid an overload to formally mentor 1-3 teams each. The lead instructor also handled all lectures and the organization and assignment of the deliverables for all groups, with the supporting faculty being responsible for the grading of the team deliverables. More responsibility and time commitment was required from the supporting faculty in this model, reducing workload for the primary instructor related to directly interacting with teams, but a similar level of effort was needed to train supporting faculty. The effort by supporting faculty also required the department to adjust other teaching loads of supporting faculty, increasing the resources consumed by capstone. A summary of the observations of this mode is listed in Table 4.

Table 4. Single principal instructor with volunteer (2019-2020) and assigned supporting faculty (2020-2021).

Scalability	Limited scalability–- course management duties for coordinating volunteer instructors outweigh reductions in team supervision
Project diversity	Very Good
Student satisfaction	Moderate–- better options, although confusion due to the separation of technical and course advising and perceived inequity in assessment of student deliverables
Cost	Moderate to high–- support instructors were compensated financially instead of granting teaching release time
Consistency of assessment	Moderately consistent, however inevitable differences occurred due to the high number of support faculty
Faculty workload	High–- reduced team responsibilities, although with higher faculty training duties

1.2.5. Split-responsibility multi-instructor (MI-S) model (2021-2022)

- Number of lead instructors: 3
- Supporting faculty
    - Volunteer instructors: none
    - Assigned faculty: none
- Number of students: 112
- Number of student teams: 22

In the 2021-2022 AY the capstone cohort exceeded 110 students. In an attempt to maintain a reasonable instructor workload and offer a variety of projects with accompanying technical expertise in the team supervisory role, a multi-instructor model was adopted with three faculty each assigned to their own section of the capstone course. Tight coordination between the instructors existed with common lectures, deliverables and grading rubrics. However, with the increase in the number of instructors, the co-supervision of capstone teams would have increased instructor workload and created additional opportunities for teams to receive conflicting technical guidance on their specific projects. As such, a split-responsibility model was utilized wherein instructors were the sole supervisor for the capstone teams within their section.

With the current approach, each instructor is responsible for supervising and grading the deliverables for 7-8 teams which, with the current level of contact hours and grading duties, is approximately equivalent to the commitment for a standard lecture course. In this arrangement, the capstone project topics are grouped into the areas of expertise of the three faculty, thus eliminating the need for external support faculty to provide adequate technical guidance to the capstone teams. However, the course syllabus, lectures, deliverables and grading rubrics are identical for course sections to make the course equitable for the student regardless of the section they are assigned to. In addition, after grading of significant deliverables, the three capstone instructors compare their findings and make grade adjustments to further enhance equity of the assessment process prior to posting assignment grades. A summary of the observations of this mode is listed in Table 5.

Table 5. Split responsibility multi-instructor model observations.

Scalability	Scalable - instructors can be removed or added as long as the team-to-instructor ratio is capped at approximately eight
Project diversity	Very Good
Student satisfaction	High - better options, limited confusion due to the coordination of the instructors, perceived fairness in grading procedures
Cost	Medium - more instructor supervision allowed cost savings
Consistency of assessment	Consistent with close coordination between instructors
Faculty workload	Medium - contact hours and number of grading assignments unchanged, but less coordination required for team management and more focused grading duties

2. Discussion

2.1. Scalability

Scalability should be considered by a department that may expect growth in overall enrollment or year-to-year variation in capstone enrollment. Highly scalable models can benefit a department by providing a quality capstone experience through changing enrollment without draining department resources through significant modifications to the model. Initial models with smaller cohorts relied on the ability of all instructors (or the sole instructor) to provide guidance and review deliverables from all teams. These models (SI, MI-J) proved to be poorly suited for scaling to larger cohorts, as the time commitments of attending meetings with all teams and reading deliverable reports quickly become infeasible for every instructor regardless of how many instructors are assigned. Scalability to growing enrollment was only found to be feasible when mentorship of each group was limited to a single faculty. This included models with supporting faculty (VF, AF), however, in those models, the requirement of training and monitoring the supporting faculty meant that an upper limit on the possible number of supporting faculty existed for a single primary instructor, greatly limiting the scalability of these models. The MI-S model presently being used allows for greatest scalability as any number of primary instructors can be included, to the point that they can effectively coordinate course structure and grading.

