SCALING UP PROJECT-BASED LEARNING IN ENGINEERING BEYOND 100 BSC STUDENTS: A PRACTICAL APPROACH

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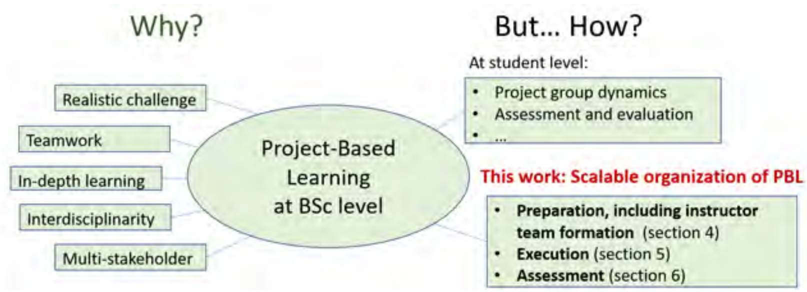
ABSTRACT

Project based learning (PBL) is commonly applied in engineering education, and evaluated positively in terms of learning outcomes and student engagement. However, ensuring depth of the taught material and limiting the workload per teacher is not obvious when implementing PBL, especially for large student populations. Here we share a practical framework to prepare and execute project based learning for groups of approximately 150 BSc students in Mechanical Engineering. We show how a team of Instructors and Teaching Assistants (TAs) allows reducing the workload of individuals in the preparation, execution, and grading phases of the project. In the preparation phase, pairs of TAs draft sections of the project manual that are tested and improved by different pairs of TAs. During project execution, the role of TAs is twofold: (1) They co-supervise two project groups together with one staff member, answering basic and administrative questions. (2) They act as experts for the project groups on the topics that they helped develop, which are sometimes outside of the direct scientific scope of the instructors. Therefore, the TAs act as *more knowledgeable others* in Vygotski's theory of constructive learning and therefore provide effective scaffolding, preventing students from getting stuck at places of difficult learning. The instructors (10 staff members, mainly of our research group) take responsibility for the execution and assessment phases to ensure quality, but at a strongly reduced workload because of TA involvement. The implementation schedule for the preparation, execution, and assessment phases of the project are included in the supplementary materials, as well as an example project description on Covid-safe train cabins.

KEYWORDS

Project-based Learning (PBL), Teaching coordination, Scaling, Durability, Agility, Quality , Standards 6,7.

GRAPHICAL ABSTRACT



INTRODUCTION

Teaching engineering is challenging, as engineering entails using *scientific principles* to *design and build* e.g. machines that *optimally make use of the resources* of nature (freely after Merriam-Webster and Britannica). Project teams in industry connect these elements, usually by bringing people with diverse backgrounds together to achieve effective solutions. Therefore, project-based learning (PBL) provides an outstanding opportunity to train engineering students in addressing complex and interdisciplinary challenges in technology and society.

The benefits of PBL include deeper understanding of the course material, knowledge retainment, communication and teamwork skills, and a social foundation for students (e.g. (Oakley et al., 2004)) and references therein). Challenges include group thinking in self-selected groups (Feichtner & Davis, 1984), insufficient weight of the project in the total grading, and lack of peer review. Research on PBL now provides solutions to most of these content- and learning related limitations. Hence, PBL is generally considered as an effective teaching method as long as pitfalls are prevented, and one that very well complements classroom-based teaching.

However, two interconnected challenges still exist in applying PBL:

(1) Scaling of project-based learning to groups larger than 100 students, as commonly required for education at BSc level.
(2) Design and execution of in-depth projects that connect a broad context, scientific analysis, and science-driven design and optimization of a realistic case.

Therefore, implementing PBL of complex projects for a large student population is far from obvious.

To address these challenges, our team developed a framework to design, execute, and assess in-depth projects for large groups (150 BSc students). A key goal is to keep the workload manageable for the instructors (staff members of our research group) while ensuring an in-depth learning experience for the students. To a large extent, these goals are met by involving a group of teaching assistants (TAs) in all phases of the project, including:

- Preparation and testing of new project manuals;
- Group supervision and question hours;
- Written assessment.

