Cross-Course Integrated Group Design Projects: $1 + 1 = 11$

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Abstract

Design is the ultimate integrating activity in an engineering program. Design engineering is exactly the coherent thread that correlates the various engineering and scientific subjects taught. Integrated courses that take basic engineering concepts and connect them to related concepts in other subject areas provide superior learning experiences for students and help produce engineers who can better understand the “global picture.” As a test of the above, and with an objective to advance the theory of teaching design engineering in an integrated fashion, the authors of this paper launched a pilot program at the University of Ontario Institute of Technology (UOIT).

1. Introduction

Design engineering is being equally described in the literature as the “enabler of innovation”¹ as well as “an iterative decision-making process”². The former statement associates design engineering with the design and development of new and improved products, processes, and technologies that satisfy specified requirements in an effective and efficient manner, whereas the latter insists on the application of basic science, mathematics, and engineering sciences to convert resources optimally to meet a stated objective.

It follows from both definitions that the role of engineers is to design, i.e., to create a product or a system to solve some initially defined set of needs, and then implement the process of determining how a design will function and whether or not a design meets the required needs or whether the needs require

further redefinition and adjustments, a process called analysis.

It is very important for this paper to emphasize that design and analysis are not mutually exclusive and that in order to create and refine a design, one must know how to analyze it. Interestingly, however, although design and analysis are not mutually exclusive, the majority of current methods for teaching engineering students would indicate that they are.

Unfortunately, the identified problem above is not new. Let the quote presented below, written by a Lockheed engineer I. J. Kubasak in 1980, and selected because its contents seem to have an evergreen value, serve as a quite old example of related criticism of engineering education.

“The majority of engineering professionals in industry generally will agree that historically, design engineering has been a very important component within the framework of the engineering profession. Yet, it seems to be the least regarded, and perhaps the least understood function in the repertory of engineering skills. What is worse, many engineering schools have deemphasized the design-oriented subjects and are favoring the more glamorous research and science courses. Our industry now is looking for engineering graduates who have learned to couple their academic training with the capability to design useful structures and systems, which is the essence of design engineering. Whatever reasons the schools have for the reductions, they should be carefully reevaluated because all engineers need to understand the design process in order to be prepared for successful careers in the industrial world [1].”

¹ Based on CEAB, NSERC, and CDEN’s definitions of design engineering.

² Based on ABET’s definition of design engineering.

2. Background

Design engineering could be also regarded as a process of continuous refinement of solutions of not always completely well defined problems.

The fundamental elements of the design process comprise the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation.

In this context, ISO standards distinguish and consider the processes of Design Review, Design Verification, and Design Validation independently, although they can be combined into a single step. It is also important to note here that the terms verification and validation are used interchangeably in papers and texts, although there are distinct differences in their terminology.

As stated in ISO 9004-1 [2] Design Review should be "distinguish from a project progress meeting" because the main purposes for the Design Reviews are to "identify and anticipate problem areas and inadequacies, and initiate corrective actions". Design Reviews can be performed by the means of discussion, comparisons and auditing. Testing, experiment or demonstration is not a must for a Design Review.

On the other hand, Design Verification should be done after a number of Design Reviews. Verification is defined as "The process of evaluating a system or component to determine whether the products of a given development phase satisfy the conditions imposed at the start of that phase." It includes all the elements of Design Review but also includes some data and objective reviews such as alternative calculations, testing and demonstrations by the means of models or prototypes.

After a number of Design Verifications are done, Design Validation can be performed. Validation is defined as "The process of evaluating a system or component during or at the end of the development process to determine whether it satisfies specified requirements." As stated in ISO 9004-1, Design Validation can be done by the means of fault or risk analysis. Testing of a number of samples is recommended so that adequate statistical confidence can be provided while testing the designed product in controlled conditions or environment such as the proposed usage environment. If the proposed products can be used in different ways, several Design Validations should be done. Similar to Design Verification, independent Design Validation is recommended.

Finally, after the validation step confirms that the specifications are consistent with the customer's requirements, the continuous solution refinement cycle may begin. It may include any kind of readjustment of the set of customer's requirements in order to better fit the actual design or thereby demand improved design solutions that were not even conceivable with the initial set of customer's requirements.

