SUSTAINABLE AIRCRAFT DESIGN IN ENGINEERING EDUCATION: CONCEIVE, DESIGN, IMPLEMENT, AND OPERATE VIRTUALLY

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ABSTRACT

In the Australian context, greater emphasis has been placed on capstone design projects to address research requirements associated with honours-level engineering degrees. This work highlights the implementation of CDIO for aeronautical engineering capstone projects. Two students in 2022 were offered a digital engineering CDIO-based capstone design project with sustainable aviation objectives as part of their thesis project. The case study highlights that many CDIO aspects can be successfully incorporated into a fourth-year engineering project for aeronautical engineering and why that succeeds. The use of digital simulation facilitates a cost-effective means by which engineered aerospace systems can be implemented, operated, and innovatively iterated by students for deeper understanding of flight.

KEYWORDS

Aircraft Design, Flight Testing, Capstone, Standards: 2, 3, 4, 5, 6, 7, 8, 11

INTRODUCTION

In all engineering education, and specifically in aeronautical/aerospace, there exists a need for imparting an increasingly complex core of technical knowledge, as well as the knowledge and skills that need be possessed for managing real systems and teams. The managing of systems and teams, necessarily, requires both functional knowledge, in addition to intrapersonal and interpersonal awareness. As the economy, and the engineering discipline, continues to grow more technically and organisationally complex, these two needs will have to be balanced by educational institutions. Whilst this balancing act maybe a cause for tension in engineering education (Crawley, 2001), the use of modern digital technology offers a solution. Significantly, authentic activities that mirror the real-world result in notably higher student engagement (Robinson, 2013). The simulation of real-world activities has been shown to facilitate students' understanding of the underlying concepts (Jimoyiannis & Komis, 2001). The use of aircraft engineering simulation software allows for the exploration of various concepts, both locally and remotely, without expending significant resources needed to envisage, evaluate, and iterate a design. Such software can allow for exploration of optimisation of requirements such as sustainability concepts, using local or remote computing resources.

Engineers must increasingly maintain an awareness of the environmental impact of technology (UNESCO, 2010). Design, prototyping, testing, and manufacture of complex machinery requires the use of natural resources and vast amounts of energy (EERE, 2022). Ironically, the exploration of engineered products that might assist in improving the sustainability of the aerospace or aviation industries, both in environmental and economic terms (Schneider, 2001), necessarily impose an ecological and monetary cost. Undergraduate programs can educate future engineers on matters of sustainability (Duarte et al., 2020). The requirement that engineering programs must educate students on environmental and sustainability matters is being highlighted by multiple organisations (NAE, 2004; Volkwein et al., 2004). The use of virtual prototyping (VP) has previously been highlighted as a form of 'sustainable engineering' (Papahristou & Bilalis, 2017) in so far as fewer resources are consumed in the prototyping of products. This virtualisation can be taken further, through the use of advanced flight simulation software, to allow for the digital operation of the final product.

The education of aerospace engineers, particularly those whose future work will involve the engineering of aircraft systems, poses a unique challenge. Though the complexity of all engineering disciplines has continued to increase, this is acutely true for aircraft design. In so far as the opportunities for the practice of engineering on aircraft have decreased, engineering science will necessarily increasingly come to dominate (Crawley, 2001). The CDIO (*Conceive-Design-Implement-Operate*) approach, which was a reaction to engineering science displacing engineering practice (Edström & Kolmos, 2014), grounds abstract engineering concepts in experience. For an upper-undergraduate level capstone project, this involves the immersion of the student[s] in every part of the lifecycle development of an engineered product (Miller & Bodeur, 2002). The *Design-Conceive* phase, during which students must learn to model and analyse various aspects of the product to be engineered, across the lifecycle of the product, is achievable for any given sub-system, but not the full aircraft. Further, within the constraints of a capstone project, the prohibitive costs and regulatory complexity make the *Implement* and *Operate* phases difficult. Within the *Implement* phase, experimental design is outside of the resources generally available. The *Operate* phase also faces challenges, not the least of which, particularly in Australia, is the complexity of integrating a component onto an aircraft. In considering the implementation of CDIO, all these challenges and opportunities, as well as the nuances of the existing University structures, must be carefully considered.

