TRAINING WELL-EQUIPPED DESIGN-READY ENGINEERING PROFESSIONALS

Remon Pop-Iliev and George Platanitis
Faculty of Engineering and Applied Science
UOIT-University of Ontario Institute of Technology

ABSTRACT
Industrial recruiters are increasingly seeking engineers that possess a unique combination of competencies that include creative design engineering skills, sound technological knowledge, hands-on shop floor experience, and clear understanding of business-related issues. A design-intensive undergraduate engineering curriculum has been developed in a brand new entirely laptop-based university around three core design courses, a program-specific capstone design course, and a design thesis. These courses were designed to provide a continuum of carefully crafted project-based team and individual design engineering experiences. The capstone design course serves as one of the final preparations for students entering into industry eager to assume the role of the new kind of preferred "hybrid" design-ready engineering profile. This paper explores the role of a capstone design course that has been developed at UOIT with a sensitivity to respond to the emergence of this demand. It also proposes a rubrics-based method of guidelines useful for clearly assigning capstone design projects as well as for assessing and evaluating students' performance on such projects in a fair and consistent manner.

Keywords: Engineering and design education, Capstone design, CAD/CAM/CAE

1 INTRODUCTION

Whenever feasible, but especially during the final year of their engineering program, students should be exposed to solving real-world design engineering problems preferably within settings that closely emulate industrial engineering situations. Engineering curricula usually accomplish this by developing a capstone design course where students divided into teams undertake different design projects that provide them with a unique opportunity to apply knowledge and technical skills learned in their previous years of study to a design problem. At UOIT, by the time they graduate, engineering students are given several opportunities to directly experience both team-based and individual design engineering project activities. These projects normally involve demands for the transformation of information such as objectives and constraints into the design and development of an engineering structure which is capable of fulfilling these objectives. For example, students specializing in the area of manufacturing may be required to develop manufacturing systems and/or processes intended for the fabrication of given or newly-designed engineering artifacts. Students are required to provide detailed analyses of their design and validate whether requirements were met through prototyping, testing, and correct implementation of their design specifications. Thereby they become well-equipped to quickly adopt and master state-of-the-art CAD/CAM/CAE tools and technologies as a day-to-day routine [1-4].

2 PERTINENT LITERATURE

2.1 Capstone Project Models

The CDIO (Conceiving-Designing-Implementing-Operating) approach [5-7], may serve well as a model for assigning a capstone project in the fourth year of an engineering design program. This approach was developed through collaborative efforts of several academic institutions developing a model for engineering education through a joint four-year program. The purpose of this program was to provide students with an education that stresses fundamental engineering systems and how to sustain productivity, innovation and excellence.

The CDIO approach defines the levels of creating an engineering design as follows [5]:

- *Conceive* – defining the need and technology; considering the enterprise strategy and regulations; and developing the concept, architecture, and business case.
- *Design* – creating the plans, drawings, and algorithms that describe what will be implemented.
- *Implement* – transforming the design into the product, including manufacturing, coding, test and validation.
- *Operate* – using the implemented product to deliver the intended value, including maintaining, evolving and retiring the system.

Such an approach allows students, for example, to learn about conceiving a product as start-up companies do, as well as exercise engineering reasoning to solve problems that are open-ended and ill-defined. In conjunction with this type of program, an evaluation method is necessary to gauge the level students have applied their knowledge.

Kundu and Raghunathan [8] point out the need for design education to meet industry requirements and propose an approach of interdisciplinary interaction between academic departments and industry contacts, creating a 'Virtual Company' for the design of a small aircraft, including production considerations.

2.2 Rubrics as Evaluation Roadmaps

A rubric based on the recently developed ICE (Ideas, Connections, and Extensions) philosophy [9] is developed herein to provide an evaluation roadmap for the capstone course to gauge students' level of understanding and application of engineering knowledge. Each component of ICE represents a level of application – **I**deas being just the basic understanding of a concept, **C**onnections describing the ability of one to relate knowledge and articulate relationships among elements of the fundamentals, and **E**xtensions showing the ability of one to take knowledge and apply it to a novel situation. The advantages of ICE rubrics have been cited by Colgan [10] versus "shareware" rubrics, the latter of which are considered relatively poor tools for evaluating students. The ICE rubrics eliminate fuzziness in descriptions between categories, as well as student behaviours and creative expression from evaluating a student's understanding of a given subject.

