REVERSE ENGINEERING AND INTRODUCTION TO ENGINEERING DESIGN

Petros Siegkas

Nottingham Trent University, UK

ABSTRACT

This paper describes practical elements during two terms of a first-year module within which CDIO standards are implemented. The aim of this practical module is for students to practice their fundamental knowledge and develop the required skills to complete projects that are structured according to industry standards. Several skills are involved in working within a professional engineering environment, beyond the strictly technical knowledge. The intention is to make the students also aware of these skills. During the first term of year one, the module includes a team-based reverse engineering project. Students are assigned to teams and given an appliance. They are expected to conceptually and physically deconstruct the device and analyze the relevant aspects of both of its parts and as a whole. Aspects would include scientific principles related to function, design considerations, the context of use, etc. The teams will then propose improvements on individual parts and the device as a whole, in terms of either function, price, manufacturing, or sustainability. The work is presented to the class and compiled into a group report. During the second term, the students are trained in design software (Autodesk Fusion 360 CAD, CAE, CAM), including basic finite element simulation, and are given two design tasks. The first is to use laser cutting to design a small wooden bridge based on certain specifications (e.g., dimensions, load-bearing), including some aesthetic elements, using limited resources (i.e., material allowance). The second is to design and optimize (in terms of mass) a support structure of certain dimensions and load-bearing capacity. The structures are then manufactured and assembled, i.e., laser-cut, and 3D printed correspondingly, weighted and tested for their load-bearing capacity. Assessment is based on a relevant portfolio. Throughout the two terms, lectures are delivered on project management and product development, as well as case studies by guest lecturers of various engineering fields. The module has been very well received with high student ratings in relevant surveys.

KEYWORDS

Introduction to engineering, design process, CAD/CAE/CAM, active learning, Standard 1, 3, 4, 5, 8, 11

INTRODUCTION

Since 2017, Nottingham Trent University (NTU) has established a new engineering department. The following paper describes practical elements during two terms of the first-year module in engineering, called Innovation and Engineering Solutions. The module covers about a third of the first-year curriculum, and the described elements account for 50% of the module grade. The module is taught across all engineering courses offered by the department, i.e., Electronic, Biomedical, Sports, and Mechanical engineering. All engineering courses are structured so that to include engineering fundamentals, e.g., mathematics, specialized modules for each course (e.g., electronics). And practical skills modules such as the module described below. The aim is to have the students practicing their knowledge and develop the skills required to complete projects that are structured according to industry standards. There is a number of skills involved in working within a professional engineering environment (e.g., team building, communication, etc.) beyond the strictly theoretical knowledge of the topic. The intention is to make the students aware of these skills, in addition to the purely engineering practical skills.

Students taking the module are either domestic or international with a wide range of educational backgrounds. Entry qualifications may vary, i.e., A level, BTEC, foundation, as well as different backgrounds in terms of the educational systems they attended. In addition, students may vary in terms of their talents and dispositions (Thomas & May, 2010). Provided the students achieved the entry requirements, the department and University have additional provisions in order to assist students in acquiring necessary prerequisite knowledge in related topics, e.g., math or chemistry, regardless of the differences in educational background. Provisions are also made in terms of learning disabilities, e.g., dyslexia, according to University guidance. The projects described below are multifaceted in a way that can allow students to build upon their strengths but also push beyond their comfort zone such that they can identify and develop new skills. Tasks were designed to require several skills, including critical thinking, effective communication, technical knowledge, science and engineering fundamentals, independent study, creativity, team building, etc. Students were guided through a structured process that aimed to facilitate active learning.

Other institutions have reported modules with similar elements in terms of technical content and structure and in accordance with CDIO standards. A reverse engineering module was used as part of innovation training (ZU et al., 2012). CAD, CAE, CAM environments, and CNC machines were used to introduce students to the engineering design tools and process as part of a 4-week independent activities course (Deweck et al., 2005). 3D desktop printers were used at NTNU for a group design project (Haavi et al., 2018) in which students were able to choose their own teams out of participants from two courses. An engineering design and optimization module, based on CDIO standards and including industry involvement, was developed as part of a postgraduate course (Quist et al., 2017). The NTU module, described in this paper, aims at integrating and introducing these tools, processes, and practices, early in the student's engineering education (i.e., first year).