2.2. Project diversity

With the broad nature of mechanical engineering, and the desire by many students to specialize in their studies, better learning outcomes and student satisfaction are reached when students can select from a diverse set of projects. High project diversity should be a goal of effective capstone models. We have quantified this metric by the number of projects offered per student.

The project diversity is reflected in Figure 5. While in 16-17 there were only 0.074 different projects conducted per student in the class, that increased to 0.12 in 2017-18, and even to 0.15 in 2019-20 (this was likely due to the participation of three volunteer instructors with only technical advice responsibilities that year). Following this progression, in subsequent years the number stabilized to about 0.12 different projects per student. In each year there are multiple instances of the same project (by student choice, not by assignment), and the average number of students per project is five (while a “normal” team size of four students is envisioned, more involved projects require a higher number, with up to seven students participating in the large teams).

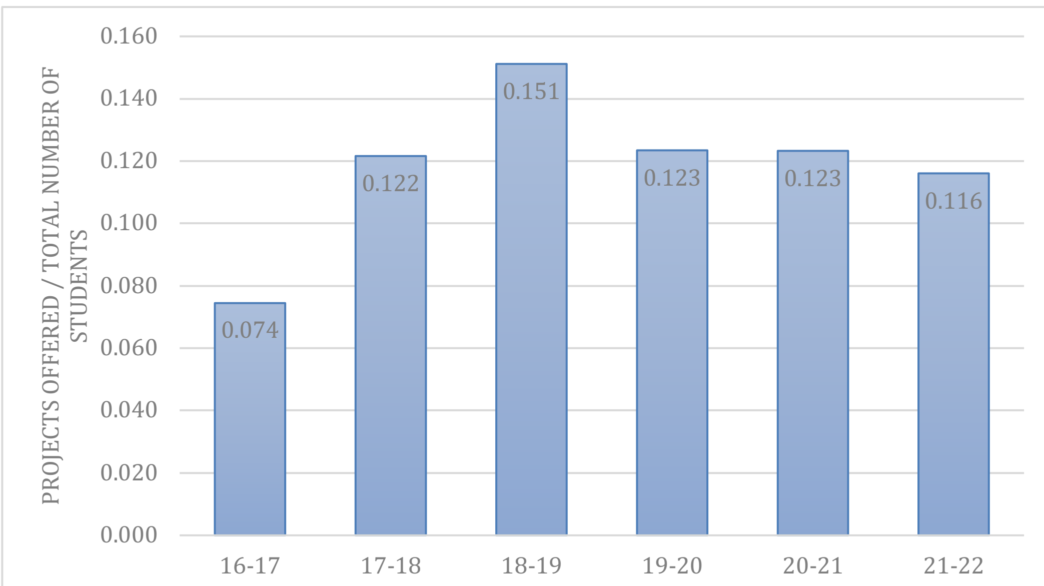

Figure 5. The number of different projects per student (measure of the variety of projects conducted).

As shown in Figure 5, it is clear that including more than one instructor drastically increases the available project diversity and quality of technical advice. This applies primarily to the technical advice and does not include the teamwork and project management support. Often (as at UMaine mechanical engineering) the lead faculty members in capstone have industry and teamwork experience, and collaborating faculty participate primarily due to their specific technical expertise. As such, in the volunteer model, the lead instructors continued to support the teamwork-relevant aspects, with the associated impact on their workload.

Increased project diversity through externally funded projects is directly tied to the number of primary instructors, and the amount of past capstone experience by those instructors. Relationships with external clients have been built over a number of years and a diversity in instructors assists with attracting clients from diverse fields.