3 THE CAPSTONE DESIGN EXPERIENCE AT UOIT

3.1 Course Importance

The capstone design course represents a culminating major design experience for engineering students at UOIT. The paramount goal of the course is to allow senior-level students to integrate their engineering knowledge and produce useful engineering creations by successfully implementing appropriate engineering design methods into creatively solving design problems conditioned with realistic constraints. This course is offered during the fall semester and it lasts 13 weeks. It is worth 3 credits. The course delivery is organized through two 75-minute lectures (design engineering and product development methodologies and tools) and one tutorial per week (project consultations).

3.2 Course Objectives

There are three important objectives in the course which were given in the course outline and are as follows:

- Expose engineering students to successfully implementing appropriate engineering design methods to creatively solve design problems conditioned with realistic constraints while using state of the art engineering CAD/CAM/CAE tools and while incorporating engineering standards.
- To train design engineering students to focus on a variety of considerations with respect to their designs, such as economic; environmental; sustainability; manufacturability; ethical; health and safety; social; and political.
- To focus on improving the students' soft skills that include: working in teams, project planning and scheduling, giving presentations, and dealing with uncertainties in a professional manner.

3.3 Learning Outcomes

In the capstone design course, students gain proficiency in: (i) applying principles of mathematics, science, and engineering science to solve problems, (ii) demonstrating the ability to understand and design a useful product in the context of solving a design problem, (iii) working effectively as part of a team, and (iv) communicating effectively design contents.

3.4 Typical Capstone Design Project Scope

A wide range of engineering design-related product, process, technology, or system development topics may be covered in this course, including study of an engineering design topic of interest to a group of students that may be proposed by them, or an original design project proposed and sponsored by an industrial partner, or a design project on a topic proposed by the academic advisor. The following sample description is provided to outline the level and scope of a typical capstone design project:

> *Design, build a prototype, and use it to demonstrate the functionality of an innovative non-fixed transportation device that can load, move through the air, and safely unload a payload of 4 unopened pop cans from point A to point B (min 10 m distance) without touching the ground surface. Design a suitable manufacturing system for device production. Assume additional constrains if needed. Provide all necessary paperwork, engineering calculations and documentation for both the device and its manufacturing system. Provide a project poster as well as a press release.*

3.5 Required Deliverables

Each group of 4-5 students is required to submit the following 7 deliverables with respect to their project, which forms in total 40% of their course grade:

- **Requirements Document (5%):** Clearly describes the project requirements, demonstrating that students understand the problem they are trying to solve.
- **Project Management Plan/Schedule (5%):** A MS Project 2003 document describing project timelines.
- **Specification/Design Document (5%):** Clearly specifies the solution and includes a design. Also demonstrates the feasibility of the design.
- **Midterm Progress Report (5%):** Includes the engineering analysis and/or motion simulation of the design demonstrating successful application of knowledge from

previously completed courses.

- **Prototype Demonstration (10%):** Demonstrates important features and functions of product for customers and is used to determine any outstanding needs as well as suggest design improvements.
- **Test Plan Document (5%):** Demonstrates validation of requirements and verifies application of specifications in design via a test case.
- **Practice Presentation (5%):** Feedback provided to help students prepare for their final presentation and prototype demonstration.

The final submission, worth 60% of the total course mark, consists of a project report write-up for both the device and manufacturing facility. It includes a logbook describing dates of group meetings, interaction details, literature and patent surveys, addressing issues such as brainstorming, concept generation, freehand sketches, communication via e-mail, etc., design decisions made with reasoning and rationale implemented, design description, and owner's and assembly manual. The final submission also includes oral presentation overheads, a physical proof-of-concept prototype, the poster, and press release, as well as a self-and-group self evaluation sheet.

