# Lessons Learned from Project Based Teaching in Aerospace at Chalmer



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# LESSONS LEARNED FROM PROJECT BASED TEACHING IN AEROSPACE AT CHALMERS

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**Abstract**

This paper shares experiences from project-based learning (PBL) in aerospace engineering courses at Chalmers University of Technology. It focuses on two project courses provided at Chalmers, where the students design and simulate aircraft and aerospace components, together with prototyping and experimental work. The paper discusses the approached used for teaching in both courses, provides student feedback, and discusses the lessons learn from PBL in the context of aerospace eductation at Chalmers. Further, the paper offers future improvements and suggestions.

**Keywords:** Project-Based Learning, Aerospace Engineering, UAV Propeller Design, Aircraft Design

## 1. Introduction

The field of aerospace engineering is characterized by a mix of theoretical principles that require effective bridging with practical applications. The main challenge of current pedagogical approaches is to effectively bridge this gap. This is often not the case, leading to students who excel in the theoretical concepts at the expense of a practical understanding of engineering. This is a reoccurring and known issue for many educators who are forced to balance between theoretical depth and practical experience. In response to this challenge, teaching methodologies such as project-based learning (PBL) have been developed. PBL is a teaching approach that engages students in authentic, ill-defined, and complex problems, where they have to define the problem, generate hypotheses, collect and analyse data, and present solutions [1]. PBL has been shown to enhance students motivation, self-directed learning, critical thinking, collaboration, and communication skills [2]. However, the implementation of PBL is not without its challenges for the educator, requiring careful planning and resource allocation and more tutoring than traditional education. The implementation of PBL courses requires constant monitoring and adjustment, as well as effective communication and collaboration among the stakeholders [1].

This paper presents a combined case study of PBL courses at Chalmers University of Technology, where students were tasked with designing, simulating, and experimentally evaluating concepts related to aerospace applications. The paper describes how PBL was integrated in the courses, how these were structured and delivered. Primarily we attempt to address the following questions:

- How can PBL be used to enhance the problem-solving capabilities of aerospace engineering students?
- What are the benefits and limitations of PBL for both students and instructors in this context?
- How can PBL be improved and adapted for future courses in aerospace engineering?

Hence, we provide a detailed description of how the above queries were addressed, and how the course attempted to utilize the benefit from learning from failure [3]. It also presents feedback from both students and instructors, offering valuable insights into the effectiveness of the course. The benefits and limitations of project-based teaching are discussed, and planned future improvements are provided.

## 2. Background

The supervisors of the course had extensive experience in supervising MSc and PhD students in aerospace engineering, and had observed some common challenges among new students, such as:

- Problem formulation and hypothesis generation: students often lacked the experience and skills to define and refine a research problem, and to formulate testable hypotheses that could guide their work.
- Scientific writing and argumentation: students did not struggle to report results but often had problems formulate hypothesis, critical evaluation of approaches and provide conclusions.
- Project planning and risk management: students always underestimated the time and resources required to complete their task which primarily could be derived to the failure of anticipate issues.
- Uncertainty and modeling limitation: students had limited experience in design of experiments and often neglected or misunderstood the error sources and effects of uncertainty in their data and model limits.

The supervisors recognized the alignment of the challenges addressed above and what PBL aims to address. Furthermore, students that had participated in other PBL courses, such as Chalmers Formula Student, were noticed to perform better than average during their thesis work [4].

## 3. Course Overview

The following sections describe the two new courses that were introduced in the recent years at Chalmers to address the need for an extended course portfolio in the field of aerospace engineering. The new courses are offered as part of the aerospace engineering track in the MSc in Mobility Engineering, but can be selected as optional courses in other MSc programs across Chalmers. Both courses are offered in the autumn but in different study periods, where Aircraft Design is offered in study period 1 (September-October) and the Aerospace Project is offered in study period 2 (November-December). Both courses run for a total of seven weeks each accounting for a total of 7.5 ECTS credits. Therefore, although studying in a relatively short period of time, the students are expected to have a study load of approximately 210 hours per course. It can be noted that at Chalmers, in each study period the students are normally enrolled in two courses with total of 15 ECTS.

