Developing Student Competency in Engineering Tools Using Open-Source Software in Undergraduate Engineering Education

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Abstract

Since the introduction of ECSA's revised Graduate Attributes in August 2023, engineering programmes have had to adapt teaching to meet new requirements. Graduate Attribute (GA) 5 emphasises competence in selecting, applying, and evaluating engineering and IT tools for complex problems, with a stronger focus on mathematical and computational foundations. Commercial CAD and CFD software, while effective, is costly and often inaccessible post-graduation, making open-source alternatives attractive. FreeCAD (for CAD) and OpenFOAM (for CFD) were integrated into a third-year heat and mass transfer module at a South African university to perform CFD analysis. These tools require students to engage directly with solver algorithms, numerical methods, and scripting, fostering deeper understanding of model development, computational efficiency, and tool limitations. Their accessibility also encourages collaborative, independent learning. The study assessed the potential of open-source tools to develop GA 5 competencies through a final assessment project. Students submitted self-reflective notes, which highlighted cost-effectiveness, improved proficiency, confidence in simulation tools, and enhanced problem-solving skills. One student noted, *"This assignment gave me a real sense of applying theory to practical engineering scenarios."* Findings indicate that open-source CAD and CFD tools can match the technical skill development of licensed software while adding accessibility and collaboration benefits.

Keywords: Undergraduate development, Open-source CAD software in education, Engineering education

1 Introduction

In August 2023 the Engineering Council of South Africa (ECSA) released their revised E-02-PE document containing changes to each graduate attribute (GA) (ECSA, 2023). The table below summarizes the key differences between the previous and latest elements of ECSA's GA 5.

Table 1: Concise summary comparing the previous (September 2020) and latest (August 2023) ECSA GA 5:

Aspect	**Previous ECSA GA 5**	**Latest ECSA GA 5**
Focus	Using appropriate engineering methods, skills, and tools, including IT.	Creating, selecting, applying, and recognizing the limitations of engineering and IT tools for solving complex engineering problems.
Key Requirements	Competence in discipline-specific tools, computational and simulation software, and IT for information management.	Emphasis on prediction and modeling, applying modern engineering tools, and understanding their constraints.
Knowledge Base	Practical use of engineering tools and IT for teamwork and productivity.	Stronger foundation in mathematics, numerical/data analysis, statistics, and computer science for detailed modeling and analysis.
Scope of Tools	Broad use of software and digital tools relevant to engineering practice.	More explicitly integrates analytical techniques, modern resources, and engineering technology.
Complexity	General application of tools for engineering practice.	A more critical approach, requiring graduates to assess tool limitations and suitability for complex problems.

Key Differences are therefore identified as:

- Increased emphasis on critical evaluation: The new GA 5 requires recognizing tool limitations, rather than just applying them.
- Stronger mathematical and computational foundation: The new GA 5 explicitly includes conceptual mathematics, statistics, and data analysis.
- Greater focus on complex problem-solving: The updated version ties engineering tools to solving complex problems rather than just using them effectively.

There is a strong emphasis on developing competency in discipline-specific software tools. While the use of open-source engineering tools is not new, this study's contribution lies in demonstrating their integration into a problem-based, collaborative learning framework aligned with the revised ECSA GA5 requirements. Previous studies confirm the computational reliability of open-source software, but literature showcasing its efficacy within undergraduate engineering education is limited. For example, (Najihah et al., 2021) showed FreeCAD and OpenFOAM produced results for a passenger ship hull simulation nearly identical to experimental data, while (Lee et al., 2020) successfully applied earlier versions to simulate an internal combustion engine and large trailer with high accuracy. In Chemical Engineering education, proficiency in CAD and CFD software is essential for modelling, simulation, and data analysis, especially under the revised GA 5. However, commercial software presents challenges: costly licenses often exceed institutional budgets, especially in the Global South, where limited IT infrastructure and support complicate maintenance and updates. Even with licenses, not all students have access to suitable computers, and installation or activation issues delay early use. Post-graduation access is also limited, particularly for graduates entering smaller firms without licensed software. Open-source alternatives like FreeCAD and OpenFOAM provide a sustainable, equitable solution. They promote self-driven learning through online tutorials and forums, fostering both technical and soft skills. This paper aims to demonstrate the potential of FreeCAD combined with OpenFOAM to develop ECSA GA 5 competencies in third-year Chemical Engineering students while addressing the cost and accessibility challenges of licensed software.

2 Educational approach and design

2.1 Pedagogical framework and learning principles

The intervention, which aimed to develop ECSA GA 5 competencies using open-source tools, was implemented in a third-year Chemical Engineering heat and mass transfer module. This module, taught by one of the authors, involved a cohort of 20 students in 2024 at a South African university, who had diverse backgrounds and varying prior exposure to engineering software. The module's design incorporated a blended learning approach that significantly emphasised industry-related problem-based learning (PBL). This framework was chosen to:

- Utilise realistic examples for problem-solving, aligning theory with practical application.
- Foster self-directed learning, allowing students to navigate challenges independently.
- Increase learning effectiveness, convenience, and accessibility for the student cohort.