2.3 Student satisfaction

All departments are required to consider student satisfaction in all course offerings for a variety of reasons. Capstone can be a frustrating experience for students who are not familiar with self-direction, which they may not experience in many prior academic activities. Student satisfaction was driven primarily by project choices - with high project diversity correlated with high student satisfaction, perceived fairness in grading, and consistency of information between groups. The SI model was limited in project diversity and also suffered from a lack of graded deliverables due to instructor workload, leaving students feeling that their grades were determined by an incomplete picture of their effort and results with little chance for feedback. Both were issues with student satisfaction, although students generally felt they received consistent information. On the opposite end of the spectrum, the VF model had very high project diversity, but with project guidance and grading divided over many faculty, consistency of both grading and information were challenges to student satisfaction. Models with support faculty (AF, VF) require time-intensive training and continued coordination throughout capstone to achieve high student satisfaction.

Student satisfaction was highest with the MI-J and MI-S models, which shared high project diversity with a relatively small number of faculty interacting with groups. The lower number of faculty compared to other models made it easier to coordinate grading and information consistency. However, more coordination effort is required in the MI-S model because, unlike in the MI-J model, not all instructors are presented at all team meetings, nor are all deliverables seen by all instructors. Hence MI-S does present some minor challenges to student satisfaction.

2.4 Cost

Funding for the capstone experience originates primarily from the mechanical engineering department but is supported by projects that have external “clients”. These clients either approach the department, or the course instructors actively seek them out. External clients are required to provide funding for their project’s hardware. An average budget for each project is $1000, not including standard consumables that are stocked in the lab.

There are two principal effects of a faculty workload reduction on the overall cost. First, instructors can dedicate more time to recruit and engage with external clients. Managing involvement and expectations of external clients to ensure the appropriate academic experience of the students can be challenging, and requires significant instructor time. In addition, developing additional contacts for the growth of external contributors does not only represent cost savings, but clearly enriches the student experience. However, this development in the absence of more formal processes, also requires a significant instructor time commitment. In the 2016-present evolution of the capstone sequence and instructor workload, external project funding has grown from 12.5% of the projects in 2016-17, to a peak of 33% in 2018-19, with COVID slowing further growth over the past two years.

A second factor affecting cost are unforeseen and reorders due to either engineering or part selection mistakes. These can easily double the cost of an individual project. It is clear that in scenarios where all teams are supervised by a single or by multiple instructors jointly, the individual attention a team can receive is diluted, which in turn triggers increased unforeseen costs. An element of the evolution of the teaching modes (made possible by lower workloads) has been the development of a much more detailed order and change-order approval process linked to a higher level of planning support and supervision. This has drastically slowed the cost overrun of the projects.

2.5 Consistency of assessment

Ensuring equitable assessment among the different groups is essential for a successful capstone experience, and close coordination among the participating faculty is required to achieve this goal. This coordination is simple for two to three lead instructors both in joint (MI-J) and split (MI-S) modes, however becomes challenging specially with participating volunteer instructors (VF), and to a lesser extent assigned instructors (AF). In both VF and AF modes, the lead instructor(s) extensively brief the supporting faculty on the expected level of engagement with student teams, however in practice the resulting level of engagement varies. This is not due to neglect, but simply because of different backgrounds and experience mentoring teams and design projects. This difference does not go unnoticed by the students. In VF mode, most deliverables are graded by the lead instructors, and thus quantitative assessment remains consistent, however in AF mode the grading of the major technical deliverables is conducted by the supporting faculty. All grades are then reviewed as an instructor team to ensure consistency, however it has become apparent that the depth and breadth of the design development of the teams varies.

Another aspect of consistent assessment is the instructor evaluation by the students. Obtaining actionable student evaluations from capstone courses can present a number of obvious challenges, including the unique nature of the course compared to the majority of an undergraduate curriculum, students performing work in teams instead of individually, and instructors acting in multiple roles (lecturer, teamwork mentor, technical advisor). These can be exacerbated by the inclusion of multiple instructors. The SI model is clearly the easiest to evaluate of the models presented.