### 3.1 Course Evaluation Procedure

Course evaluation formally entails three meetings with the student's representatives. One meeting at the beginning of the course to present the course structure and planned activities, a mid-term meeting to follow-up on the course progression, and a final meeting with a programme representative to discuss the final course evaluation. These meetings target the course general alignment (learning outcomes, teaching activities, and assessment) and how this is perceived by the students. To support the meetings and to get timely feedback on strategic activities, the student's representatives will be provided with guidelines on key aspects that need to be evaluated during the ongoing year. The formal feedback is collected using tailored student surveys at the end of each course and used to perform the necessary course adaptations for the subsequent course occurrence.

### 3.2 MMS240 Aerospace Project

The Aerospace Project course started in 2022 as part of a new master's program at Chalmers. During the first year the course had only six student, but in 2023 the number of students increased to 18, therefore a progressive growth of the course in the subsequent years is expected. The course is open for all master's programs at Chalmers, but primarily targets students from mechanical engineering, mechatronics, engineering physics and product design due to the course prerequisite of fluid dynamics. The aim of the course is to teach the students on how to approach advanced aero and thermodynamic research in the field of aerospace, by a hands-on approach. The course empathizes on methodology and design for investigation in complex problems with limited information and an open solution space. The course is structured based on Bloom's taxonomy in the context of engineering education [5]. At the end of the course the students should be able to:

- critically, independently and creatively identify and formulate problem specification;
- master problems with open solutions spaces, this includes to be able to handle uncertainties and limited information;
- apply previously learned theory, simulation methods and tools to handle industrial mechanical engineering problems;
- create appropriate simulations models and experiments to solve a specific problem;
- use sensitivity studies and uncertainty analysis in design and assess the most critical aspects for a particular application case;
- critically evaluate the final design and provide alternative investigation methods and approaches;
- give written and oral presentations of a larger technical investigation.

### 3.2.1 Available Resources

The Aerospace Project course was designed around delivering experimental results. This was aimed to motivate the students and to provide them with hand-on experience of applied experimental work. The available resources vary substantially between different teaching institutes but the division of Fluid Dynamics is a host for Chalmers' Laboratory of Fluids and Thermal Sciences. Regarding aerospace equipment, this laboratory has a low-pressure turbine facility, a low-pressure compressor facility, a closed-loop general purpose wind tunnel, and comprehensive instrumentation for aerothermal investigation. The two turbomachinery facilities were found to be too complex to integrate in a seven-week student course. However, the general purpose wind tunnel is believed to provide an excellent environment for student work. Several design problems were discussed where most were dismissed due to high complexity, highly specific prerequisites or high initial investment cost. Two initial student cases were identified for which the laboratory was well equipped, and are believed to be adequate for the student's level – the numerical and experimental evaluation of aircraft propellers, previously defined as part of conceptual aircraft design. A comprehensive infrastructure was already in place for propeller preliminary design, including production and testing capabilities that were developed in previous years during projects at various educational levels (BSc, MSc and PhD). For design and geometry parameterization, the in-house blade element moment theory (BEMT) design tool OPTOPROP [6] was readily available. For rapid production, Prusa SL1S Speed 3D printers were available, providing low manufacturing cost and excellent geometrical conformance to production propellers and other potential aircraft components. For propellers testing, a Tyto Robotic 1585 proppeller stand had been modified and assembled as part of a previous BSc project [7] and an in-house developed test rig was available. For aircraft component aerodynamic testing, a six-axis balance, multi-hole pressure probes (MHP) for wake studies, and smoke generators were readily available to the students. In addition, the standard student workstations (Intel i9 processor, 32GB RAM) were adequate to perform the required CFD simulations with satisfactory accuracy for the low-speed UAV propeller and individual aircraft components.

### 3.2.2 Design Problem of Study Year 2023

The course was designed around a real-world design problem. In 2023 the task was to design, simulate, and test a propeller for a small UAV. More specifically, the students were asked to design a propeller for a 8-kg, high-performing blended wing drone (BLWD), with a lift-to-drag ratio equal to 20, flying at a cruise speed of 25 m/s. The results from an improved propeller performance would also benefit the in-house developed blended wing drone designed by Miltén and Svensson [8], shown in Fig. 1, since no suitable of-the-shelf propeller was identified for the specified mission requirements.