3.6 Assessment and Evaluation

An evaluation guide is proposed using the course requirements. These requirements were used to create the rubric, which will serve as a roadmap for future offerings of the course in evaluating students' work, as well as to determine to what level students have applied their knowledge and skill in each of the requirements for this and similar fourth-year engineering design courses. Table 1 outlines the proposed rubric intended for assisting instructors with the assessment and evaluation of capstone design projects.

Table 1: Rubric Developed for the Assessment and Evaluation of Capstone Design Projects

Elements	Ideas	Connections	Extensions
Logbook	- Provides chronological order of meetings and assigned tasks to members - Provides project scope info	- Clearly outlines steps to show design progression - Outlines intended goals to achieve - Relates goals to requirements	- Includes email correspondence with step-by-step, daily log - Provides daily learning and application
Requirements Document	- Lists requirements of design and considers customer needs	- Relates customer needs to design requirements - Distinguishes necessities versus luxuries	- Suggests optimization of design methods to accommodate needs - Considers additional features useful to customer
Project Management	- Provides project schedule of events and submissions	- Organizes plan/schedule by milestone deliverables	- Considers consequence of late submissions and plans for advanced completion of deliverables (margin of error)
Specification/Design Document	- Provides outline of approach to design problem	- Shows several possibilities of solutions based on design requirements	- Considers iterative nature of design and incorporates "what if" branches to flowchart
Midterm Design Document	- Provides minimal amount of background search, concept generation, and design ideas	- Shows coherent information flow from significant background search to possible design solution	- Demonstrates preliminary results of final design - Identifies plan for further design refinements - Relates results to original requirements
Test Plan Document	- Identifies possible experiment for validating design	- Uses analytical solution to hypothesize behaviour of actual system - Verifies behaviour by experimentation	- Considers possibility of unexpected behaviour as related to predicted and measured results of testing procedure - Suggests design refinements for improving robustness
Background Search	- Lists products and available patents - Provides general pictures of existing designs and products	- Discusses pros and cons of existing patents and products - Presents diagrams clearly and outlines key functions and merits	- Relates existing products to needs of new design - Improves design based on merits and deficiencies of existing patents and products -Provides critical review of literature covered
Brainstorming	- Discusses needs and comes up with sufficient ideas to satisfy them - Provides organized list of ideas with simple freehand sketching	- Relates existing ideas to create new concepts - Exhibits creativity in satisfying customer needs	- Considers additional features to improve device - Provides logical sequence in developing new ideas - Strives to come up with wild innovative ideas while exercising caution about feasibility and manufacturability - Strives to generate energy-saving related ideas
Sketching Ideas	- Suggests several designs and provides sketches - Shows organization of ideas	- Shows how each requirement fits together - Labels components to identify key features and provides description - Draws freehand sketches of realistic proportions	- Provides realistic visualization - Shows approximate dimensions - Clearly describes features and functions - Takes into consideration feasibility and manufacturability of design
Concept Development and Screening	- Compares existing concepts - Derives new design from best one - Demonstrates moderate use of the House of Quality	- Discusses feasibility of each concept - Provides organized charts for evaluating designs - Generates modular concepts - Proficient user of House of Quality	- Addresses the entire system (global picture) - Uses multiple interconnected Houses of Quality - Considers limits and other operation environment factors - Makes reasonable assumptions for economical design - Cchooses the best concept using appropriate tools