2. Problem Statement

Engineering students take a large number of engineering courses, taught to significant depth and complexity, where they learn to analyze. At the same time, the students take isolated courses in design, so that integration of these subject areas into a coherent thread is seldom considered. Thereby, students normally get little opportunity to experience the interconnection between design and analysis.

In terms of best practices for teaching engineers design, the trend is to provide a continuum of design related courses. For example, within the mechanically oriented engineering programs at University of Ontario Institute of Technology (UOIT), there is a continuum of design courses of a general nature which have increasing levels of difficulty so as to match the pace at which students grasp engineering knowledge:

- Year 1: Engineering Graphics and Design
- Year 2: Concurrent Engineering and Design
- Year 3: Computer-Aided Design
- Year 4: Design Thesis

The above general courses are complemented with a variety of program-specific capstone design engineering courses:

- Automotive Component Design
- Automotive Systems Design
- Machine Design
- Manufacturing Systems Design
- Mechanical Systems Design
- Mechatronic Systems Design
- Thermofluids and Energy Systems Design

The engineering curricula at the Faculty of Engineering and Applied Science (FEAS) at UOIT have been carefully designed with the view that team-based design projects improve motivation and engagement in achieving learning objectives. Therefore, it is and it will be common in all design engineering-based courses at FEAS to have the integration of all the topics covered throughout the course achieved through major team-based design

and CAD modeling projects with increasing complexity [3-5]. However, before the presently described attempt, there was no integration between the various analysis courses (e.g., kinematics and dynamics of machines, solid mechanics, thermodynamics, etc.) and the above continuum of design courses at UOIT.

The motivation of the authors of this paper lies in addressing this problem in order to attempt to advance the theory of teaching design engineering in an integrated fashion.

The immediate goal of this effort is to break down the barrier created by traditional course offerings and provide a novel method of delivery that will provide integration between design and analysis courses.

The primary objective is to create a close-to-real-life practice of training engineering students in implementing design engineering fundamentals using CAD tools by combining it with implementing engineering analysis and decision-making fundamentals using CAE tools in an integrated cross-course manner and in a multifunctional team environment.

3. Applying the Concept of Integration

Aiming towards implementing the best practices in preparing effectively graduates with useful workplace engineering skills, an integrated group term project was conceived developed and assigned to simultaneously serve two third-year (fifth-semester) courses: ENGR 3030U: Computer Aided Design (principal instructor: Professor Remon Pop-Iliev) and ENGR 3270U: Kinematics and Dynamics of Machines (principal instructor: Professor Scott Nokleby). Having a common project across two courses will allow for the level and depth of the project to be increased as opposed to having separate smaller projects in each class. It is also expected that students will thereby learn more efficiently that design and analysis are not mutually exclusive.

Course Description of ENGR 3030U. Geometric/solid modelling, computer graphics and feature modelling. Finite element analysis, discretization and modelling, selection of elements, treatment of boundary conditions, checking for accuracy. Design optimization, optimization models, algorithms for optimization. State-of-the-art software packages will be introduced and case studies will be employed. 3 credits; 4 hours of lectures and 2 hours of laboratories per week.

Expected Learning Outcomes of ENGR 3030U.

Students who successfully complete the course should have reliably demonstrated the ability to: (i) understand the role of a CAD/CAM/CAE system in the context of the product cycle; (ii) represent curves and surfaces using parametric equations; (iii) understand key issues in CAM and the data associativity benefits of CAD/CAM systems; (iv) demonstrate proficiency with a commercial CAD/CAM/CAE system to represent and solve real engineering problems; and (v) the application of CAE tools (e.g., finite element analysis) and rapid prototyping machines in design evaluation. The hands-on practice in the use of computer-aided design and drafting tools will give students confidence in the use of these tools in their subsequent courses and for employment.

Course Description of ENGR 3270U.

Classification of mechanisms; velocity, acceleration and force analyses; graphical and computer-oriented methods of analyses; balancing, flywheels, gears, gear trains, and cams. Introduction to Lagrangian dynamics; Lagrange's equations of motion; Hamilton's equations, and Hamilton's principle. 3 credits; 3 hours of lectures, 2 hours of laboratories, and 1 hour of tutorials per week.