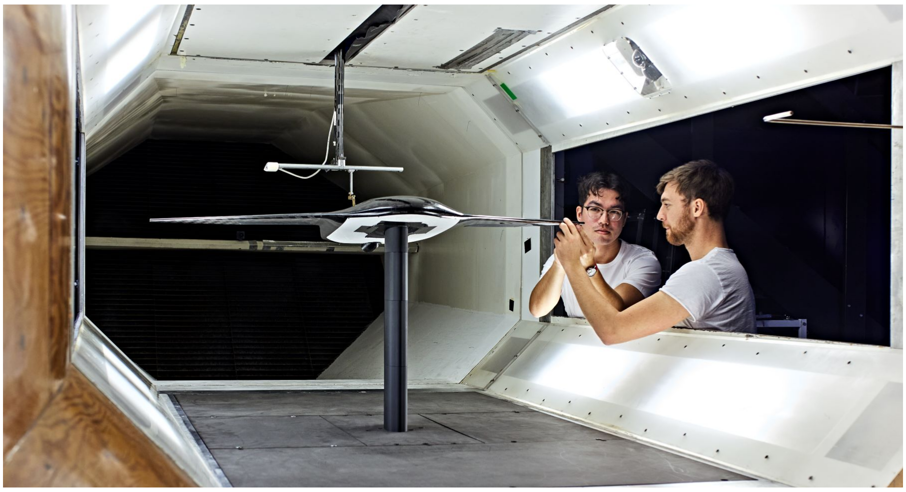


Figure 1 – Chalmers UAV platform mounted on a balance-arm in Chalmers wind tunnel

The task of designing a propeller was chosen, partly because of the readily available infrastructure (as described above), but also due to the balance of representative challenges typically faced by aerospace engineers. The task requires the application of various skills and knowledge, such as aerodynamics, materials and manufacturing, critical model evaluation on several levels and uncertainty estimation. This makes the task challenging enough for graduate students but still limited and contained for supervisors. Most of the tools available in the course are not as such prepared but for example, the in-house developed BEMT Python tool enables the students to generate reasonable functional designs immediately, provided that a reasonable set of inputs is used. This allows the student to have full and open access to the code for modification and mitigates much of unnecessary coding required when setting up a module to generate an initial design. This places the task on a higher level and directs the students to focus on understanding the fundamentals of propellers design and performance. A similar principle is applied to the CFD modeling and experimental testing, where some of the most repetitive and non-value-adding tasks are pre-solved, while maintaining the fundamental challenges and open design space.

### *3.2.3 Course Structure*

The course was structured into independent project work, lectures and weekly tutoring sessions. Each lecture aimed to highlight areas typical for shortcomings for new MSc and PhD students, provide some theoretical background and introduce the in-house developed tools. The sessions provided a platform for the students to discuss their ideas and challenges, and to receive feedback from the instructors and peers:

1. Problem formulation, fundamental propeller physics and BEMT
2. Uncertainties, planning and risk mitigation
3. Experimental and numerical tools
4. Post-processing and analysis of results

In essence, the course aims to equip students with the ability to handle complex problems, apply theory to practical scenarios, create and evaluate designs, and effectively communicate their findings. In addition to the propeller design, the students had to write a conference paper to communicate the results. This report served two purposes. First, to improve the student's communication skills, but the far more important aspect was to iteratively concretize the full cycle from the initial research idea to the development of a critical rationale with respect to the problem formulation, methodology definition, result presentation and conclusion. This was achieved by creating three intermediate reporting deadlines, allowing for a feedback from the instructors at different maturity levels of the report:

**Deliverable 1** A complete draft report where hypothesis, method, results and conclusion were populated. Sketched plots with pen and paper were encouraged. The report purpose was to force the students to formulate the content in the complete report and gain a holistic view of the complete delivery.

**Deliverable 2** A further matured draft report. For example, a detailed method section with and uncertainty estimation was requested. Most groups had to revise their approach since they identified limits in the results to support their conclusion. This deliverable was typically 7-8 pages long and was handed in just before the beginning of the experimental test campaign.

**Deliverable 3** A final report of 5-6 pages was handed in at the end of the course. The target for the final report was to replicate a quality of a typical aerospace conference paper.

### *3.2.4 Student Outcomes 2023*

During the year 2023 the class of 18 students was divided into 6 groups. All the groups managed to produce a propeller that worked satisfactory but the level of detail and approach varied substantially. A few examples of approaches are mentioned below in ascending order for depth and complexity but not necessarily grade.