Throughout the semester, students were prepared for a Final Assessment of Module Outcomes (FAMO) project, which served as the module's summative assessment, replacing a traditional examination. This individual heat exchanger design project was structured around a real-world industry design request, mirroring authentic engineering scenarios. Students were required to use FreeCAD and OpenFOAM to simulate, optimise, and critically assess their design choices. This approach ensured that the open-source software was not just an add-on, but an integral tool for solving complex engineering problems within a practical, industry-aligned context. The module's assessment plan (summarised in Table 2) was designed to incrementally prepare students for the FAMO project, which explicitly utilised open-source software for ECSA GA 5 development.

Table 2: Assessment plan summary:

Participation mark		**60%**	**Notes & Comments**
Reading assignments	5%		Given to prompt students to prepare for in-person class sessions, laying the foundation of their module knowledge base.
Tutorials	15%		Given as assessment for learning aiding in applying the mathematics needed for CAD and CFD simulation.
Practical assignments	30%		Aimed at introducing student to FreeCAD and OpenFOAM. The executed practical fluid flow scenario has to simulated in FreeCAD in conjunction with OpenFOAM.
Class tests	50%		Given as assessment of learning of the fundamental principles governing fluid flow and heat and mass transfer.
FAMO Project		**40%**	Final assessment of module outcomes - Specific focus on ECSA GA 5 development, where a complex problem is presented which must be simulated and critically evaluated using the open-source software tool.
Individual Project	100%		
Module Mark		**100%**	60% Participation mark + 40% FAMO Project - Sub-minimum of 40% for both participation mark and FAMO Project

2.2 Integration of FreeCAD and OpenFOAM into module content

To effectively introduce and build student proficiency with FreeCAD and OpenFOAM, the following elements were implemented throughout the semester:

- Initial Orientation: Students received an overview of CAD and CFD software, its relevance, and the FAMO project requirements in the first class session of the semester.
- Theory-Practice Link: Theoretical concepts were continuously contextualised with practical applications in CAD and CFD software during lectures and tutorials.
- Resource Provision: A "How-To Guide" was provided, detailing software download, OpenFOAM add-in installation, and linking to relevant YouTube tutorials and mini-tutorials to aid familiarisation. Students had seven weeks for project completion.
- Group Practicum: A collaborative group session allowed students to familiarise themselves with the software through a less intensive simulation, receiving feedback to prepare for the FAMO project.
- Dedicated Support: A module assistant provided logistical and technical support for software installation and usage, minimising adoption barriers.
- FAMO Project Submission: The project required online submission of simulation details, source files, residual graphs, and output proof, along with a three-minute video defence and self-reflective notes for proficiency evaluation, and perceived learning.

3 Challenges faced and lessons learned

This section discusses the primary challenges encountered during the module's intervention, followed by key lessons learned from both the lecturer's observations and students' reflections, highlighting their relevance to fostering competency, collaboration, and critical engagement with engineering tools.

3.1 Challenges

The main challenge in implementing FreeCAD and OpenFOAM was human perception. As the software was free and open-source, many students and staff held a negative bias, presuming it was less capable than commercial packages for CFD analysis. This perception exacerbated frustrations over minor logistical issues, despite the open-source tools actually presenting fewer technical problems than commercial alternatives.

While formal developer support was absent, the availability of numerous informal online user forums proved crucial. Engaging with these forums not only aided problem resolution but also facilitated a richer learning experience. Students developed essential IT-related problem-solving skills by independently seeking solutions, rather than relying on predefined manuals available when using licenced software. This process inherently promoted 'connection' within a broader community of users. Furthermore, this self-driven approach to troubleshooting reinforced the updated ECSA GA 5's emphasis on critical evaluation and independent problem-solving.

3.2 Lessons learned

The integration of open-source software yielded significant educational benefits, as observed by the lecturer and corroborated by student reflections. From the lecturer's perspective, students demonstrated marked improvements in technical skills, problem-solving abilities, and adaptability, achieving similar proficiency levels to those using commercial software while also gaining a deeper understanding of underlying algorithms and modelling limitations, consistent with ECSA GA 5. The open-source nature specifically facilitated open, cloud-based collaboration due to the absence of license restrictions, fostering a more connected learning environment. Students' reflections underscored their increased confidence in applying theoretical knowledge to practical engineering scenarios, improved problem-solving skills, and enhanced resilience in navigating complex software challenges. Students also showcased a better theoretical basis of reasoning from which they critically evaluated the proficiency of the software. These comprehensive lessons, providing valuable insights into both technical and soft skill development, are detailed further in Tables A.1 and A.2 in the Appendix.