Here we qualitatively describe key learnings from combining and refining existing methods over the past years. In our view, these have made a profound impact on the quality of the project as well as the workload and enthusiasm of the staff and the TAs. The goal of this article is to share our learnings, to inspire fellow teachers who face the challenge of implementing PBL of complex topics to large groups. Thereby, we hope to contribute to the education of the next generation of engineers, in particular their realistic problem solving ability. In the following, we concisely review the state of the art on scaling of PBL. Subsequently, in section 3, the learning goals of the project are discussed. Section 4, 5, and 6, describe the preparation, execution, and assessment, respectively. Our experiences are concluded in section 7, including an outline for future improvements.

STATE OF THE ART

Scaling project-based learning

Implementing PBL has a high threshold for faculty members, as simultaneous changes are required in the curriculum, instruction, and assessment (Barron et al., 1998). These challenges become even more significant for large student populations, where feedback is required for many project groups (Domínguez & Jaime, 2010). Google Scholar searches on “scaling project-based learning” and “project-based learning for large groups” revealed several strategies for scaling PBL. For laboratory projects, Sanders et al. (Sanders et al., 2016) described how a bring-your-own device (BYOD) concept alleviated the need for large amounts of equipment. Laboratory projects for 60 students were held manageable by dividing daily supervision among TAs, unifying the tasks of each group, and a clever exchange of technical information between groups that motivated all groups to perform well. For large student populations, peer-assisted feedback within groups (Robinson, 2013) and between groups (Bhavya et al., 2021; Sanders et al., 2016) is widely applied. Meta-review of the student’s peer reviews by teaching assistants adds credibility and consistency to peer review among students (Bhavya et al., 2021). Botha (Botha, 2010) describes a project for 1500 BSc students, where non-written assessment of entrepreneurial activities was a key element in keeping the workload manageable. Alternatively, a population of 2000 MSc students was divided into subgroups of up to 30 students, that each execute their own project under supervision of one staff member (Wallin et al., 2017). Dominguez and Jaime (Domínguez & Jaime, 2010) applied PBL to a subset of students of a course in database design learning, reporting that PBL results in higher grades but at a larger time investment of students and teachers. More examples of PBL were very comprehensively reviewed and tabulated by Chen and Yang (Chen & Yang, 2019), but the provided examples of PBL for more than 100 students are limited to subgroups smaller than 50 students that were spread over multiple years or multiple classrooms.

In the above references, no example was found for scaling of projects in BSc education with a high level of complexity. However, solving real-world engineering problems requires analysis of many elements that may grow in complexity or uncertainty when more information is obtained. To solve such “wicked” problems effectively, a rich knowledge background and experience with related problems and their solutions is highly beneficial. Connolly and Begg (Connolly & Begg, 2006) describe how PBL was implemented in small groups, to address wicked problems in database analysis and design. Similarly, effective engineers must be able to systematically solve complex problems. Below, we describe how PBL was implemented to teach high-level problem solving skills in engineering to a large group of students.

CONTEXT AND CONTENT OF THE COURSE

At the University of Twente (UT), PBL has been part of the bachelor in mechanical engineering (ME) since 1994 (Peters & Powell, 1994). Here we focus on the project in Thermal and Fluid engineering, part of the second year of the BSc in ME. The students have participated in 6 projects before starting our project in Module 7 of the BSc. About 150 students follow the project. The weight is 7 European Credits (EC), equivalent with a total study load of 196 hours. The project is accompanied by courses on Fluid Dynamics and Heat Transfer of 3.5EC each, as shown in Figure 1. Combined, the project and the courses form a module that spans 9 week, including two weeks for examinations. Part 1 of the project (2 weeks time) only includes phase 1: the literature review. This focused start was chosen as it does not require prior knowledge of fluid mechanics and heat transfer, and to allow them to set up their team. Part 2 of the project contains all other activities except assessment and is planned by the students. Here, their knowledge from the literature review and the initial course materials enables them to start with the fluid and thermal analysis part of the project (phase 2). Based on the literature and this technical analysis, the students design an optimal solution (phase 3). In parallel to phases 2 and 3, the students conduct an ethical analysis and an experiment. The project is concluded with a project report describing all results, which is graded per group. An oral exam leads to an individual grade, which is weighted equally to the report grade. All project information is shared with the students via a Canvas environment.