- Identified the most suitable of-the-shelf propeller for the mission APC (16×12) and benchmarked their own design against it. The student design supersedes the aerodynamic performance at the design point. However, issues with manufacturing have limited the confidence in the experimental results.
- Designed a satisfactory propeller but focused on maximizing measurement quality. Concluded that torque was the limiting factor and suggested increasing the wind speed to 35 m/s to mitigate the worst uncertainty. Highlighted important installation effects with the experimental setup.
- Focused on evaluating the accuracy of the in-house tool OPTOPROP tool for low-Reynolds applications, identified that the lack of low-speed airfoil data for the NACA 16-series family leads to large errors. The group therefore added support to generate airfoil data via XFOIL. Further, they have generated a NACA 4-series blade and improved the agreement between OPTOPROP and CFD simulations with 9 percentage units.
- Designed a propeller taking into account the total weight of the propulsive system. The group presented the smallest propeller of all groups.

Figure 2 shows snippets from a student report. The modified Tyto Robot test mount together with the student 3D-printed propeller is shown to the right. The propeller is integrated into a structure representative for a blended wing body. In the center is a diagram with performance curves and to the left is an illustration of the mesh utilized in STAR-CCM+ to model the propellers performance. One of the student groups is reporting their results at the current conference with the title "Low-speed propeller for UAV applications, from design to experimental evaluation".
The course 2023 was well received with a 4.2 out of 5 in the course evaluation. This relatively high evaluation indicates that the students are appreciating the course. Some insightful comments from the course evaluation below:

- "Maybe add more testing. It would be fun to somehow tie it together with the aircraft design course, instead of the new flying competition".
- "Very interesting and useful assignment to write an academic style paper for the report".
- "Good course literature, but more structured time and better checking in for the project for dysfunctional groups would have been helpful".

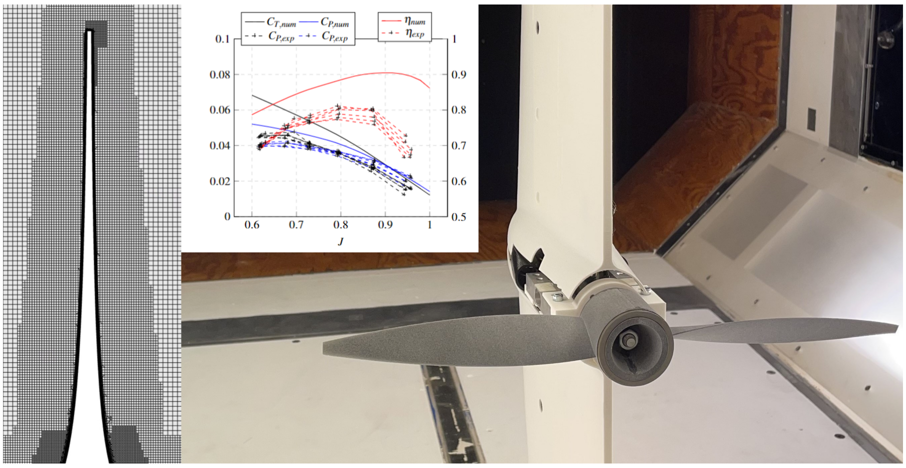



Figure 2 – CFD mesh, propeller performance curves and a propeller mounted as a pusher in the wind tunnel on a Tyto Robotic test bed from a student report.

#### *3.2.5 Future Improvements*

There are some obvious improvements that in hindsight should have been different from a practical perspective. The propeller hub that was manufactured as a relative large cylinder for simplicity in CAD but should have been much smaller. The Tyto Robotic test mount is simple, cheap and has a very simple interface for students but the laboratory has more stable and sensitive measurement equipment such as a MBA500 and SCXI-1520 which is incorporated in the coming year. One key take-away, which aligns well with the authors impression is that the students did not sufficiently front load their task.