As with many engineering programs, both in Australia (Wild, 2022) and internationally (Halim et al., 2014; Todd et al., 1995), students at UNSW Canberra have the opportunity to undertake a design capstone course. The existing structure of design and capstone courses currently undertaken by undergraduates inside the School of Engineering and Information Technology (SEIT), emerged over four years ago from an approach far closer to problem/project-based learning (PBL), but has been able to extend towards CDIO with the advent of commercial-off-the-shelf simulation. The existing assessment structure is such that, with proper guidance from the supervisor and external design reviewers (i.e., industry experts), the student faces challenges like those experienced in professional engineering occupations. The student must submit interim engineering reports, engineering deliverable reports, and present an oral defence of their engineered solution, simulation, and prototyping before a panel of professionals (UNSW Canberra, 2022a, 2022b). The supervisor for each project, along with assisting technical advisors, and the panel of professionals, are all selected for a given project based upon their professional expertise in the design space. Opportunities for aircraft systems engineering within the capstone projects, particularly those focussed on iterative design amidst flight-test simulation, have recently been enhanced by upgrades to the University's flight simulation laboratory.

To examine this CDIO pedagogy in more depth, two students in 2022 were offered a more extensive digital engineering CDIO-based capstone design project with sustainable aviation objectives as part of their thesis project. It was hoped that this in-depth extension would document why the CDIO approach, as implemented, was working well and provide insight into wider implementation in the aeronautical engineering context. Hence, the credibility of this research is in both the underpinning four years of extant CDIO pedagogy for over 120 students, informed for improvement by the in-depth case study with two students.

The aim of this work is to demonstrate how traditional design, build and fly (DBF) CDIO PBL activities (Hansman, 2009) can be modernised with digital engineering. This facilitates meaningful aerospace engineering outcomes with minimal resources. An all-digital ecosystem can facilitate an aerospace CDIO capstone project, or with access to 3D printing and a suitable wind tunnel, practical extensions are possible. The implementation of CDIO for capstone engineering research projects continues previous work applying computational thinking to undergraduate capstone projects (Wild, 2022).

ADAPTING A CAPSTONE PROJECT COURSE

The general plan for a CDIO approach within the existing capstone project, and the actions required of the case study student[s], are here outlined. Initial consideration had been given to the application of the approach to a capstone project course based upon the engineering of RPAS (remotely piloted aerial systems). The engineering of RPAS has previously been put forth as suitable for engineering education (Maroney & Soban, 2018), for many of the same reasons previously highlighted, and with many of the same potential educational benefits. Thus, coupling RPAS with a virtual/digital CDIO approach provides equivalent educational opportunities. Students do create a 3D print and wind tunnel testing which is physically representative at scale to move beyond the pure digital realm. Virtualisation, and in particular virtual prototyping (VP), has the potential for improving outcomes in engineering education (Bhatt et al., 2009). The design of a system or sub-system for a crewed aircraft requires more multi-disciplinary thinking, going beyond mechanical considerations, and considering the human, social, and economic elements (Sadraey & Bertozzi, 2015).

Outline

The vast complexity of a modern aircraft, in terms of engineering and compliance, means that assigning the task of design, to an operational standard, was not viable for the capstone. The use of teams of students could, within a different program, conceivably allow for such a task. The existing structure of the capstone, which makes use of self-selection into an individual supervisor's project, restricts the number of students that would be available. Future modification of the capstone project could resolve this issue. With the expectation of low student numbers, working across a relatively short period (one year), the system design task must focus on a single system, for one aircraft concept. Much consideration must be given to the aircraft, with a particular concern as to modification and sustainability matters. Any system selected should be modifiable to a particular end, through multiple potential schemata. In so far as this allows for each student to develop their own approach to engineering the system, it also requires that the student consider the "factors that set the context of the system goals" (Crawley et al., 2011). Viz., the other student[s] represents a competitor against whom any engineered solution is to be benchmarked.

The *Conceive-Design* phase consumes the majority of the first semester, and therefore the first course of the capstone. During this phase an initial review of existing solutions, both implemented and experimental, is expected. Development of the system is initially completed using traditional pen-and-paper calculations, prior to the use of computer-aided design tools. As the intention in the case study was for the design of an aircraft with improved sustainability credentials, the selected aircraft concept may differ substantially from those that the student[s] has much experience of from earlier aeronautical engineering courses. Therefore, simulation of an established model of the aircraft is necessary during this phase, so as to establish the boundaries of the work. This simulation may be completed in any suitable software that produces accurate aircraft output data. Progress is assessed throughout the process by the supervisor, expert presentation panels, and importantly student self-realisation when aspects don't work.