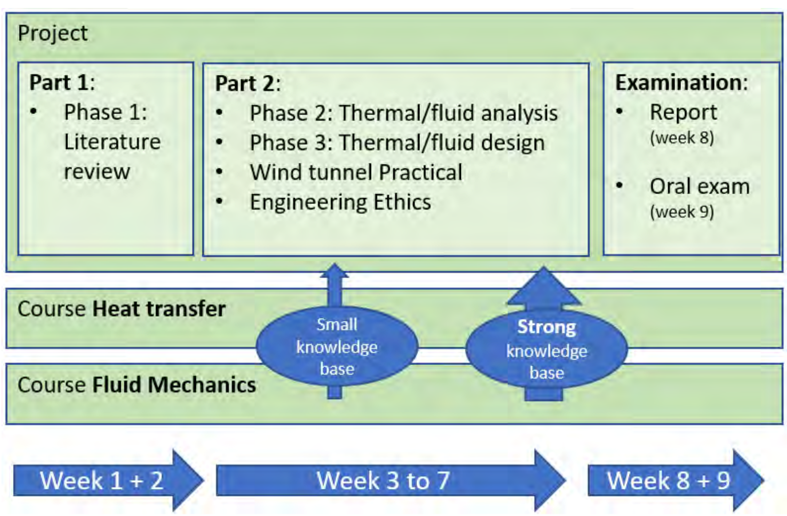


Figure 1: Project overview

Learning goals

The following learning goals are pursued during the project.

1. ***Phase 1: Literature review**. Given lectures on finding, reading, and writing scientific articles, students are able to do independent literature research as demonstrated by a report chapter in which two important designs are investigated and compared based on at least 10 academic references per design.*
2. ***Phase 2: Analysis of heat transfer and fluid flow**. Given lectures on heat and mass transfer, the students are able to model the system both numerically (with an explicit first-order solver they develop) and theoretically (with a simplified, lower-dimension model), discuss the two main limitations and two boundary conditions of each approach, and compare the results.*

3. ***Phase 3: System design****. Based on the literature review, a lecture by experts from industry, and a numerical solver (OpenFoam), the students are able to design and optimize a realistic system configuration. The relevant boundary conditions must be incorporated, and the main limitations of their modeling approach must be discussed.*
4. ***Engineering Ethics****: Given an ethical case and two ethics lectures, the students are able to evaluate the impact of their work from an ethical perspective based on applying the 7-step framework* (Van De Poel & Royakkers, 2007) *as provided in the lectures.*
5. ***Experimental****: Given a written tutorial, basic knowledge of MATLAB, and an oral instruction, subgroups of 2 to 3 students are able to derive a theoretical model for a simplified but relevant version of the system, build the corresponding setup at home, perform measurements, and compare the results between theory and experiment.*
6. ***Dissemination****: Given lectures on report writing and project planning, the students are able to effectively communicate their results by delivering well-organized, complete, and well-written reports within the deadline and substantiate their report in an oral exam.*

The learning goals are translated into the project manual, of which an example is provided in supplementary information (SI) file 1. The project manual contains the "case description" including a general introduction that states the societal relevance as well as the technical challenge. The manual includes starting references for the literature review, guiding questions for the analysis and design parts, the ethics assignment, and practical details such as the submission deadlines for sections or reports and the examination dates. Additional descriptions are provided for guiding the experiments (SI file 2) and OpenFoam (SI file 3). The performance levels are described by a Rubriks (SI file 4).

PREPARATION OF THE PROJECT

Formation of the instructor team

Ideally, the instructor team for a group of 160 students consists of 10 academic staff members including one project coordinator and 10 TAs. "Tutor teams" that consists of one instructor and one TA then supervise two project groups of eight students each.

The TAs are typically 3rd or 4th-year students who participated in the project as 2nd-year students. Therefore, they are familiar with the level of the students and can judge which topics would be exciting for the future students to learn about. To attract an academically strong and enthusiastic team of TAs, we select a strong project group and invite this group to become our TAs for the next year. We select this group by discussing among the instructors which group stood out in terms of academic performance during the project, ability to collaborate, and enthusiasm. Approximately 50% of the students that we approach become TA. This is a profound improvement as compared to posting TA vacancies on general platforms, which previously resulted in fewer candidates with mixed credentials. The group of TAs is completed by experienced TAs that stay on for another year. As described below, the TAs are trained in-depth on different parts of the content of the project in the preparation phase, enabling them to guide the project groups building on this knowledge.