Many of the course evaluation procedures used by universities will not apply well to the models presented. The student evaluation software utilized by UMaine, by default, asks students to evaluate all instructors jointly for co-taught courses. No easy option was presented to have students evaluate a project mentor separately from the course instructor in the models where different faculty serve these roles. With the MI-S model, no option existed to separate anonymous responses into teams advised by each instructor. These shortcomings mean that evaluating students' capstone experiences effectively is reliant on instructors soliciting and considering responses to a self-developed set of questions that relates to the unique nature of a capstone course and the specific model of instruction.

When supporting faculty are included in the instructional team, it becomes very difficult to evaluate the quality of advising given to each team, even with custom developed student evaluation questions. The sample size for a specific faculty may be a few or even a single team, and with no prior, similar experiences to compare to, student feedback of the supporting faculty is rarely actionable. Reliably evaluating cooperating faculty is only possible by the course instructor(s) attending meetings with cooperating faculty, further increasing workloads of instructors.

2.6. Faculty workload

While initially the motivation was to create a larger diversity of projects and to improve the assessment points of the course, the consideration of sustainable workload for the lead instructors soon became a critical element, that was finally addressed by increasing the number of assigned instructors to the course. Figure 6 shows the progression of the number of students advised by the lead instructors over the timespan (note that the full cohort is shown if the lead instructors jointly advise all students).

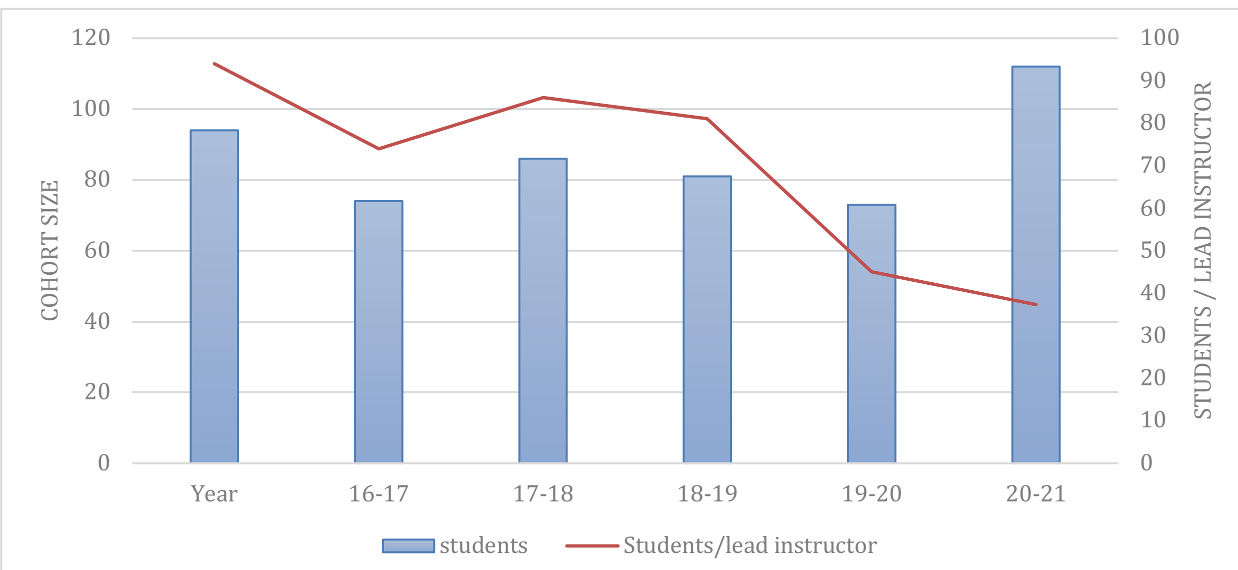

Figure 6. Student numbers as compared with the number of students each lead instructor manages (students are counted twice if both instructors manage all the students together – joint supervision mode).