4 Critical reflections and conclusions

The integration of FreeCAD and OpenFOAM for CFD analysis at an undergraduate level in a South African university proved highly promising. The advantages observed significantly outweigh the challenges faced, demonstrating the suitability of these tools for engineering education.

A core takeaway is that open-source software effectively aided the development of ECSA GA 5 competencies, fostering critical evaluation of tools, a stronger mathematical and computational foundation, and enhanced complex problem-solving abilities. Students not only matched the technical proficiency typically seen with licensed software but also gained a deeper engagement with modelling limitations, and manual workflow setup, thereby 'co-creating' their computational understanding due to a lack of formal user manuals. Open-source tools uniquely support the themes of 'connection, collaboration, and co-creation'. Their unrestricted accessibility directly addresses significant challenges associated with commercial software, such as high licensing costs and post-graduation inaccessibility. This is particularly pertinent in the Global South, where limited IT infrastructure and support often complicate the use of commercial packages. Furthermore, the reliance on numerous informal online user forums for troubleshooting provided a richer learning experience, equipping students with essential IT-related problem-solving skills and promoting self-directed learning and resilience, a form of personal 'co-creation' of their learning strategies.

In conclusion, the findings showcase FreeCAD and OpenFOAM as reliable and impactful tools for developing well-rounded engineering graduates. This approach offers a sustainable and equitable solution for engineering education, promoting continuous learning and skill development beyond the confines of university, and providing valuable insights for other engineering disciplines reliant on Computer-Aided Design (CAD), CFD, and similar computational packages that often face similar accessibility challenges.

5 References

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Appendix

Table A.1: Lessons learned: the lecturer's perspective.

Module outcome	Lessons Learned
Using FreeCAD and OpenFOAM	Students learned to navigate complex engineering tools despite initial steep learning curves. Confidence in using these tools grew as students practiced and completed tasks. Simulation errors prompted critical problem-solving and troubleshooting. Requires deeper understanding and manual setup, rather than using pre-built commercial solvers, aiding in reaching GA 5 outcomes. Students learn to assemble and troubleshoot their own workflows rather than relying on vendor support. No license restrictions; enables open, cloud-based collaboration with version control
Application of Theoretical Knowledge	Students connected classroom theory to real-world engineering problems, gaining insight into practical applications. FreeCAD enabled Students to engage with the computational results in such a way that they could vary system parameters to find the best solution via an inquisitive trial-and-error based approach helping them to understand how design parameters affect performance and the importance of optimization.
Problem-Solving and Adaptability	Challenges with simulations, designs, and calculations fostered resilience and adaptability. Students gained confidence in iteratively refining designs and finding creative solutions.
Time Management and Project Planning	Many students highlighted the importance of starting early and allocating time effectively. The project emphasized realistic planning and the consequences of underestimating task complexity.
Communication and Reporting	Developing reports and video presentations enhanced communication skills. Clear articulation of technical concepts to diverse audiences was a valuable takeaway.
Collaboration and Independence	Students balanced teamwork with independent problem-solving, learning to seek help when necessary. They developed the ability to work autonomously while meeting project goals. Open-source tools are freely available, allowing students to collaborate without license constraints and use version control systems for group work.

Table A.2: Lessons learned: the student voice.

Theme	Student Reflections
Gaining Practical Skills	**Student 1:** "I feel much more confident in my ability to design a heat exchanger from scratch... This experience has strengthened my technical skills and problem-solving abilities." **Student 6:** "I have significantly improved my problem-solving and time management skills... Overall, this assignment has been a transformative learning experience."
Overcoming Challenges	**Student 5:** "FreeCAD is not beginner-friendly... but by starting with simple designs, I was able to build my confidence and apply the same concepts to more complex designs." **Student 7:** "I struggled to simulate my complex design but learned the importance of flexibility by scaling my values to run a simpler model."
Importance of Standards and Accuracy	**Student 3:** "Managing the allowable pressure drop while ensuring efficient heat transfer was a significant challenge, but it helped me understand the importance of optimizing design parameters." **Student 10:** "It is crucial for a product to be safe, reliable, and effective, which adhering to industry prescribed standards, ensures."
Resilience and Adaptability	**Student 2:** "I overcomplicated everything at first but learned to focus on the outcomes and simplify the process." **Student 9:** "This project taught me how to teach myself, fight through difficulties, and better manage my time."
Personal Growth and Confidence	**Student 4:** "Through repetition and problem-solving, I gained a deeper understanding of the design process and its practical implications." **Student 11:** "This assignment gave me a real sense of applying theory to practical engineering scenarios and significantly improved my proficiency in simulation tools."