Expected Learning Outcomes of ENGR 3270U.

Students who successfully complete the course should have reliably demonstrated the ability to: (i) know the various types of mechanisms in common usage, and how to classify for purposes of analysis; (ii) understand the basic concepts of velocity, acceleration and force, and their interaction with each other in kinematics and in dynamics; (iii) solve problems in kinematics and in dynamics by use of graphics and by use of computer-oriented methods; (iv) understand the principles of balancing rotating components such as wheels and shafts; (v) understand the need for flywheels and be able to design them for various applications; and (vi) carry out analysis of common engineering components such as gears, gear trains, and cams.

Although the main themes of these two courses are distinct and the courses are quite different, the scope of the major term projects in both courses were essentially focused on advanced discrete product design, which includes theories and methods underlying the conceptualization and creation of new products, engineering and decision analysis, as well as team management. These similarities between the courses provided unique opportunities for cross-course integration.

4. The Integrated Group Term Project

In general terms, the assigned project required students to design and analyze a mechanism that will be dedicated to perform some pre-determined desired task within a provided set of constraints. Students were expected to use the knowledge and various tools they will be introduced to in ENGR 3030U Computer-Aided Design (or have been previously introduced to in ENGR 3200U Engineering Graphics and Design and ENGR 2310U Concurrent Engineering and Design) to conceptualize, design, document, and build the mechanism using a suitable design kit (LEGO Mindstorms®). The project was also used to tie together concepts developed in both classes. At the same time, students will be using their knowledge of mechanisms gained from ENGR 3270U Kinematics and Dynamics of Machines to analyze, optimize, and refine their design.

Project Objective. Design a mechanism that will handle wheels in a required fashion within a given industrial layout.

Assigned Tasks. Three conveyor belts are delivering different size wheels. Figure 1: shows a sketch of the layout. The wheels need to be picked up from one of the three input conveyors, rotated 180° around an axis parallel to the plane of the shop floor and stacked on a holder on the output conveyor using a mechanism that students are required to design. Two wheels of the same size must be stacked one atop the other on the output conveyor. Both the input and output conveyors work in an indexing fashion, i.e., they are not continuously moving, but move only when a new wheel needs to be positioned for pick-up on one of the input conveyors or when two wheels have been staked on the output conveyor. In order to ensure that the output conveyor moves once two wheels have been stacked on the holder, some form of mechanical counting mechanism needs to be designed and used.

Up to 5% bonus marks were promised to be given in each course if the proposed mechanism was capable of servicing more than one of the input conveyors.

Students were required to form and work in groups common to both classes. The success of the groups was judged on the merits of their overall design and analysis documented and presented.

It was recommended to the students that they use some form of linkage as their mechanism to achieve the desired task. The mechanism should be kept as light as possible, yet each component should have a

minimum static factor of safety of 2.5 and a maximum static factor of safety of 5 (anything over 5 will be considered over engineered). In addition to the above, a mechanical device for counting the number of wheels stacked on the output conveyor also needed to be designed along with the holder used for holding the stacked wheels in place on the output conveyor.

Figure 1: Sketch showing the layout of the three input conveyors and one output conveyor that should be serviced by the newly-designed device.

Assigned Set of Project Constraints. A FEA (Finite Element Analysis) of the design must be performed along with a simulation of the mechanism using MSC.visualNastran 4D. All FEA/simulation results must be verified with sample calculations. HINT: Select the appropriate materials and perform strength calculations based on the loads and stresses assumed.

The wheel handling mechanism must be designed to handle the real sized wheels and maximum weight of 50 kg. A proof-of-concept scaled prototype of the design must be constructed using the provided LEGO Mindstorms Kit. Students were allowed to use any of the parts in the kit, including the various sensors, but no additional parts were allowed to be added. The functionality of the prototype had to be demonstrated during the oral presentation.

Students were cautioned not to design their actual mechanism as a bunch of LEGO pieces enlarged! HINT: Use Unigraphics NX3 to design a real life product - not a LEGO-based mock-up.