The instructors are staff members of our research group. Since the TAs cover the technical details of the project, the instructor pool can be flexibly expanded by experienced staff in thermal or fluid engineering, or even adjacent STEM disciplines such as solid mechanics or materials science. As the workload is manageable and leads to two-way learning on the project topic, our staff happily participated. Over the past year, the instructor pool was even frequently expanded by staff from other groups who volunteered to join! Guidance of more than two project groups per staff members is possible, but during the examination week this approach requires reading more than four reports within a few days which is challenging. Therefore, we aim for at most two project groups per staff member.

Take-away: A pool of instructors and TAs is created more than 6 months in advance. The TAs are trained to become enthusiastic experts who keep the workload manageable during execution of the project.

Preparation and testing of the project manual

The project is mainly prepared by the project coordinator and the TAs. After choosing a topic together with the instructors, key sub-topics are selected and placed in context by the coordinator. Subgroups of two or three TAs develop questions on these topics (Figure 2) and design the experiments, that will eventually constitute the core of the project manual. The project coordinator guides this process in biweekly meetings with the TAs. Simultaneously, the coordinator aligns the project with the lecturers of the accompanying courses (*Fluid Mechanics I* and *Heat Transf*er).

As shown in Figure 2, each topic is drafted by two TAs and tested by two different TAs. The four TAs then together improve on the question, and provide an answering model that benefits the instructors during the project. In this process, the TAs identify threshold concepts and pitfalls that the students will experience, as well as the order of magnitude of the outcomes. The testing by the TAs reduces errors in the project manual to a level that minimal changes are required during the project, limiting questions and complaints from both students and instructors. In addition, these four TAs become expert on the topic that they developed together. They are positively challenged and become knowledgeable on creating complex project, making them better engineers too. They develop into advanced learners to a level within the zone of proximal developments of the students. Therefore, the TAs are very effective in answering specialized questions on “their” topic and the lead in answering these during execution.

One month before starting the project, the draft project manual is checked by the coordinator for consistency. The instructors also receive a draft copy including answers developed by the TAs, providing them the possibility to comment and improve. The project manual is finalized in the week before the start of the project, and distributed to the students on the first day of the execution phase.

Take-away: New project manuals are created and tested primarily by the TAs, lowering workload for the staff while training the TAs as experts to answer questions during project execution.

Formation of the project groups: Hybrid between self-formed and instructor-formed groups

The project groups of 8 students are formed on the first day of the project, by combining self-chosen sub-groups of up to 4 students.

In this way, we balance two needs. On the one hand, combining students that may not know each other aids their exposure beyond their friends and reduces the risk of group thinking. If applicable, we divide the (few) female students who are not part of a subgroup into either zero or at least two women per group (Feichtner and Davis 1985). Simultaneously, the subgroups protects students by minimizing their risk of isolation, as they can team up with friends. After 6 modules with teacher-established project groups, students crave for a project with a self-formed group. After initial experiences with fully self-formed groups, this hybrid approach functions to the satisfaction of instructors and students.

The resulting project group size of 8 students exceed the typically recommended maximal group size of 5 to 7 students (Oakley et al, 2004, Feichtner and Davis 1985), but fit our project well as the student are sufficiently matured in PBL. As our project is large in scope and duration, groups typically divide themselves into smaller sub-groups that work on specific learning goals. This is allowed by the instructors, as learning goals (phases) 1, 2, and 3 can be carried out separated in time, and are sufficiently broad in scope to allow the subgroups to work on different aspects of each learning goal. For learning goals 4 and 5 (ethics and practicals), all students have to personally participate in smaller assignments to ensure obtaining the desired knowledge level.

Take-away: Large project groups that are partly self-selected enable effective learning for students that have experience with PBL.