FIRST TERM: REVERSE ENGINEERING

During the first term of the first year, the students are required to complete a reverse engineering project during weekly 2-hour lab sessions. The intended learning outcomes roughly include an introduction to the basics of engineering design, engineering considerations within the design (e.g., materials), processes, and methods of working (e.g., team collaboration). The students are assigned into mixed teams, in terms of engineering courses, in order to avoid potential clustering of similar dispositions and, therefore, to introduce some diversity in the teams. Each team draws a number from a ballot that corresponds to an appliance or device that the team would have to work on. The project was structured in a way common for industry, i.e., with the use of three "gateways" or checkpoints as feedback opportunities at which the students would have to pause and provide certain deliverables as a form of formative assessment. Upon passing the gateway, the students are 'allowed' to progress to the next stage of the project. Roughly, the project "Gateway 1" would include tasks of an initial analysis of the product in terms of external description, concept analysis, function, need it serves at a specific and general context, price, market and history and then if possible some potential improvements at first instance, that could be analyzed further during the next stages. Passing through to "Gateway 2" the students would physically disassemble the device to its constituent parts for which a bill of materials would be filled. The function, materials, price, etc. of each part would be recorded, and pictures of each part would be numbered and archived. The students would be able to use any available reliable source to obtain the relevant information and understand the potential reason behind the design considerations and function of each part. The part would then be numbered and placed on boards in an orderly manner (Figure 1).

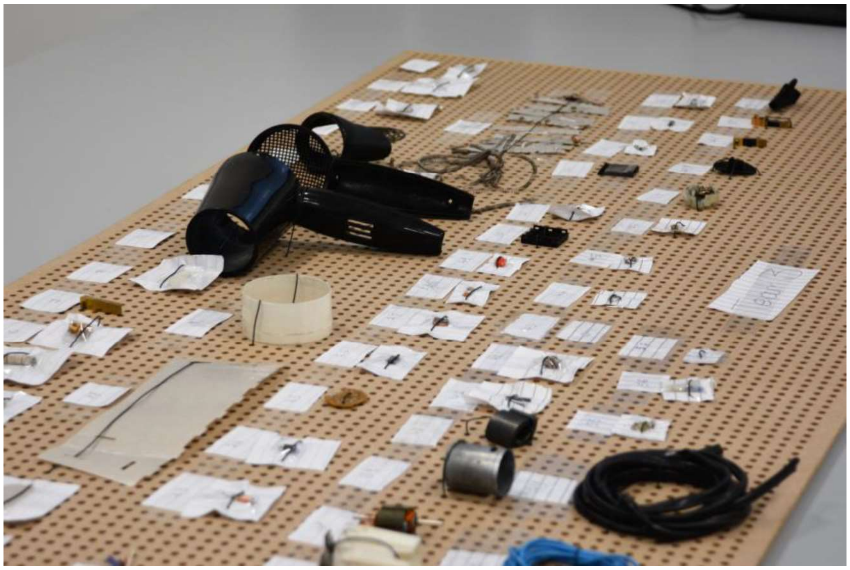

Figure 1. Example of a board with parts from a reverse engineering project

Progressing to the 3rd gateway, the students would have to deliver two paragraphs for each part. The first paragraph would have to be a description and a critical evaluation of the role of the part in the device. The second paragraph would need to propose, when possible, potential improvements in terms of either price, function, manufacturing, or sustainability. Each team would then finally need to present their findings to the class (formative assessment) and get feedback from peers and tutors. They would then compile a report that would be the actual item on which they would be graded (summative assessment).

Each lab session would start with a brief (approximately 10 minutes) introduction to content relevant to the lab tasks for the day. In parallel to the lab sessions, there would be lectures, delivered at a different time, that would cover design and product development aspects (Eppinger & Ulrich, 2015). Additionally, invited guest lecturers would deliver talks on case studies from their professional experience. This would assist in eliciting important aspects and approaches to product design and engineering projects through experienced practitioners. All content, including recorded lectures, would then be available for students to access online.