The *Implementation* phase is spilt across the end of the first semester, and the beginning of the second semester. The phase begins with the integration of the systems into the established model. As the integration is completed virtually, it is necessary to ensure the model is not modified, other than for that system. Testing utilising standard flight-testing methodologies is then completed. During this process, any modifications made are documented in a design document. As with traditional flight testing, and indeed the testing of any engineered system, simulation of the aircraft model produces vast amount of data. The data must be analysed to confirm the operation of the system, and the comparative performance. Progress is assessed throughout the process by the supervisor and is formally assessed, for course one in the first semester, through a *viva voce* and a submitted interim report.

The *Operate* phase occurs in the second semester, following the testing portion of the *Implementation* phase. Planning for operations, even within a simulated environment, requires the preparation of modified checklists, data extraction procedures, and suitable documentation. Use of the modified model by novice pilots, with particular focus on the implications of the new system, is then completed. Those operating the aircraft are required to provide formalised feedback, using a variety of industry standard tools. The use of more technical tools for the objective performance of the aircraft and system performance are supplemented by pilot evaluation tools, including the NASA TLX (Hart & Staveland, 1988) and Cooper-Harper rating scale (Cooper & Harper, 1969) and aeronatical engineering standards for flight test (*Flying qualities of piloted airplanes*, 1980). Progress during the *Operate* phase, as well as the testing portion of the *Implementation* phase, is assessed by the supervisor. The final assessment, for both the second course and the capstone, is through another *viva voce* and a final report.

Working with the CDIO Standards

This work was undertaken within the existing capstone framework. Thus, the approach must achieve the same outcomes, and to the same level. Furthermore, the approach must work within the Australian Qualification Framework (AQF), whilst incorporating CDIO.

Within the Australian Context

AQF is the national policy for regulated qualification in Australian education and training (AFQ Council, 2013). The revised framework published in 2012 is made up of 10 levels, from a high school diploma (Senior Secondary Certificate of Education) at level one to a doctorate at level 10. A standard three-year bachelor's degree is at level 7. A four-year degree may be at the AQF7 level or could qualify for AQF8 if considered a Bachelor Honours degree (AFQ Council, 2013). The requirement for AQF8 is a substantial research component in the 4th year, equivalent to the year extension offered to general science and other three-year programs where a student completes a research year undertaking a major capstone project with an associated thesis (AFQ Council, 2012). For engineering programs in Australia, the change to the revised AQF structure resulted in a significant increase in the time and effort associated with the capstone engineering project, bringing it in line with science honours programs to meet the AQF8 requirements. Historically, Australian engineering graduates of four-year degrees were only considered to have graduated with honours if they achieved a suitably high score. Under the revised AQF, all graduates must complete a substantial research component such that they meet the criteria to graduate with honours (AFQ Council, 2013). As such, under the revised AQF structure, the term honours, such as to "graduate with honours", no longer means meritorious achievement (AFQ Council, 2012).

Prior to the implementation of the AQF structure, engineering education research had already identified issues in engineering capstone courses (Rasul et al., 2015). Specific concerns included a lack of preparation, marking issues (such as supervisor bias), course assessment dimensions (the outcomes or the journey), and limited training and support for supervisors (Wild, 2022). The doubling of effort in many honours capstone courses to meet the AQF8 requirements, and the need to have all students complete a thesis, has likely only exacerbated these issues. As such, implementing a digital engineering solution with CDIO offers an ideal solution for aeronautical and aerospace engineering programs.

Within the Existing University Course Framework

CDIO Standards 2, 3, and 4, which address curriculum development, are well addressed within the capstone implementation. Standard 2, which regards learning outcomes, requires that there be precise and comprehensive outcomes for the skills, including personal and interpersonal skills, and disciplinary knowledge (Crawley et al., 2014). The present CDIO implementation aligns with the institutions mission, and the required proficiencies are set for all outcomes (UNSW Canberra, 2022a, 2022b). The overall curriculum integrates, over multiple years, the skills, processes and system building competences, thereby addressing Standard 3. The existing degree structure includes courses that provide scaffolding for understanding the practice of engineering, including the process and interpersonal skills, thereby addressing Standard 4.

The fifth and sixth CDIO Standard address the design-build experiences and workspaces that support hands-on learning. The existing curriculum for those progressing towards the capstone includes, among others, the *Aircraft and Systems Design 1 (ASD1)*, and *Aircraft and Systems Design 2 (ASD2)* courses. These courses use a design-implement experience, at a basic level in *ASD1*, and at an advanced level in *ASD2*. Throughout *ASD1* and *ASD2*, as well as multiple other courses and the capstone, learning and experience is conducted in specialist engineering workspace; including, the flight simulation laboratory.