### 3.3 MMS236 Aircraft Design

The course of Aircraft Design started in 2022 and it has been given two times. In the first course instance a total of 10 students were enrolled, for the second instance, in 2023, the number of students was above 30. The students had mixed backgrounds: mechanical engineering, mechatronics, engineering physics and product design. The course teaches the discipline of conceptual aircraft design following a set of predefined top-level requirements and constraints. It relies on classical methods provided in the literature [9], combined with project-specific goals that challenge the students ability to make informed design decisions, and at same time fairly evaluate the impact of such decisions on the aero-mechanical stability performance of the aircraft. The top-level learning outcomes are structured based on Bloom's taxonomy in the context of engineering education [5]. After the course the student should be able to:

- carry out an entire process of aircraft conceptual design, having as a starting point a pre-defined set of top-level requirements;
- appreciate and discuss the interrelationship between the different disciplines of aircraft design;
- differentiate between the different components involved in design and identify the most critical ones for a particular application case;
- evaluate the final design and provide solutions or alternative layouts for the most critical components;
- present and report their work to peers.

The course material is quite comprehensive, since it attempts to interrelate all the disciplines of aeronautical engineering, which makes the relative short teaching period a challenge while attempting to accommodate the most important concepts. Therefore it was decided that the best approach would be to make the course revolve around a large design project that runs in parallel with the lectures,

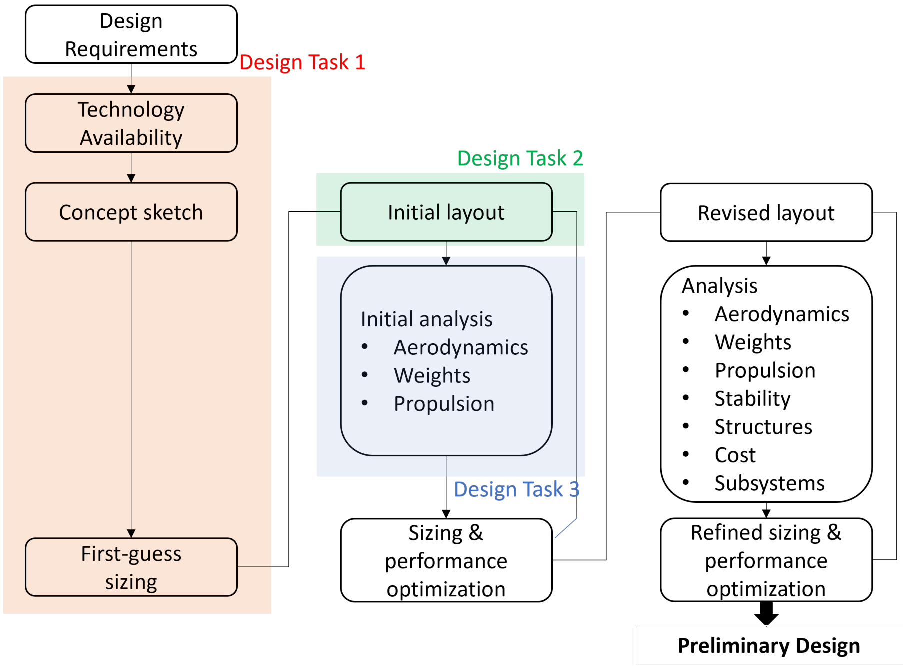
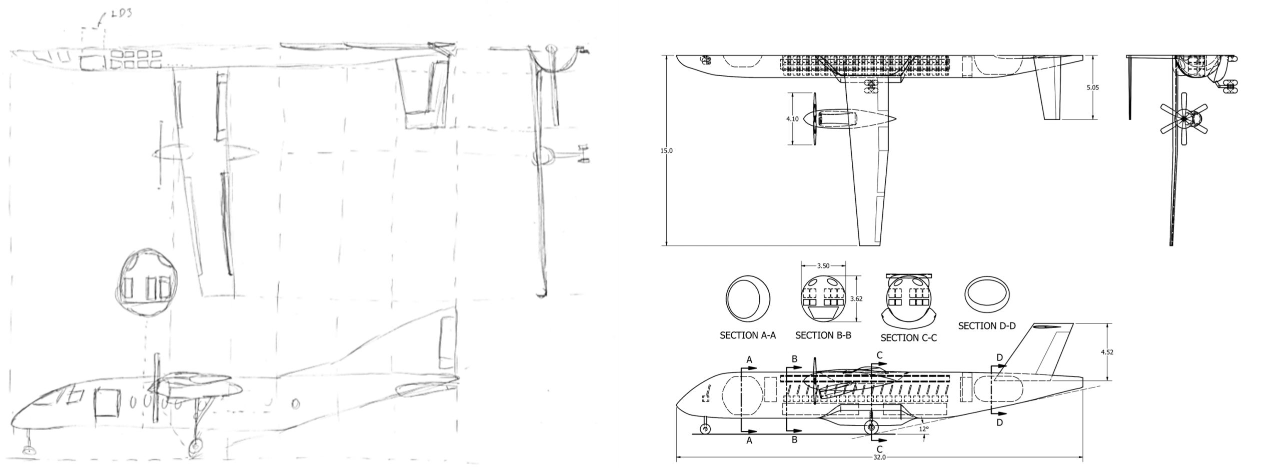