The reverse engineering project structure and content were chosen so as to try and enable active learning as much as possible. The method is also included in the NTU teaching development framework standards. The students were given direction and instructions so as to perform actions collectively. During the process, i.e., dismantling an appliance, the students would have to engage in critical thinking and reflect, so that to be able to describe each part's function within the appliance and its relation to the whole. This is in alignment with (Bonwell & Eison, 1991) (p.iii) who argue on the value of student actively performing actions and thinking on the actions they are performing. Additionally, the students would be encouraged to research each part, e.g., materials, using any medium they choose (e.g., internet, library) and at their own pace. In this way, they could build their own knowledge, connect the new ideas and form an enhanced understanding (Brame & Director, 2016) in a wider context, e.g., considering the need that the appliance is serving, the appliance itself, and the relation to individual parts. This was in alignment with the work of (Tynjälä, 1999) (p.365) who recommended the choice of tasks that enhance the process of active knowledge construction.

The team element was designed in a way so as to promote inclusivity. The students were mixed regardless of educational background and furthermore between different courses. This was done to promote diversity of backgrounds, and potentially mixed talents and dispositions. The variety of tasks would also enable students of various educational backgrounds to engage in the process. Some tasks were more technical, e.g., dismantling a device and identifying functions, which could potentially be easier for the student from a more technical background, and some tasks more theoretical such as written descriptions. The students could choose tasks that either felt more comfortable doing or try venturing outside their comfort zone and develop in new areas. This would give the opportunity for everyone to engage, participate, and contribute. Commonly, engineers are assigned to teams. The skill to be able to effectively collaborate within a team can be important in a professional environment.

The literature on collaborative learning, i.e., students working in teams towards a common goal (Prince, 2004), suggests that a social element may enhance the process of constructing meaning (Tynjälä, 1999) and that peer to peer interactions may promote the development of 'extended and accurate mental models' (Brame & Director, 2016). The idea of constructive alignment as an effective method in teaching is also proposed in the literature (Biggs, 2011). The premise is that the learning outcomes, teaching and learning activities, and assessment tasks should be aligned. In this example, the students would perform tasks observed and guided by the module leader, which would result in the deliverables that would compose their assessed work. Through this process, the learning outcomes would be achieved. This method was preferable rather than lecturer performing tasks and observed by the students. Engineering is an example of a discipline that involves practice as well as the accumulation of various information.

Arguably, this project at the beginning of the first year gives students the opportunity to rethink the way they view everyday objects. This would align with the idea of threshold concepts in which acquired concepts, that might be challenging for learners, can lead to conceptual transformation and reveal hidden interrelatedness (Schwartzman, 2010).

The teaching in this example was aimed to give structure and case study experiences leading to the desired outcomes. The students engaged in discussions within the team during the various parts of the project, e.g., the practical dismantling of the appliances, led to reflection and analysis. Their work was presented verbally to the class, which allowed them to practice an important required skill and get feedback from both their peers and tutors. Feedback during the gateways and from their peers after the presentation would be incorporated in the required report for their actual assessment. The project was designed as a multi-layered learning experience. Rather than going through a description of case studies in a lecture format given by a tutor, a more practical approach was implemented to approach the desired outcomes.

During the laboratory sessions, there was high attendance, and students seemed quite eager to proceed with the projects. There were certain elements that seemed to produce excitement, e.g., the ballot draw for the appliance assignment, or especially towards the dismantling stage. On several occasions, the students would try and stay longer beyond the session so that to continue working. This, however, was not possible due to room bookings. Teams seemed engaged in relevant discussions that seemed constructive, pleasant, and cheerful. Tutors would periodically pass by the groups and join the conversation answering any potential question and suggesting guidance as to how they could find out relevant information. Arguably, the pleasant social element and the excitement during tasks (e.g., dismantling devices) could be elements of positive reinforcement within the learning experience. Positive reinforcement could be an effective motivational factor, preferable to a negative one, e.g., the threat of a bad grade.