3-view Drawings	- Provides 3 views of each part designed - Shows some dimensional information - Considers relationship between drawings	- Adheres to ANSI standards - Applies adequate dimensioning and tolerances to build parts properly - Uses some GD&T information - Labels individual parts and associates them with assembly and BOM	- Displays clear dimensions and understands tolerance and GD&T application - Understands how drawings related and parts fit together - Uses additional views to provide clarification details, scaled adequately
3D Renderings of Final Design	- Shows physical makeup of components pictorially using realistic rendering	- Clearly labels features - Highlights key functions and features	- Uses exploded views to show how components fit together and relates to functions - Provides functional views with components positioned accordingly
CAD Package proficiency (NX4)	- Demonstrates ability to create realistic 3D renderings - Understands extended use life of product	- Shows proficiency in designing key features and associates them with required functions - Understands cyclic use of product and identifies maintenance points	- Manipulates shapes of varying complexities to create fully functioning virtual models - Relates life cycle of product to material properties of components and optimizes design for extended use and minimal maintenance
Motion simulation package proficiency (MSC Visual Nastran)	- Creates motion simulation to validate design requirements - Identifies problems in design of moving parts	- Improves design for efficient parts movement - Considers required restrictions to part motion	- Manipulates design to optimize motion of moving parts using minimal energy/actuator inputs - Addresses and analyses serviceability and maintenance issues
FEM package proficiency (NX Nastran)	- Uses computed stresses and strains to select appropriate materials for components	- Considers design requirements and constraints in selecting materials while maintaining optimal functionality - Employs appropriate boundary conditions for computations	- Determines failure modes and considers modes such as bending and twisting of components in dynamic analysis
Assembly Drawing	- Shows components assembled in 3D drawing with adequate clarity	- Provides component labels with respect to parts list - Uses exploded views to show assembly of parts	- Shows relationship of components in assembly to individual drawings - Distinguishes standard and custom parts. - Draws components in functional positions
Bill of Materials	- Lists parts used for assembly - Provides part numbers and manufacturer (std.)	- Provides part nos., quantities, and corresponds each to assembly - Identifies standard and custom parts - Understands subassembly and full assembly relationships	- Provides sizes and material for standard and custom parts - Understands relationships of parts with product function
Tolerances	- Provides generalized tolerances - Understands use of tolerances for dimensioning/sizing	- Tolerances related to fits of parts in assembly - Considers manufacturability of components when tolerancing - Understands the relationship between tight tolerancing and manufacturing cost increase	- Understands different types of tolerances with respect to functionality of components (clearance, interference, etc.) - Uses largest possible tolerances that allow the device to function properly - Provides additional GD&T information and understands relationship to acceptability of designed feature
Owner's and Assembly Manual	- Outlines basic procedure for assembling product - Provides advertisement-like renderings	- Provides assembly instructions and relates components to functions in a user-friendly manner - Provides useful renderings to assist with instructions	- Considers product use in terms of safety and environmental friendliness while providing operation and assembly instructions - Uses renderings to highlight key features and product functions and relates them to assembly and operation
Prototype Demonstration	- Builds reasonable scale presentation of design	- Builds working model capable of essential functions	- Develops working model capable of robust functionality for range of environments
Manufacturing System for Product	- Suggests system capable assembling final design	- Considers restrictions of assembly production to available labour and human capability	- Develops user-friendly system with automated features to assist human labour in product assembly
Practice Oral Presentation	- Provides rundown of design procedure	- Summarizes design using mix of information slides and renderings - Considers time restriction	- Relates key functions to requirements - Distinguishes requirements and additional features - Uses animations to demonstrate functions of design
Oral Presentation	- Discusses ideas for final design - Outlines methodology used - Limited implementation of feedback from practice presentation	- Provides highlights of key features and functions - Uses 3D renderings to present functions - Makes use of feedback from practice presentation	- Makes use of animations to show assembly and function - Demonstrates functioning prototype - Organizes presentation from practice feedback and makes additional own improvements
Poster	- Provides information and renderings of final design	- Organizes information to clearly outline design problem and show approach to solution	- Shows realistic 3D renderings and uses exploded assemblies to relate parts and functions - Outlines future direction of design
Press Release	- Shows demonstration of functioning device	- Connects functions of device with customer needs - Enthusiastically promotes device	- Demonstrates satisfaction of design with respect to robustness, economics, and environmental considerations
Report Write-up	- Outlines basic categories/sections - Provides activity summary and problem understanding - Describes design process	- Connects categories throughout report - Provides coherent descriptions - Shows relationships between customer needs and design	- Provides detailed explanations and expands to new ways of thinking - Draws conclusions regarding design and suggests further research - Provides design justification - Shows design optimization to maximize incorporation of customer needs

3.7 Students' Comments

"The course is a great deal of work, but does an excellent job at preparing us for the personal thesis. The layout of the course was excellent and allowed us the time to fully complete a well laid out project that encompasses all the things we've learned through the past 3 years."…"The content of this course will prove later in industry to be very helpful."