Phase	Topic	Preparation	Testing	Final check	Execution		
Phase 1	Lit. Review	Coordinator					
Phase 2	Topic 1	TA1 + TA2	TA3 + TA4				
	Topic 2	TA1 + TA2	TA3 + TA4	Coordinator + Instructors			
Phase 3	Topic 3	TA3 + TA4	TA1 + TA2			Planning and execution: decided by project groups	
	Topic 4	TA3 + TA4	TA1 + TA2				
Ethics		TA5 + Ethics-Instr.					
Practical	Exp.1	TA1 + TA3	TA2 + TA4				
TIME:		Sept+Oct	Nov+Dec	Jan	Feb	Mar	Apr

Figure 2: Example of phasing and work distribution during the preparations of the project. The red bar indicates the oral exams.

EXECUTION OF THE PROJECT

Supervision of the project groups

Each project group is guided by a tutor team that consists of one instructor and one TA. Typically, the instructor and the TA meet with each group once per week. The goal of the meetings is to discuss progress, to ensure that all major project goals were addressed by each group, and for informal formative assessment. The role of the instructors in project group supervision is twofold:

1. Provide the students broad context in fluid mechanics and heat transfer, by explaining key principles or underlying mechanisms.
2. Help resolving insufficient performance or conflicts.

The role of the TA during the project is complimentary:

1. Help organizing the meetings with the instructors.
2. Provide answers to questions on specific content or results, based on recent experience with the project in the same role as the students in the project group. Their role as more knowledgeable other in the zone of proximal development (McLeod, 2012) bridges the communication gap arising from the difference in experience between the instructor and the students.
3. Guide students to TA-specialists on specific topics if knowledge beyond that of the instructor and the assigned TA is required.
4. Occasionally meet with the project groups alone, in case of absence of the instructor.

Take-away: The TAs form a bridge between the project groups and the instructors, enhancing the learning of the students and preventing that trivial questions take the instructor's time. At points of difficult learning the scaffolding by the TAs is especially effective.

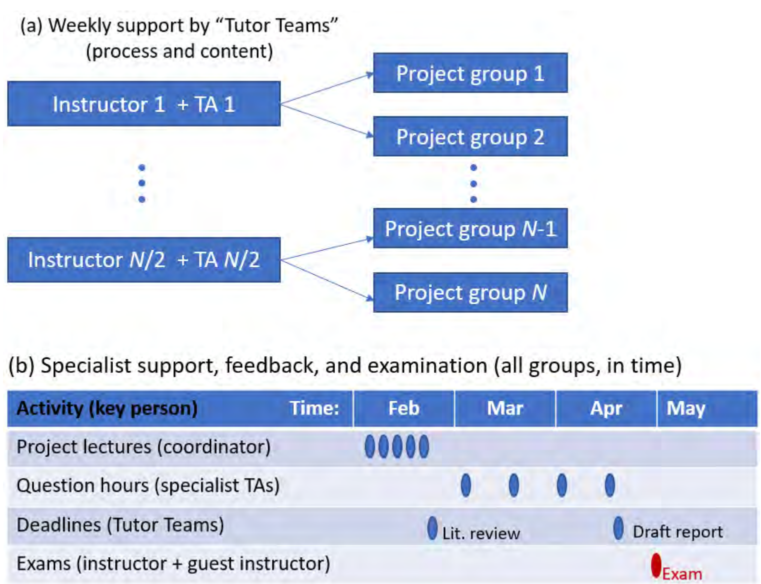


Figure 3: Support of the project groups. (a) Each project group receives weekly support on content and process from one tutor team. Each tutor team guides two project groups. (b) TA "specialist support" for lectures and question hours is available throughout the project. The deadlines for the literature review and draft report are indicated. Here, the tutor teams provide formative feedback. Examination (oral and grading of the report) is executed by two instructor (including the one from the tutor team).

Scaffolding: Project lectures, question hours, and online help

Project lectures are scheduled in the first three weeks of the project, to familiarize the students with the topic and content of the project. Six lectures are scheduled as follows:

1. Introduction lecture. Here, the topic is introduced, the workflow of the project is shared with the students, and planning tools (Gantt chart) are refreshed;
2. Lecture on reviewing academic literature, by an information specialist from the UT;
3. Ethics I, providing an introduction to ethics. The ethics lectures are delivered by an ethics teacher who is familiar with engineering students;

4. Guest lecture by company/organization that relates to the project topic;
5. Ethics II, providing a toolbox that students have to apply to an engineering ethics case.