The resulting reports that were submitted by the students were of a good standard with a high overall average mark. Student surveys scored high in overall student satisfaction. In combination with the various opportunities at which students got feedback either by their peers or tutors, the increased interest and enjoyment could arguably be the reasons for the student performance. A peer review element was also included. Confidential peer review forms were submitted in which students had to rate their team members from a scale between 0-5, with 0 being no contribution or absent, and 5 being significant contribution above average. Action in terms of grade differentiation within a team was only taken when multiple members of a team rated a teammate with 0 or 1. Additionally, within the report, a section was included that would roughly summarize the parts with which each member contributed. The team grade was a reflection of the collective result. The grades were also moderated in accordance with NTU regulations. However, individual efforts within team projects are practically difficult to assess precisely. It remains a challenge for tutors to establish a system that would accurately and perfectly capture individual effort. Nevertheless, the long-term individual benefit, in terms of knowledge and experience, is often proportional to engagement and effort, regardless of the grade. Overall the goals of the module were achieved, and important skills were elicited and practiced in agreement with the relevant literature. The students were exposed to several challenges and were benefited in various ways.

SECOND TERM: WOODEN BRIDGE AND SUPPORT STRUCTURE OPTIMISATION

Having reflected on design concepts and considerations during the reverse engineering project, the students would then progress to design projects for the second term. They would be asked to complete two small projects (wooden bridge, optimizing a support structure) that would include basic characteristics of typical engineering projects, i.e., resource restrictions, functional and dimensional specifications, some space for creativity, etc.

During the second term of the same module, the students are introduced to laser cutting, which is a manufacturing technique that involves cutting sheets of material using a laser beam. The assessment would be based on a portfolio style presentation of their work. Prior to the start of the project, guest instructors were invited from a CAD software company (Autodesk) in order to train students on Fusion 360, which would be used for the projects. We organized three days of training with company instructors on campus. Within this time, the students would follow the instructor's steps for small tutorial projects that would include all the necessary steps, which would then be useful for their module. During these tutorials, the students would be assisted at each step by the instructors. The students were also provided with online tutorials and teaching resources related to the topics that were covered during class.

After the software training, the students would be encouraged to research bridge designs and then use Fusion 360 software to design their own. The type of bridge was left open for the students to decide; however, there were some resource restrictions (in terms of use of the material), basic dimensions, and load-bearing specifications (support 1kg). Apart from the purely functional side, the students were urged to include an aesthetical aspect of their designs. The design should be made in a way that would be compatible with the manufacturing method (i.e., laser cutting). The use of adhesives for structural purposes was prohibited. That would provide them with an opportunity to further think and understand the manufacturing method and how manufacturing affects design.

The wooden bridge project had 3 "Gateways," which would serve as formative assessments of the student's progress. The students would have to submit predefined deliverables on which they would get feedback. Those were all necessary stages that would be included in their final portfolio as parts of their summative assessment.

For the first gateway, the students would have to use the software to design a bridge (to be manufactured with the laser cutting method) and assemble it virtually as a three-dimensional model. The second gateway would include using the software for the simulation of the bridge with the predefined load. Potential improvements would be made to the design, if necessary, to reinforce the structure. For the third gateway, the students would use CAM (computer-aided manufacturing element) to ensure compatibility with the manufacturing method, export the drawings in a format compatible with the laser cutter and queue for cutting and assembly (Figure 2). On the final day of the term, the session was organized as an event in which the students test their design for structural integrity. Prizes were given by guests from an independent, engineering-related, professional body on the best bridge design.

Similarly, for the support structure design, an initial template of a support structure was given with certain dimensions defined. The structure would have to be optimized using the simulation tools and stress distribution in order to reduce the use of the material as much as possible for supporting a 5kg load. The structures would then be 3D printed, weighted, and tested on the final day of the term (Figure 3). A small prize was given to the student with the lightest structure that would support the 5kg.