4 CONCLUSIONS

The development of a capstone design course is a key component in the engineering curriculum and is the culmination of the entire engineering design experience of undergraduate engineering students. A chart with rubrics was proposed as an assessment and evaluation roadmap for capstone design projects. The rubric outlines three levels of learning according to the ICE methodology for each deliverable and the various important components expected from students. Instructors may find these rubrics useful to assist students with understanding the expectations of the course for satisfactory marks and/or use them as a consistent guide to grade the submitted projects.

REFERENCES

[1] Nokleby S.B. and Pop-Iliev R., "A Design Challenge-Incorporating Design into the First Year Engineering Curriculum," *Proceedings of The 2nd CDEN International Conference on Design Education,* Kananaskis, AL, Canada (2005)

[2] Pop-Iliev R. and Nokleby S.B., "Concurrent Approach to Teaching Concurrent Design Engineering," *Proceedings of The 2nd CDEN International Conference on Design Education,* Kananaskis, AL, Canada (2005)

[3] Pop-Iliev R. and Nokleby S.B., "Cross-Course Integrated Group Design Projects: 1 + 1 = 11," CDEN 2006, *Proceedings of The 3rd CDEN/RCCI International Design Conference,* University of Toronto, ON, Canada, pp. 303-308 (2006)

[4] Pop-Iliev R. and Nokleby S.B., "Designing Competent Design Engineers," *Proceedings of TMCE 2006,* Ljubljana, Slovenia, ISBN 961-6536-04-4, pp. 97-104 (2006)

[5] Brodeur, D. R., Crawley, E. F., Ingemarsson, I., Malmqvist, J., Östlund, S., "International Collaboration in the Reform of Engineering Education," *American Society of Engineering Education,* Session 2260, Montreal, QC, Canada, (2002)

[6] Gustafsson, G., Newman, D. J., Stafström, S., Wallin, H. P., "First-year Introductory Courses as a Means to Develop Conceive-Design-Implement-Operate Skills in Eng. Education Programs," *SEFI Conference, Florence,* Italy (2002)

[7] Armstrong, P. J., Kee, R. J., Kenny, R. G., and Cunningham, G., "A CDIO Approach to the Final Year Capstone Project," *1st Annual CDIO Conf.*, Kingston, ON (2005)

[8] Kundu, A. K. and Raghunathan, S., "A Proposition in Design Education with a Potential in Commercial Venture in Small Aircraft Manufacture," *Aircraft Design*, Vol. 3, pp. 261-273 (2000)

[9] Young, S. F., and Wilson, R. J., *Assessment and Learning: The ICE Approach*, Winnipeg: Portage & Main Press (2000)

[10] Colgan, L., "Out of the Mouths of Babes," OAME/AOEM Gazette, (2003)

ACKNOWLEDGEMENTS

The authors would like to thank the Natural Sciences and Engineering Research Council (NSERC) of Canada, General Motors Canada Limited (GMCL), and UOIT for financially supporting UOIT's Design Chair budget, part of which supported this research work. The authors are also grateful for the hardware and software provided by the PACE (Partnership for the Advancement of Collaborative Engineering Education).

Dr. Remon POP-ILIEV
Faculty of Engineering and Applied Science, University of Ontario Institute of Technology
2000 Simcoe St. N., Oshawa ON, L1H 7K4 Canada
remon.pop-iliev@uoit.ca
+1 (905) 721 8668 x2553