Online help: A question board is provided via Discord. Here, students ask questions at any time and TAs help them typically within 2 days. The goal is to prevent students to get stuck for too long on less-important issues, such as scientific software that might not work or complex mathematics that has no direct connection to the engineering challenge. Building on their knowledge from the project preparation, the TAs (together) provide the role of topic-expert during the question hours and the discord server. This approach prevents excessive preparation by instructors for which the project is outside their core research area.

Plenary *Question hours* are organized with two instructors and two TAs. These question hours are held weekly, starting from week 4. The meetings are in-person, enabling the instructors and TAs to identify questions that occur in multiple project groups. Such major bottlenecks could be addressed on-the-spot or by providing additional documents via the project website on Canvas.

During the project, scaffolding leads to growth and maturation of the students that we see most clearly reflected in the level of the students' questions during the question hours. For example, in the first weeks, students would get really dissatisfied with a poorly posed question or high-level guidance (such as: you may try a, b, or c, instead of pointing to the "correct" answer). Towards the end, the students would say: "I read the question, I tried a, b, and c, I made assumptions X and Y, and then I obtain two possible results that are a bit different. Can you help me to understand how to address this difference and how to choose?". We believe that this step in the development of students is critical in becoming effective engineers.

Take-away: The paradox between (1) PBL, (2) going in-depth with a large group of students, and (3) managing workload is solved by providing strong scaffolding (lectures, question hours, and online help) in a joint effort by instructors and TAs.

How to connect the project with courses that run simultaneously?

In initial versions of the project, it was shifted by 4 weeks with respect to the courses (starting earlier and running longer). This time-shift enabled the students to acquire working knowledge from the courses on fluid mechanics and heat transfer that they could apply to the project. After a UT-wide shift to self-contained 9-week modules that each includes courses and a project, the project and the courses run simultaneously. Therefore, students cannot build on working knowledge from the courses on fluid mechanics and heat transfer at the start of the project.

To maintain an interesting and on-topic project, the literature study (one of the learning goals) was condensed and implemented in Phase 1 (the first two weeks of the project). The literature review was supported by a lecture of an information specialist. This approach has several benefits:

- This knowledge provides the context for part 2 of the project. The students become involved in the topic and are able to analyze and design relevant solutions in the later phases of the project.
- The students focus on literature reviewing without having to integrate this new skill with other learning goals.

- The students train their reading skills of academic material (as opposed to teaching material), preparing them for their future BSc and MSc assignments.

ASSESSMENT OF THE PROJECT

Formative assessment

Two weeks before the report submission deadline, each project group was required to submit a draft report for formal formative assessment. The tutors and TAs both provided feedback on these reports with a focus on learning goals 2,3 and 6.

Summative assessment

The final grade of the students consists for 50% of a group-based grade for the report, and for 50% of an individual grade based on an oral exam. For the report, the Rubrics (SI file 4) shows the expected level per learning objective. However, the grading can deviate from the Rubriks. For example, mutually inconsistent subsections are reflected by lower grades, and truly in-depth or creative work is rewarded with more points. The instructor assigned to a project group and one additional instructor graded items 1, 2, 3, 5, and 6 of each report. At least one of these instructors was experienced, in having executed the project in previous years. Learning goal 4 (ethics) was graded by the Engineering Ethics teachers. In addition, sections of all the reports were graded by the TAs for learning goals 2, 3, 4, 5 and 6. These sections corresponded to the expert knowledge of the TAs. This approach of combined per-report grading and per-section grading was chosen to assess consistency between the assessment of different groups while keeping the workload manageable. The grades from the instructors and TAs were normalized on a scale from 1 to 10 (any grade above 5.5 represents a pass), and are compared in Figure 4. The general trend is that a correlation exists between grading by the instructors and the TAs. However, the instructors grade on average a 6.9 with a standard deviation of 0.8, whereas the TAs grade on average 6.5 with a standard deviations of 0.7, based on grading of 16 project groups. For the three largest outliers the instructors gave +0.8 points or more relative to TAs. These differences originated from three different tutor teams, and given for reports that show good internal coherence or creative ideas despite weaknesses in specific sections.