Active learning (Standard 8), through active experiential learning methods, is employed through the degree program, including the capstone project. The use of design-build projects and simulated professional engineering practice engage students in thinking about new ideas, and require overt student response (Brodeur & Crawley, 2005). These forms of experiential learning, and especially simulated professional engineering practice, are enhanced by the chosen learning assessments (Standard 11). The assessment of a student's understanding of fundamental disciplinary knowledge is achieved prior to the capstone course, with further verification through review of submitted design documents. The use of *viva voce* as an end-of-course evaluation of learning, and the continuing assessment of progress by the supervisor, allows for the assessment of such things as personal and interpersonal skill, process, and system building skills.

The present implementation of a CDIO approach does not address all twelve CDIO Standards, or even the seven essential standards. However, the value of the CDIO Standards is not about any given standard, but rather the aggregate approach (Edström & Kolmos, 2014).

CASE STUDY

Two 4th year engineering students at UNSW Canberra were engaged to undertake a sustainable aviation engineering capstone project, based upon earlier research on box-wing technology (Somerville, 2019). After discussions it became clear that their prior and concurrent enrolment in the Aircraft Systems Design (ASD) courses in the aeronautical engineering program at UNSW Canberra facilitated a higher level of design and development. Given previous work had investigated aerodynamic characteristics and potential sustainability impacts, new work would be able to focus on practical and operational aspects. This facilitated the use of CDIO, where the supervisory team as the stakeholders had expressed an interest in the flight testing of a box-wing aircraft to evaluate the dynamics and control of the novel structure. The ability to digitally implement the aircraft design through PlaneMaker and operationally test in X-Plane provided an opportunity to implement flight-test engineering approaches, following the concept and design phases (Franklin et al., 2022).

UNSW Canberra has implemented a flight simulation laboratory for a decade, with a focus on flight safety. The current iteration makes use of modern technology, along with synthetic flight trainers, and twenty workstations with HOTAS flight controllers. The primary flight simulation software utilised in the lab is Laminar Research’s X-Plane. X-Plane is a flight simulator engine that implements an actual aerodynamic model, blade element theory. That is, X-Plane makes use of “computational fluid dynamics”, as opposed to a “physics engine”, meaning that actual aerodynamic parameters are calculated to model the aircraft, accurately. The ability to display and log these parameters makes it ideal to use in basic laboratory activities (Somerville et al., 2022). Included with the X-Plane software is PlaneMaker, a package for the engineering and modelling of aircraft. This means that students can implement and operate any aircraft conceived and designed into X-Plane.

Applicable CDIO Syllabus

Looking at the CDIO syllabus, the digital engineering and flight testing of sustainable aerospace vehicles maps to a significant number of points. These are giving in Table 1.

Project Overview

Utilising the NASA Project Template from the CDIO Knowledge Library, the project overview is given below.

“1.1. Overall goal or purpose”
The project was implemented to design and test a box-wing aircraft for use in general aviation. This was for a team of engineering students working for a full year (two semesters). While aerodynamics of box-wing aircraft has been previously studied, stability and control research is not as mature; hence, the focus was on practical flight-test engineering of a previously

optimised design. This was facilitated by the X-Plane with PlaneMaker software (Franklin et al., 2022).

Table 1. Applicable CDIO Syllabus Items from Crawley et al. (2011)

2.1.1	Problem Identification and Formulation	3.2.5	Graphical Communications
2.1.2	Modelling	3.2.6	Oral Presentation
2.1.5	Solution and Recommendation	4.1.2	Impact of Engineering on Society and Environment
2.2.2	Survey of Literature	4.1.6	Visions of the Future
2.2.3	Experimental Inquiry	4.2.6	New Technology Development and Assessment
2.2.4	Hypothesis Test and Défense	4.3.4	System Engineering, Modelling and Interfaces
2.3.4	Trade-offs, Synergies, Judgment and Balance in Resolution	4.3.5	Development Project Management
2.4.5	Critical Thinking	4.4.1	The Design Process
2.4.8	Time and Resource Management	4.4.6	Design for Performance, Sustainability, Safety, etc
2.5.1	Ethics, Integrity and Social Responsibility	4.5.1	Designing a Sustainable Implementation Process
3.1.1	Working in teams	4.5.5	Test, Verification, Validation and Certification
3.1.3	Stakeholder Engagement	4.6.1	Designing and Optimizing Sustainable and Safe Operations
3.2.3	Written Communication	4.6.2	Training and Operations
3.2.4	Digital Communication		

“1.2. Societal context and relevance”

A box-wing aircraft offers considerable fuel savings over conventional aircraft planforms (Somerville et al., 2015). A study of the potential impact found that in the case that a large training aerodrome utilised a fleet of box-wing aircraft in place of conventional aircraft, the direct reduction in CO2 would be 700,000 kg, while lead emissions would be reduced by 135 kg, per year (Somerville et al., 2018).