The tasks leading to the portfolio were chosen in order for the students to acquire some necessary skills for prototyping with consideration to available manufacturing methods. The projects served as an introduction to designing, modeling, manufacturing, and then presenting their work. The CAD software was taught by experienced instructors, i.e., professional experts, and then online resources were provided to revisit the material and potentially expand their knowledge. During the projects, the students would have to engage in active learning, i.e., individually performing tasks and building their own knowledge and understanding of the available tools (NTU academic policy and practice). All guidance material would be available online at the NTU online learning system, i.e., NOW, and students could monitor their own progress in addition to the feedback they would be receiving.

The assessment would "encourage the students to position themselves as active learners" Aswin et al. (2015, p257) towards critical thinking and constructive judgment of their work. In this example, both formative and summative assessments require the students to perform the necessary tasks and then present them visually, which puts them in a position to view them as a third party and reflect. The portfolio representation would have to present their work and convey the skills that the student has used to complete the project. The tasks were directly linked to the learning outcomes as they were necessary for the effective use of the manufacturing method at hand. This is in alignment with the authors mentioned above and the concept of constructive alignment. The students having to exhibit their process within a portfolio allows them to view the process themselves and gives them a greater picture of the steps required for prototyping and communicating an idea and its implementation. Revealing the relevance of a taught topic can increase motivation. This was implemented in teaching mathematics (Deshler & Burroughs, 2013). However, it could also apply to other disciplines. Potentially, when students see the value of certain skills, they might be more motivated to acquire them. On this occasion, the students were able to experience a creative process from concept to prototype.

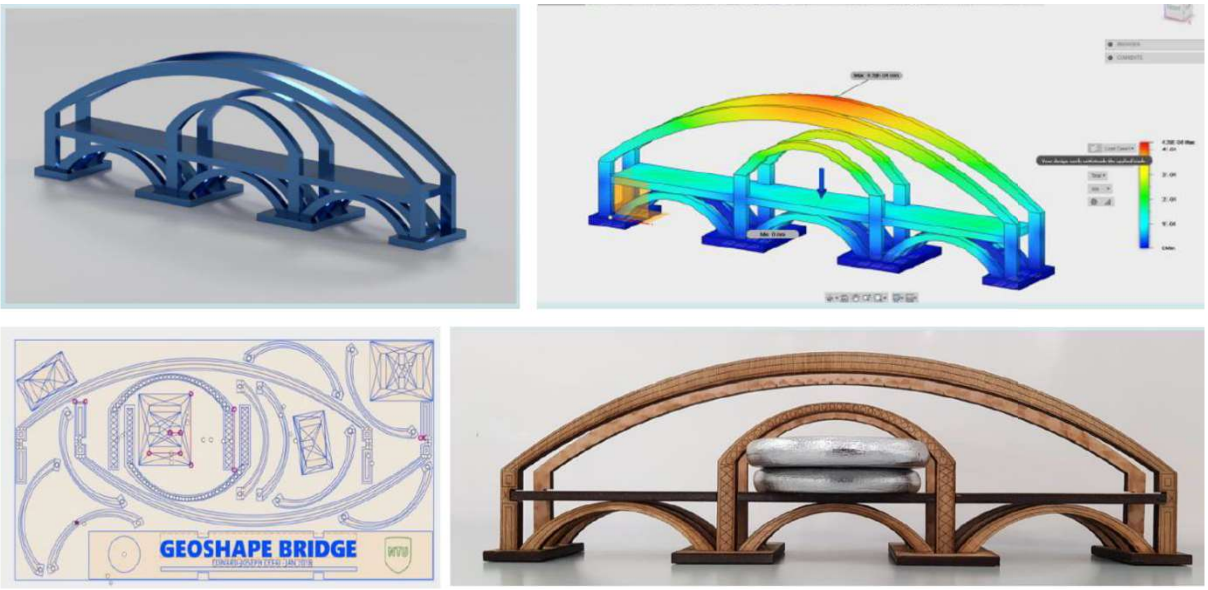

Figure 2. Example of a wooden bridge project (example of student work curtesy of Mr. Edward-Joseph Cefai)