In a deliberate attempt to mimic the interpersonal realities attributed to real workplace design teams, the students were advised that, except in extraordinary circumstances, fluctuation of the

members of the groups during the duration of the term would not be permitted. Thereby, like in a real-life workplace scenario, students will have to learn to collaborate in a decent fashion even with people they would rather wish to avoid.

Suggested Resources:

- Laptop equipped with:
 - Unigraphics NX3
 - NX Nastran
 - MSC.visualNastran
 - MATLAB with Optimization Toolbox
 - Microsoft Office
- LEGO Mindstorms Kit.

Marking scheme. The overall integrated group term project was marked for: completeness, originality, technical merits, clarity, quality of engineering reasoning, calculations, drawings and manual, and the overall robustness of the adopted design concept. The following is the breakdown of the marks per both project segments and course.

1. Engineering Project Report:
(Max: 18% ENGR 3030U + 12% ENGR 3270U)
2. Demonstration of a full functioning prototype using the provided LEGO Mindstorms® design kit.
(Max: 2% ENGR 3030U + 8% ENGR 3270U)
3. Oral Presentation
(Max: 5% ENGR 3030U + 5% ENGR 3270U)

Sample Results. Figure 2 shows an example of a group's final CAD design along with a picture of their Lego Mindstorms® proof-of-concept prototype. Note that the role of the proof-of-concept prototype was to verify the functionality of their design, not to be an exact model of their proposed design.

Figure 3 shows another example of a group's final CAD design. The figure also shows an example of the FEA analysis performed. Note that all FEA results had to be verified with hand calculations.

It should be noted here that the introduction of LEGO Mindstorms® design kits provided an equal starting point to all student design groups in responding to design challenges and proved to have had a strong impact on improving their visualisation and prototype building skills. On the other hand, exposing student groups to performing in class presentations improved their organization, presentation and time management skills, and proved beneficial for gaining workplace-like exposure and invaluable experience.

Figure 2: a) CAD model of final design; b) poof-of-concept prototype. Group members: Hasan Ahmed, Theodora Biney, Zak Dennis, Pierre Hinse, Adam Kraehling, and Samveg Saxena.

Figure 3: a) CAD model of final design; b) FEA analysis. Group members: Steven Anderson, Kyle Dabrowski, Daniel Lau, Kyle Mullin, Jason Parise, and Philip Peco.

5. Pedagogical Elements Achieved

The cross course integrated group design project had a number of pedagogical and other benefits:

1. It is the hands-on project-based training on how to arrive at solutions that adds significant value and excitement to the learning experiences of engineering students.
2. The students were subdivided into project teams consisting of 3 to 5 people suitable for full implementation of the project-based approach to design engineering training.
3. To foster and emphasize the hands-on component of the training in an innovative way, each group of students was provided with a LEGO Mindstorms® design kit that assures all groups with equal opportunities for project-related prototype building and visualization.
4. A close-to-real-life training practice of engineering students was achieved through combining the implementation of design engineering fundamentals using state-of-the-art CAD tools with implementing engineering analysis and decision-making fundamentals using state-of-the-art CAE tools in an integrated cross-course manner and in a multifunctional team environment.
5. The project provided horizontal integration of the engineering curriculum. Students did not learn the design and analysis material in isolation, but instead were provided the opportunity to comprehend how design and analysis are interconnected.
6. Having one project that spanned two courses, allowed a more challenging project to be assigned to students when compared to having separate projects for each course. Students were more motivated to do their best since the overall success of the project would affect their marks in two courses.
7. The project reinforced concepts of concurrent engineering and design which are critical for modern engineers.

6. Summary

It seems that a substantial culture change in teaching design engineering appears to be an immediate necessity. The authors see the described cross-course integration attempt as a first step towards an integrated engineering curriculum that has design as its central theme; a curriculum where analysis and design are brought together. Embedding innovation in design engineering training while ensuring that the educative design engineering cases are industry driven and realistic is used extensively within this concept as a practical means for

overcoming the inherent difficulty of teaching creativity, strategic thinking, and innovation in design engineering education.

The level and quality of the work created by the students exceeded the expectations of the authors. The results confirmed that the idea of integrating design and analysis courses was an effective tool for teaching engineering students.

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7. References

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