Figure 3 – Aircarft Design course main design tasks and their relation with the process of conceptual aircraft design.

supported by tutorials, project working sessions and student seminars. It should be noted, that during the project the students sometimes make design choices that are far from ideal due to the still limited knowledge in the early stages of the course. Still, the purpose of the project is not to examine the students for the best possible design, but rather for their approach to design and analysis. In the course end, each student will have the opportunity to evaluate the design choices and present solutions in an individual written assignment supported by an oral examination.
The course main book is *Aircraft Design: A Conceptual Approach* by D. Raymer [9], and therefore most of the teaching follows Raymer's approach to conceptual design and analysis. Hence, the teaching is divided into two distinct lecture blocks. The first block is comprised of lectures that are primarily connected to design. These lectures run in parallel with the design phase of the project. The second block of lectures is connected with design analysis and are provided in parallel with the analysis part of the project. To properly bridge between the theoretical concepts and practice, tutorial sessions are provided for some specific tasks. This is done mainly in connection with the usage of supporting design software, such as OpenVSP, and evaluation software such as VSPAERO, since the limited time does not allow for individual familiarization with the most important software elements.

### *3.3.1 The Design Project*

The students are provided in the beginning of the course with a design project that is developed in connection with a "client". The client can be from an industry or from a research project at Chalmers. The project teams are composed of 3-4 students. In special cases, e.g. for doctoral students, working students, individual project work is also allowed. In the current format, the students are allowed to form the groups with the support from the examiner in special cases. The project structure follows Raymer's approach to conceptual design, see Fig. 3, with progressively increased complexity for adequate scaffolding. To support sufficient feedback periods, the project is divided into three design tasks. Each design task requires the submission of an intermediate report and/or the participation in a seminar.
**Design Task 1 (DT1)** starts with a set of top-level requirements that are provided by the teacher and/or "client". These are design requirements that during the project are complemented with design and certification criteria. It follows with a study on the future technology that is expected to be available for the final product. It also includes the very first aircraft draft, "back of the napkin" concept sketch, see Figure 4-a), that will lead to a first sizing based on statistics for aerodynamics and struc-




(a) (b)

Figure 4 – a) Example of first "back of the napkin" concept sketch (DT1). b) Example of the finalized Dash-1 design (DT2).

tural models of existing aircraft. At this point the students are advised to individually hand draw their concepts, and as a group agree on the best design to be carried over into the fist iteration. Design Task 1 is a simple task and is expected to be carried out during the first two weeks of the course. The outcome should provide a first-guess sizing that can be used to start the Design Task 2 activities. At the end of DT1, the student is expected to:

- Relate design requirements with initial aircraft size and weight.
- Be able to carry out preliminary trade-off design studies.

**Design Task 2** covers all the elements that are required to establish an initial aircraft layout (Dash-1). The very first layout already provides a general 3D representation of the different sections of the aircraft and internal compartments, see Figure 4-b). The size of the wings, control surfaces, landing gear and propulsion unit are some of the aspects that are also integrated in the Dash-1 design. The requirement to establish a 3D geometry will be covered by NASA OpenVSP [1] parametric aircraft geometry tool. OpenVSP allows to define a 3D model based on typical aircraft geometrical parameters. Design Task 2 is expected to run for 3 weeks, at the time of completion the students are expected to deliver a draft of the design report while focusing on the following elements:

- Carry out an initial design (Dash-1) including lifting surfaces, fuselage, propulsion, internal compartments, landing gear.
- Appreciate and discuss the interrelation between thrust-to-weight and wing-loading and their importance in design.
- Be able to locate the dash-1 design in a constraint diagram.