The projects were designed to have several feedback opportunities for the students, e.g., the "Gateways," which are formative assessments. According to Hattie and Timperley (2007, p.86), the aim of feedback is "to reduce discrepancies between current understandings and performance and a goal." In addition, often in engineering, there are more than one ways to reach a goal or solve a problem. Feedback is also given in order to help students with practical difficulties or to point out a potentially more efficient way that a certain outcome could be achieved. Deconstructing the goals, examining the process, and identifying the activities towards progress, allows students to step back and reflect on their approach. More specifically, in this example, the software has a number of tools for designing structures, and a manufacturing process might have certain strengths and limitations. Helping the students use the tools in the best way, and designing with efficient manufacturing in mind adds another important dimension to their work. The intermittent formative assessments allow for picking up on weaknesses and working with the student towards developing new skills, early in the project, and before the summative assessment. This approach also provides the student with a general process of regularly evaluating their work and identifying weaknesses and areas for improvement. "Gateways" or checkpoints, i.e., scheduled points within a project were they can stop, reflect, and seek advice, is a process often used in professional engineering environments. This is in agreement with the NTU quality handbook were the inclusion of reflection and future development is promoted. Ashwin et al. (2015, p. 253) also point out the importance of "assessment for longer-term learning." Regular formative assessments in the form of discussion also assist students in developing a way of thinking that is related to their subject area. As was done in this example, and during the gateway discussions, the students were able to better understand the value of the process and enter into a dialogue with the tutors to clarify any ambiguity. This enhances the experiential learning aspect, which is important in practical skills. Practical elements can be more complicated to express in a written manner than it is to demonstrate and discuss. By understanding the important and relevant values and principles through experience, the students can develop or enhance their internal value system that feeds to their creativity. Developing an internal professional value system is important. Similarly, Hattie and Timperley (2007, p. 91) advocate "self-regulation." During the projects, tutors would try and provide suggestions for alternative ways to proceed for various tasks and explain the benefits and potential costs of each. Students were given choices rather than instructed on a single course of action. The purpose was to promote the development of an internal values system and empower the students with choice and ownership over their projects.