There is no clear decrease in instructor workload by simply adding volunteer mentors to the class. Figure 6 shows a decrease in instructor workload from 2018-19 to 2019-20 caused by the collaborating instructors now being formally assigned to the course and taking over responsibility for their team(s). However, this figure only illustrates the students assigned to the lead instructor (which indeed drops) but fails to take into account the significant coordination effort that the lead instructor carries. The training and support of volunteer faculty members, especially in light of complex assessment requirements for ABET, is equally as time consuming than advising the teams directly. Arguably there is a training effect after the first iteration, and the training effort decreases in due course, however often collaborating volunteer faculty members rotate in and out of capstone participation, and thus still maintains this high training requirement.

Assigned supportive faculty members receive some credit or pay within the work assignment model of the unit; in the case of the mechanical engineering capstone the assigned instructors volunteered for the overload, and then received overload pay for the 2 course sequence ($1000 for the sequence per supervised team). These faculty are expected to be sole mentors to groups, and complete grading activities, which reduces workload on primary instructors. However, it was found that, in addition to still extensive training efforts, the primary instructor must expend a large amount of effort to ensure consistency of assessment and direction across all supporting faculty.

The only real decrease in faculty workload happens when the cohort is split into sections, with each lead instructor only being responsible for his or her section. This modality was introduced for the current capstone class and has proven to be highly effective and sustainable.

3. Conclusions and future work

The motivation for a mechanical engineering department to revisit their mode of assigning instructors to capstone may come from several sources, such as growing enrollment causing a breakdown of a single-instructor (or other) model, or lack of student satisfaction of the current model. When considering changes, the following aspects of a model can be considered, with the following lessons learned from the experiences at UMaine mechanical engineering.

3.1. Primary instructors joint supervision or split supervision

It is typically an advantage of multi-instructor courses that students are exposed to multiple viewpoints. Capstone instruction models with joint supervision have this advantage, and it is well placed at a time when students are developing their ability to be an effective member of an engineering team. However, models with joint supervision suffer from low scalability and overall generally high workloads on instructors. Split supervision models provide a distinct advantage to departments where the number of enrolled capstone students may change significantly from year-to-year. They are highly scalable and provide manageable workloads at nearly any scale. They do rely on close coordination between faculty to manage assessments and student satisfaction, but this effort is far outweighed by the workload saved compared to joint supervision. The split instruction model, albeit very closely coordinated, is proving to be the only sustainable model at Umaine, with future work aiming at increasing mentorship opportunities for additional supporting faculty.

3.2. Supporting faculty

Supporting instructors, much like primary instructors, are typically added to both reduce the workload and to augment expertise for more project diversity. At UMaine mechanical engineering, supporting instructors were introduced both as volunteers, doing the technical mentoring of one or two teams that are aligned with their field of expertise (with all lecturing and course organization the responsibility of the lead instructor/instructors, and team meetings conducted jointly), or as assigned instructors that were paid an overload to formally mentor 1-3 teams. The aim of formally assigning the instructors was to ensure a higher commitment to the level that in addition to team meetings, also included the grading of the common deliverables (as organized by the lead instructor/s). During the application of this model (2020-2021), the intention was to decrease the workload of the principal instructor over the volunteer model used previously. This was partially achieved; however, the additional substantial training and coordination of the assigned instructors neutralized any workload benefits over the sole-instructor model. A challenge of delegating grading to individual supporting instructors who may rotate in and out of the capstone sequence over the years, is that it is very difficult to ensure equitable grading and supervision, with often differing instructions, advice and expectations. This is clearly reflected in student feedback, who voiced discontent with the method. That is the reason why the volunteer joint-supervision model with the lead instructor/s was chosen initially (2018-2020). This model only requires the volunteer supporting instructors to technically mentor the teams, offering the advantage of exposing the students to multiple viewpoints, while ensuring an equitable assessment of all teams by the lead instructor. However, the workload of the lead instructor is not reduced over the sole-instructor model; rather it even increases slightly to coordinate the volunteer instructors.