**Design Task 3** starts with the Dash-1 design and will include the implementation of reduced order methods for the evaluation of aerodynamic, structural and stability performances. The Dash-1 design can therefore be analyzed to verify how it performs, pointing out the direction(s) in the iterative design process. During this phase, the students are also expected to make progress with less support from the tutors and to be able to make independent strategic (although limited) design decisions. At the time of completion, the students are expected to finalize the report by adding the analysis part. After DT3 the students are expected to:

[1] http://openvsp.org/

- be capable of carrying out an aerodynamic performance estimation using classical bookkeeping methods for skin friction drag and low fidelity CFD (VLM) for induced drag calculations;
- define the structural layout of the Dash-1 design and apply classical methods to estimate the structural performance;
- re-arrange the lifting surfaces to comply with the stability margins.

### *3.3.2 Feedback and Assessment*

There are three main examination elements in the course: the design project (60%) the final presentation (20%), and the final individual assignment (20%). In addition each student shall compile a project diary describing their contribution. The design tasks, although being part of the same design project, are expected to give different contributions to the learning outcomes (see above). For instance, the students are expected to build-up on critical thinking as they make progress in the design project, but they are also expected to build up experience in the practice of aircraft design. The lectures are expected to provide a balanced learning experience with particular emphasis in some key theoretical concepts and how these bridge with practical aspects. The individual assignment and oral examination are expected to evaluate the student ability to critically judge the final design, but also to evaluate in a broader sense how the student relates to the intended learning outcomes.
The intermediate and final seminars mainly target rhetoric and the promotion of critical thinking. During the seminars, the examiner promotes a live discussion with the audience, hence acting mostly as a facilitator and avoiding lengthy and detailed feedback. Individual group feedback is provided at a later stage during the subsequent project working sessions in connection with the completion of each one of the design tasks.

### *3.3.3 Student Outcome 2023*

In 2023 a total of 36 students were enrolled in the course. The majority of the students were able to produce high quality project work for which some examples are provided in Fig. 5. The course was well received with an overall impression score of 4.43 in a 0-to-5 scale. The 2023 project revolving around a liquid hydrogen turboprop was also well received by the students (score of 4.6), primarily because it targets a relatively new and sufficiently challenging concept. The lectures, guest lectures, tutorials, study visit were also very much appreciated without any special remarks. During the course board meeting the students highlighted one important aspect connected to project based learning. All the students felt that working with a single project allows them to develop a good understanding on how to carry over the design and how to approach a given aircraft concept. However, it was also pointed out that being too much project specific has its own drawbacks. For example when designing aircraft, there are specific methods that are application dependent and/or applied when dealing with different flight regimes, or even when employing different propulsion systems. Working with a single concept in a project will leave some of these aspects out of the practical experience, and this was highlighted by the student comments in the evaluation survey:

- *"A very practical approach to a difficult topic, not too overwhelming, would benefit from more examples of applications and different approaches, since a lot of the calculations are statistical rather than empirical relations based on physics."*
- *"More examples of application of design principles in lectures."*

To overcome this drawback, few suggestions were provided by the students, including the addition of more practical examples in the lectures and tutorials, which is going to be provided as part of the 2024 curriculum.

## 4. Discussion and Lesson Learned

The experience of students that complete either or both of these courses have notable benefits when starting the master's thesis at the department. The students meet the learning outcome and come