The individual grades were determined during the oral exams, by the tutor team as well as the additional instructor who graded the report. The first 45 minutes, each student was asked 2 to 3 questions about a part of the report. If the student knows the answer, we probed for more depth to find the limit of knowledge. If the students do not know the answer, the fellow students are allowed to step in and help or answer. In this fashion, the first 45 minutes usually gives a reasonable indication of the knowledge level of each student. In the second hour, additional questions were asked. Here, students whose performance was not clear from the first 45 minutes is assessed by asking additional questions.

The relatively heavy weighing (50%) of the individual grade was chosen to incentivize individual contributions to the project. For some groups, the individual grades were comparable to the group performance. For other groups, free riders or exceptionally talented students were identified during the orals, and adequately graded. The time slot (2x45 minutes) was chosen to provide a balance between assessing the students fairly and maintaining the positive atmosphere required for a fruitful discussion. Longer exams had been tried in previous years, but all staff agreed that it merely led to exhaustion of both students and staff during the exam.

Take-away: Hybrid oral and written assessment by tutor teams and one extra instructor per project group provides a balance between time consumption of the instructors and precision in the grading.

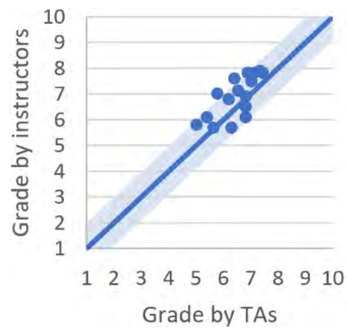


Figure 4: Comparison of grades for the reports provided by the instrutors and the TAs. Each data point indicates one project group. The line indicates equal grading, the shade indicates the ±1 point bandwidth

CONCLUSIONS AND OUTLOOK

We describe practical suggestions for impementing of PBL for large groups of BSc students, aimed at reducing the workload per instructor by attracting and educating a pool of TAs and by spreading the supervision and assessment load among instructors while improving the depth and quality of the learning.

A team of instructors and TAs is created over 6 months in advance. New project manuals are created and tested primarily by the TAs, lowering workload for the staff while training the TAs as experts to answer project-specific questions during project execution. During the project, the TAs also form a bridge between the level of the project groups and the level of the instructors, enhancing the learning of the students and preventing that trivial questions taking the instructor's time. The paradox between (1) PBL, (2) going in-depth with a large group of students, and (3) managing workload is solved by providing strong scaffolding (lectures, question hours, and online help) in a joint effort by instructors, TAs, and guest speakers. Hybrid oral and written assessment by tutor teams and one extra instructor per project group provides a balance between time consumption of the instructors and precision in the grading.

Reducing the per-person workload for an in-depth BSc project for a large group of students has broadened our knowledge on content, improved interaction between teachers and learners, and enhanced our motivation to be examples to our students. Future work may improve the scientific embedding of this approach, and more systematically evaluate the impact of changes made on the project outcomes.

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SUPPLEMENTARY INFORMATION

The supplementary Information is available online via de CDIO website.

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BIOGRAPHICAL INFORMATION

Cornelis .H. Venner is Chair of the Engineering Fluid Dynamics Group at the University of Twente, presently leading the ME-MSc tracks "Aeronautics" and "Energy and Flow". He holds a PhD from University of Twente, 1991, in the area of Thin layer flow/Lubrication and Multigrid/Multilevel methods, and held visiting scientist and Postdoc positions at the Weizmann Institute of Science, Rehovot, Israel, and at Imperial College, London, UK. He has 30+ years of expertise in theoretical and applied research and leading research projects in different areas in fluid mechanics.

Claas Willem Visser is an associate professor in Mechanical Engineering who develops multi-scale functional materials, by converting fluid droplets or bubbles into solid "building blocks" and stacking these. The multi-scale nature of these materials enables optimizing their mechanical, acoustic, electrical, and biological properties for various applications. He holds an MSc and PhD in Applied Physics from the University of Twente, followed by a 2-year post-doctoral Rubicon fellowship at Harvard University. Claas Willem worked at Tata Steel Research Development and Technology from 2006 to 2011, and founded UT-spin-off IamFluidics in 2018 where he is currently chief scientific officer.

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