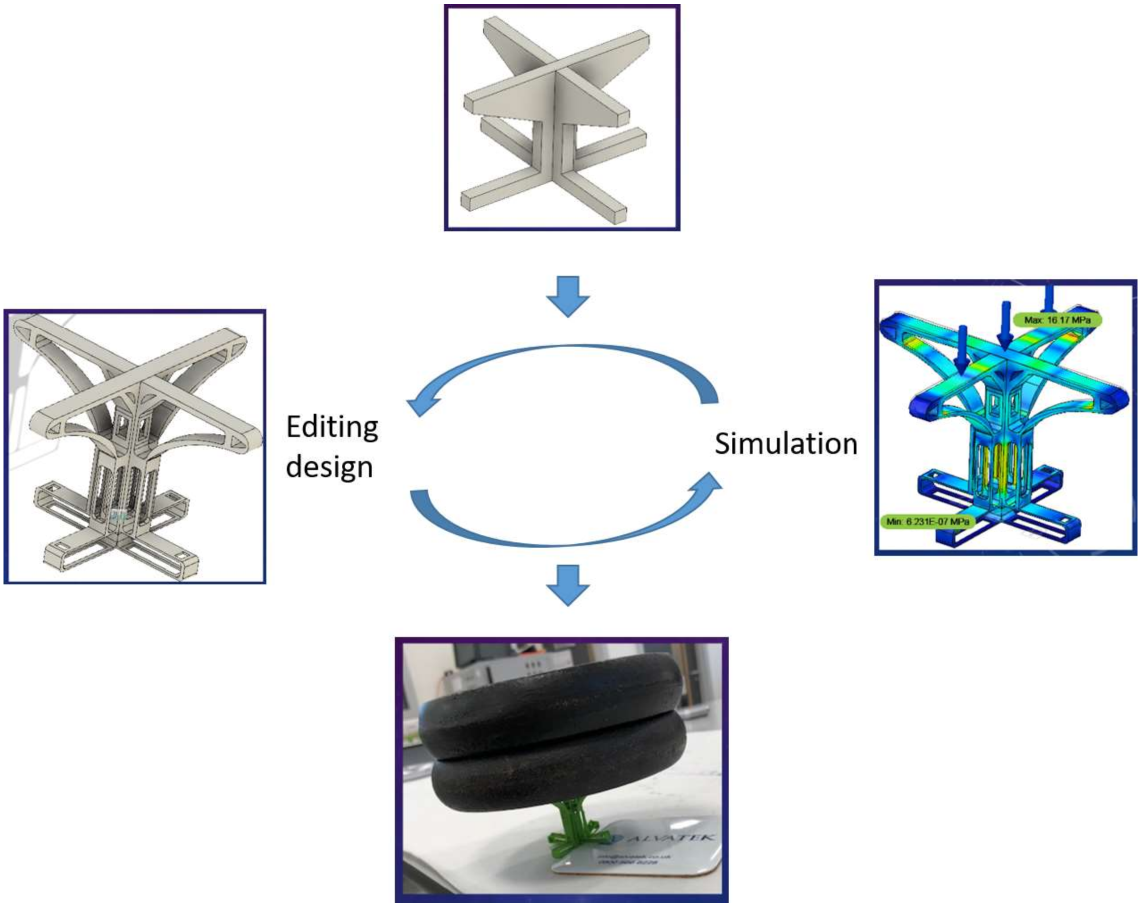

Figure 3. Example of the optimization process for the pier support structure (example of student work curtesy of Mr. Christie Teehan)

Students were encouraged to discuss and assist each other with practical difficulties in using the tools. The final day at the end of the term was also aimed at students seeing the work of their colleagues. Explaining a concept or discussing it amongst peers is a way to increase one's understanding of it and reveal weaknesses (Falchikov, 2013). Richard Feynman was a known advocate of using teaching for increasing one's own understanding. As he mentions, the questions of learners can reveal general ambiguities (Feynman & Leighton, 1992). Explaining something in a simple manner often requires depth in understanding it. Similarly, the students would have the opportunity to explain their design to their peers or tutors and assist others with their approach.

Student attendance was quite high for these sessions, and students seemed absorbed in their tasks. Even though some might have initially struggled with the software, they progressively improved. Students recognized that it was challenging; however, they also recognized the value of the process. On one occasion, a student said that it was "the most creative thing" she had ever done. Students would engage and ask questions, and often they would proceed to resolve the problems with the assistance of their peers. Whenever a prototype was manufactured, there was obvious interest from peers.

In terms of sustainability, biodegradable material, i.e., wood, was used for the bridge designs, and recently funds were secured in order to obtain the necessary equipment to recycle used 3D printed filament from older projects.

The level of competency in the software varied significantly in the beginning. However, the discrepancy seemed to reduce as the projects evolved. Tracking the progress between the formative assessments and the final product, there was a noticeable improvement (also noted by an academic observer). The progress was reflected in the evolution of designs and the choices made by the students, e.g., to focus on either aesthetics, efficiency, structural integrity. The submitted portfolios were of very good level, and the cohort's overall grade was relatively high. The process of having an idea and using modern software and manufacturing methods to bring into reality was appealing and helped generate interest that arguably increased the attendance. The portfolio and the manufactured structures gave the students, in addition to the completion of the module, a record of their process and a tangible object (e.g., the bridge) that would represent their experience and gained knowledge.

CONCLUSION

The practical elements of two terms of a first-year module were described above. The module was designed as an extended introduction to engineering. Various elements of CDIO principles and educational literature were implemented in the context of teaching and supporting learning, and assessments and feedback, for engineering topics. The elements included a reverse engineering project which provided the students with some context and allowed them to explore various relevant aspects of product cases. They were able to apply knowledge from other modules of the curriculum (e.g., fundamentals) in explaining the principles behind the function of the products and consider aspects such as product lifecycle and alternative, improved designs. The reverse engineering project was followed by two design exercises that included elements of CAD, CAE, CAM, and manufacturing as well as optimization concepts that were then physically tested. Active learning was central throughout the module.