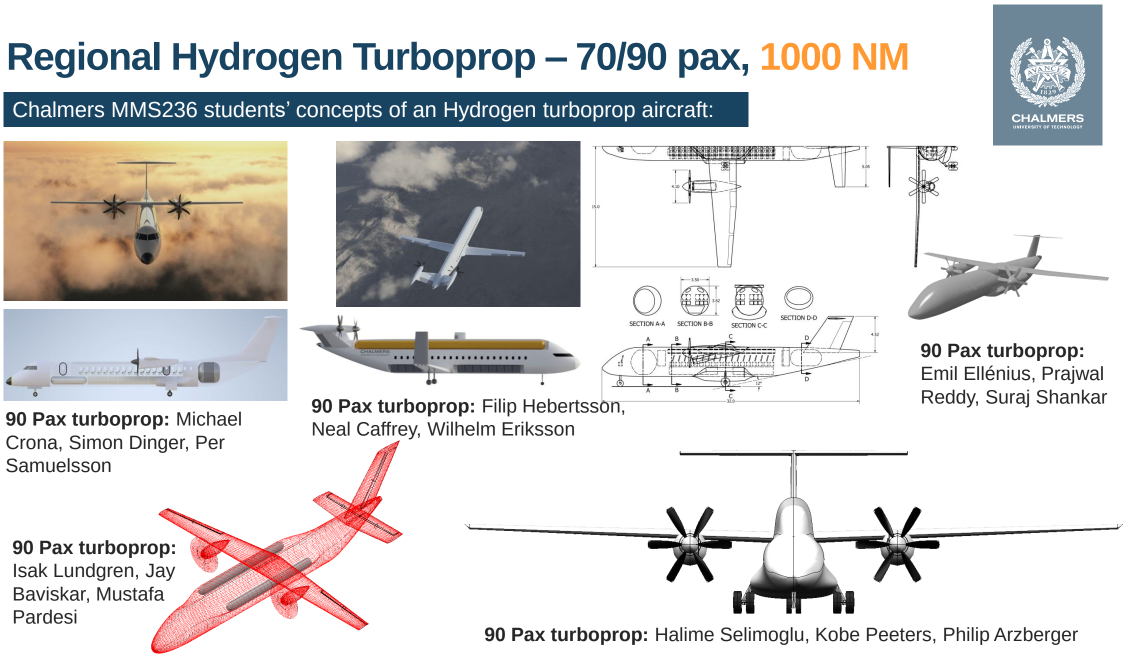



Figure 5 – Example of Design Project outcome from 2023, where the students were asked to design a hydrogen powered turboprop.

better prepared to be able to critically appreciate the impact of the design choices, modeling approaches and design for experimental test campaigns. One key benefit that might otherwise be overlooked is that the PBL teaching provides personal insight of the high-cost of faulty and early design decision due to bad focus and improved planning for potentially issues throughout the project. The allowance for failure is an important feature to integrate in a PBL course, as it provides a very effective teaching method. A representative example is the uncertainty estimation task in the Aerospace Project course. During the lecture, the students are handed a basic Python script for error propagation and are clearly advised, but not forced, to use it when setting up the test matrix by using numerical data as initial values. Most groups fail to perform this analysis adequately in their first attempt, so after hours of testing the groups realize that the measuring device is not sufficiently accurate for the current approach. Some of the students are able to correct the measurement hardware at the spot, but most come back (well prepared) for a later session. This is something that the students have found frustrating at the moment but believed to be very useful and memorable.
However, even if the courses embrace failures, mistakes have to be honest and the rationale that leads to the error should be sound. This is partly the focus for the draft reporting throughout the work, which is essential for every project based course. Students have very limited experience of writing the whole thought process from start to end, design a hypothesis and argue why the results they propose will provide a conclusive answer. A lab notebook could arguably have provided the same framework but the report format was believed to motivate students to carefully describe the entire work process and outcome on something they have to deliver in the end. The first hand-in assignments are typically very challenging for the students to perform and require substantial tutoring. Once one successful cycle is completed, the students tend to learn how to update and revise the report relatively independently.
The experience of a full cycle from problem formulation, hypothesis and achieve null-results are often be critical to posses before MSc thesis work where the impact of a late null-result can be critical.

## 5. Conclusion

The paper shares in detail how two courses for project based learning have been set-up for aerospace teaching at the division of Fluid Dynamics at Chalmers. In conclusion:

- The adaption of project based learning have, according to student evaluations, provided an engagement and enriching study environment and solidifying complex engineering principles by applied real-world representative multifaceted challenges.

- Students have reported a heightened sense of engagement and responsibility towards their learning, attributing it to the real-world relevance of their projects, while still requesting more.
- Instructors have observed noticeable improvements in students' abilities to work collaboratively, think critically, and manage projects effectively. These abilities were clearly observed for students who after the courses conducted MSc thesis at the department or at our industrial partners.
- It is important to emphasize that the high demand for PBL courses necessitates meticulous planning, substantial resources, and continuous adaptation of course content, which require ongoing attention.

## 6. Acknowledgement

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## 7. Copyright Statement



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