3.3 Faculty coordination

The capstone experience at UMaine mechanical engineering, as is the case at many universities, is unlike the majority of courses that make up the curriculum. Therefore, students are especially unsure about the course structure, the expectations, and what they are to do. When multiple instructors are involved, inconsistency in either grading or instructions can be frustrating. With more faculty involved, it is more difficult to ensure consistency. The AF model where supporting faculty contributed primary direction and grading of teams, appeared at first to have extensive advantages in project diversity, scalability, and flexibility for faculty to move in or out of capstone every year. However, these were all outweighed by the difficulty in assessment, reduced student satisfaction from inconsistency, and the effort needed to improve the consistency. A major factor in UMaine mechanical engineering moving forward with a MI-S model is the relative ease of coordinating between a limited set of 2-3 faculty. However, this coordination is essential to the student satisfaction and consistency of assessment across capstone.

3.4. Future modalities

In the future, and with continuous growth in mind as well as the transition to a new collaborative capstone space used by multiple departments, the multi-section split supervision model will be employed, and increased involvement of volunteer mentors will be sought.

References

[1] "Criteria for Accrediting Engineering Programs, 2020 – 2021 | ABET." https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2020-2021/ (accessed Jul. 26, 2021).

[2] H. I. Abu-Mulaweh and N. A. Abu-Mulaweh, "Case study: Industry-sponsored mechanical engineering capstone senior design program," *International Journal of Mechanical Engineering Education*, vol. 47, no. 4, pp. 371–381, Oct. 2019, doi: 10.1177/0306419018791975.

[3] N. Zhu, "Effectiveness of involving the industrial and business professions into mechanical engineering capstone course," *International Journal of Mechanical Engineering Education*, vol. 46, no. 1, pp. 31–40, Jan. 2018, doi: 10.1177/0306419017718920.

[4] A. Qattawi, A. Alafaghani, M. A. Ablat, and M. S. Jaman, "A multidisciplinary engineering capstone design course: A case study for design-based approach," *International Journal of Mechanical Engineering Education*, vol. 49, no. 3, pp. 223–241, Jul. 2021, doi: 10.1177/0306419019882622.

[5] K. Thomas, K. Wong, and Y. Li, "The capstone experience: student and academic perspectives," *Higher Education Research & Development*, vol. 33, no. 3, pp. 580–594, May 2014, doi: 10.1080/07294360.2013.841646.

[6] C. D. Pérez, A. J. Elizondo, F. J. García-Izquierdo, and J. J. O. Larrea, "Supervision Typology in Computer Science Engineering Capstone Projects," *Journal of Engineering Education*, vol. 101, no. 4, pp. 679–697, 2012, doi: 10.1002/j.2168-9830.2012.tb01124.x.

[7] J. J. Pembridge and M. C. Paretti, "Characterizing capstone design teaching: A functional taxonomy," *Journal of Engineering Education*, vol. 108, no. 2, pp. 197–219, 2019, doi: 10.1002/jee.20259.

[8] R. Esselstein, "Finding the Right Capstone Course Model," *PRIMUS*, vol. 23, no. 4, pp. 385–391, Mar. 2013, doi: 10.1080/10511970.2012.751944.

[9] S. Hackman, J. Sokol, and C. Zhou, "An effective approach to integrated learning in capstone design," *INFORMS Transactions on Education*, vol. 13, no. 2, pp. 68–83, Jan. 2013, doi: 10.1287/ited.1120.0098.

[10] W. A. Friess and A. J. Goupee, "Transformation of a Mechanical Engineering Capstone Experience," in *2019 IEEE Frontiers in Education Conference (FIE)*, Covington, KY, USA, Oct. 2019, pp. 1–4. doi: 10.1109/FIE43999.2019.9028435.

[11] W. A. Friess and A. J. Goupee, "Using Continuous Peer Evaluation in Team-Based Engineering Capstone Projects: A Case Study," *IEEE Transactions on Education*, pp. 1–6, 2020, doi: 10.1109/TE.2020.2970549.