The projects were structured in a multifaceted way, in terms of useful skills and technical knowledge. These elements were included within the assessments. The projects had several elements of typical engineering projects, including limited resources and also space for creative thinking—aspects of working within teams or individually were also elicited. Equitable individual assessment in team projects can be a challenge. However, some mitigating elements were added (e.g., peer reviews, task allocation summary) that could sometimes correspond to equivalents in professional environments. Overall the module was very well received and scored highly in student feedback surveys.

ACKNOWLEDGMENTS

Running practical modules can be resource-intensive. The author would like to acknowledge the assistance of the NTU technical staff and tutors during the laboratory sessions, and of prof. Neil Mansfield and several guest lecturers for delivering inspiring lectures.

BIBLIOGRAPHY

Ashwin, P., Boud, D., Coate, K., Hallett, F., & Keane, E. (2015). Reflective teaching in higher education. Bloomsbury Publishing.

Biggs, J. B. (2011). Teaching for quality learning at University: What the student does. McGraw-Hill Education (UK).

Bonwell, C. C., & Eison, J. A. (1991). Active Learning: Creating Excitement in the Classroom. 1991 ASHE-ERIC Higher Education Reports. ERIC.

Brame, C., & Director, C. A. (2016). Active learning. Vanderbilt University Center for Teaching,

Deshler, J. M., & Burroughs, E. A. (2013). Teaching mathematics with women in mind. Notices of the AMs, 60(9)

Deweck, O. L., Kim, I. Y., Graff, C., Nadir, W., & Bell, A. (2005). (2005). Engineering design and rapid prototyping: a rewarding CAD/CAE/CAM and CDIO experience for undergraduates. Paper presented at the Proceedings of the 1st Annual CDIO Conference, Kingston, Ontario, Canada,

Eppinger, S., & Ulrich, K. (2015). Product design and development. McGraw-Hill Higher Education.

Falchikov, N. (2013). Improving assessment through student involvement: Practical solutions for aiding learning in higher and further education. Routledge.

Feynman, R. P., & Leighton, R. (1992). " Surely you're joking, Mr. Feynman!": adventures of a curious character. Random House.

Haavi, T., Tvenge, N., & Martinsen, K. (2018). CDIO design education collaboration using 3D-desktop printers.

Hattie, J., & Timperley, H. (2007). The power of feedback. Review of Educational Research, 77(1), 81-112.

Prince, M. (2004). Does active learning work? A review of the research. Journal of Engineering Education, 93(3), 223-231.

Quist, J., Bhadani, K., Bengtsson, M., Evertsson, M., Malmqvist, J., Enelund, M., & Hoffenson, S. (2017). (2017). CDIO based engineering design and optimization course. Paper presented at the Proceedings of the 13th International CDIO Conference, Calgary, June 18-22, 2017. 298-314.

Schwartzman, L. (2010). Transcending Disciplinary Boundaries. Threshold Concepts and Transformational Learning, , 21-44.

Thomas, L., & May, H. (2010). Inclusive learning and teaching in higher education. York: Higher Education Academy, Tynjälä, P. (1999). Towards expert knowledge? A comparison between a constructivist and a traditional learning environment in the University. International Journal of Educational Research, 31(5), 357-442.

ZU, H., TIAN, M., SONG, Y., & YAN, Y. (2012). Exploration and Practice on Reverse Engineering Comprehensive Innovation Training Based on the CDIO Mold. Value Engineering, 2012(27), 57.

BIOGRAPHICAL INFORMATION

Dr Petros Siegkas is a senior lecturer at the NTU Department of Engineering and has been involved in teaching Innovation and Engineering Solutions, Industrial Design and Product Case Studies, and Sport Technology. Research interests include solid mechanics and engineered materials.

Corresponding author

Petros Siegkas
Nottingham Trent University (NTU)
Department of Engineering
Clifton Campus, College Dr, Clifton,
Nottingham NG11 8NS UK
Petros.siegkas@ntu.ac.uk