“1.3. Integration (e.g., where project fits in a course, program, or curriculum)”

The project was an optional part of the Bachelor Honours capstone research project. All students are required to complete an individual project, where possible working collaboratively with other students on related projects. The students have completed three years of an undergraduate aeronautical engineering program, including flight mechanics, aerodynamics, flight dynamics and control, propulsion, as well as materials, structures, and other general mechanical engineering (thermodynamics and fluid mechanics etc). Importantly, students had participated in Aircraft System Design 1, and would be co-enrolled in Aircraft System Design 2. The ability to digitally design and flight test an aircraft is covered as part of Aircraft System Design. That knowledge base includes learning about flight test engineering including human factors, and covered tools such as the Cooper-Harper rating scale.

“1.4. Description (e.g., complexity, duration, group size and number, budget)”

The prior knowledge gained during the Aircraft System Design course[s] facilitates a high level of complexity, where students can utilise their skills to conceive and design a new aircraft with the aid of basic computational fluid dynamics tools (covered in their undergraduate courses), which can then be implemented and operated in a digital simulation. The project was a yearlong undertaking, facilitating the entire CDIO process. In the specific case, a pair of students worked together on the project, each tackling different approaches to flight control.

“1.5. Learning activities and tasks (brief summary)”

In general, students complete a capstone research project for the degree. In the aeronautical application here, the students digitally design, build, and fly a test vehicle. The sustainable nature of the project is to conceive and design a vehicle with reduced emissions, with the chosen technology that of a box-wing. Students were expected to take ownership of the minor body of research and reflect this to the wider community via presentations and written submissions. The assessment tasks included:

- **Interim Report and Viva** to outline the scope and significance of the intended research, including initial design, in report form and with an oral defence.
- **Project Seminar** to present the final findings of the research project in oral form.
- **Research Summary** to present the final findings of the research project in written form.
- **Deliverables** to address the outcomes of the research project.

CONCLUSION

In the Australia context, a greater emphasis is being placed on capstone projects to address research requirements associated with honours level engineering degrees. The further requirement to educated engineers about both functional knowledge, and intrapersonal and interpersonal awareness, appears to be addressable by implementation of a CDIO approach, where four years of capstone design students have graduated with exposure to the process through simulation of their designs. The aim of this work has been to show the implementation of a digital engineering CDIO-based sustainable aeronautics capstone research project to better appreciate how CDIO is effective and how to further improve the capstone design subject. We have presented a case study of an aeronautical engineering capstone research project, undertaken by a team of two students at UNSW Canberra. Many improved CDIO approach characteristics were identified to improve fourth-year engineering design subjects or research projects for aeronautical engineering. The use of digital simulation has also proven to be a cost-effective means by which engineered aerospace systems can be implemented and operated.

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Keith Joiner was an Air Force aeronautical engineer, project manager and teacher for 30 years before joining UNSW to teach and research test and evaluation. As a Director-General he was awarded a Conspicuous Service Cross and for drawdown plans in Iraq a U.S. Meritorious Service Medal. His 1999 PhD was in reform of calculus education and he is actively researching classroom environments with collaborative learning, management and teaching of artificial intelligence, interoperability, cybersecurity, and advanced test techniques.

Timothy Lynar Tim's primary research focus is the application of machine learning to cyber security. Tim has a background in simulation, modelling, machine learning and distributed computing including cloud and IoT systems. Tim's current modelling efforts are pertaining to cyber security particularly to the epidemiology of Cyber security and, Modelling Complex Warfighting. Tim has a passion for innovation and was a Research staff member and Master inventor at IBM Research for 7.5 years in that time he led the intellectual property development team of the Australia Lab and submitted over 100 patent applications. Tim joined the University of New South Wales - Canberra in 2019 where he is researching and applying machine learning to complex problems.

Graham Wild has been a senior lecturer in Aviation Technology the University of New South Wales, in Canberra Australia since 2020. He has authored and co-authored over 150 scientific papers. His current research interests are around intelligent systems, AI, data and analytics, and advanced technology in aviation and aerospace, for education, training, safety, and sustainability. His current funded research focuses on health monitoring of hypersonic flight vehicles. He is a member of the IEEE, SPIE, and AIAA.

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