ESTABLISHING FAIR OBJECTIVES AND GRADING CRITERIA FOR UNDERGRADUATE DESIGN ENGINEERING PROJECT WORK: AN ONGOING EXPERIMENT

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ABSTRACT

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. Methodologies focused on assessing and evaluating the developed learning outcomes and the students' ability to adequately combine design engineering project work with knowledge from coursework and integrate these with practical applications exist and are continually evolving. However, these methodologies may still be improved. In this research, a universally applicable methodical tool, developed in recent years, that is generally useful in knowledge evaluation exercises, was directly applied to the design engineering field. Each component of the proposed model represents a different level of application starting from one's basic understanding of a concept, the ability of one to relate knowledge and articulate relationships among elements of the fundamentals, and finally culminating into the ability of one to take knowledge and apply it to a novel situation. Rubrics (charts describing learning at different levels of development) were developed to evaluate students' level of knowledge application for the three core design courses and the capstone course. The results of this study proved that the model is quite useful in evaluating the learning process of students via design projects and methods can be developed to customize and maximize its use.

Keywords: *Design, Engineering, Education, Rubrics, Assessment, Evaluation*

1. INTRODUCTION

Engineering curricula are expected to create a strong design engineering focus and provide the basis for systematically training undergraduate and graduate students in critical thinking and attaining engineering competence through finding and capturing design knowledge for intelligent and innovative reuse later. Thus, there is an obvious need in engineering education to develop technical innovators. Yet the current education system is seldom successful in attaining that objective.

The inclusion of design projects early in the undergraduate engineering curriculum, as a common remedial measure, is not a new concept for fostering innovation and the majority of engineering schools are implementing it. However, the fact that design engineering projects are of open-ended nature and are quite complex confuses not only students but faculty as well. Although there are virtually no right or wrong feasible design engineering project solutions, there are definitely bad, good, better, or excellent solutions that may involve a different level of students' creativity, ingenuity and innovation. A design project's complexity arises from the imperative to integrate elements of mathematics, basic science, engineering science, and complementary studies into a predetermined engineering report format in order to fully describe the solution of a given engineering problem. This makes both the students' task to perform well on design engineering projects and the instructors' task to assess and evaluate students' project work in a fair manner quite problematic and fuzzy. In this context, it is of paramount importance to develop a fair and reliable method of evaluating systematically to what level students are applying this knowledge, that is: are they only gaining the basics, or do they extend their knowledge beyond the fundamentals? Also, as students progress through their academic careers, they learn and review at increasingly higher levels. As such, their level of understanding must also increase.

1.1. Background

In recent years, accreditation boards are prescribing "outcome-based" assessments of the engineering design curriculum. Such criteria focus on the ability of students to apply knowledge of mathematics, science, and engineering science. This requirement extends to designing and conducting experiments and analyzing data, as well as developing a system, component, or process to meet certain needs. Engineering design has thereby become a key component in engineering programs. The group of Chairs in Design Engineering, established by the Natural

Sciences Research Council of Canada (NSERC) since 1999, has been undertaking an initiative to define the Engineering Design Competency that education institutes may use in developing their engineering programs [1]. In a related paper [2], Strong and Stiver discuss various barriers affecting the delivery of engineering design curriculum at postsecondary institutions. They indicated that engineering programs traditionally have been separated into disciplines and that this streaming of the various engineering fields at universities is believed to not serve design engineering well.

May and Strong [3] present survey results of students enrolled in capstone courses at Canadian institutes to self-rate their confidence level in a range of skills required in engineering design, as well as alumni of Queen's University Applied Science in the industry to rate graduating students skills and knowledge in design and development techniques. While students in general said they felt confident in learned design skills, industry respondents have identified many areas that recent graduates are lacking in. This result clearly shows that improvements are needed in engineering curricula to address industry's requirements of graduating students.

A standard, though, is lacking in evaluating high-quality design education, as pointed out in a paper by Kundu and Raghunathan [4]. They emphasize 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. UOIT's DESIGN STRATEGY

The University of Ontario Institute of Technology (UOIT) and its Faculty of Engineering and Applied Science (FEAS) are young institutions. They received their first class of students in September 2003. However, the newness of the institution combined with the timely endowment of the NSERC-GMCL Chair in Innovative Design Engineering (since October 2005), the strong institutional and senior management support he is receiving, as well as the extensive technology-enabled communication infrastructure and laptop-based web-centric teaching approach provide the ideal setting for the creation, prompt adoption, and implementation of advanced and innovative practices in teaching design engineering, without having to go through the burden of modifying or abandoning traditional ones. These were the key enabling factors for the conceptualization of UOIT's design engineering strategy, the creation of modern design engineering curricula, and the design and development of state-of-the-art design laboratories.

The paramount goal of the Chair's Action Plan is to establish a novel concurrent approach to innovative design engineering training and education, the essence of which is achieving "the consideration of all downstream challenges which are likely to affect a graduate's professional career at the outset of the future engineer's education." His mission is to provide meaningful contributions towards substantially improving Canada's capacity in design engineering through establishing a Centre for Innovative Design Engineering and Research (CIDER) and managing a competent team that will facilitate the introduction and propagation of distinctive educational approaches aimed at training competent engineers who will be instrumental in meeting effectively emerging needs for innovative products, processes, technologies and services. As a result, 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 (recently replaced by a two-part capstone design course in each of the engineering programs). These courses were designed to provide a continuum of carefully crafted project-based team and individual design engineering experiences. The significance of the core design courses has been further augmented by implementing integrated cross-course design projects among compatible design courses and those with strong emphasis on engineering analysis [5-8].

UOIT's graduating students have already created a track record of exceptional performance competing with other universities at the provincial engineering competition level among 16 engineering schools. The outstanding performance of our Junior Design Team (3rd Prize in the Junior Design Competition) in the 2006 Ontario Engineering Competition (OEC) and the most recent exceptional results of our students at the OEC 2007, i.e., 1st Prize in the Junior Design Competition and 3rd Prize in the Senior Design Competition [9], are nothing but quite remarkable achievements we cherish and are very proud of.

3. PROBLEM STATEMENT

Design engineering education naturally requires tackling problems that are open-ended, that is, where no single solution exists. Figure 1 shows the association of closed- and open-form education. Traditionally, engineering subjects teach theories and fundamentals and are very structured, with problem assignments having unique answers (that is, solutions are closed-form). In such a scenario, grading is relatively straightforward (the answer is either right or wrong). However, offering open-ended problems in design engineering education to cover industrial requirements makes the methodologies for assessment and evaluation of student efforts more complex and more difficult to implement.

In addition, real-world applications are rapidly becoming more interdisciplinary, emphasizing the need for engineering students to experience design engineering across several disciplines. Product realization is a more concurrent and less linear process, where a design team must exhibit a wide variety of skills and knowledge of several engineering fields. Engineering programs help with this requirement by setting up their roadmaps of academic study to include courses from engineering disciplines outside their own.

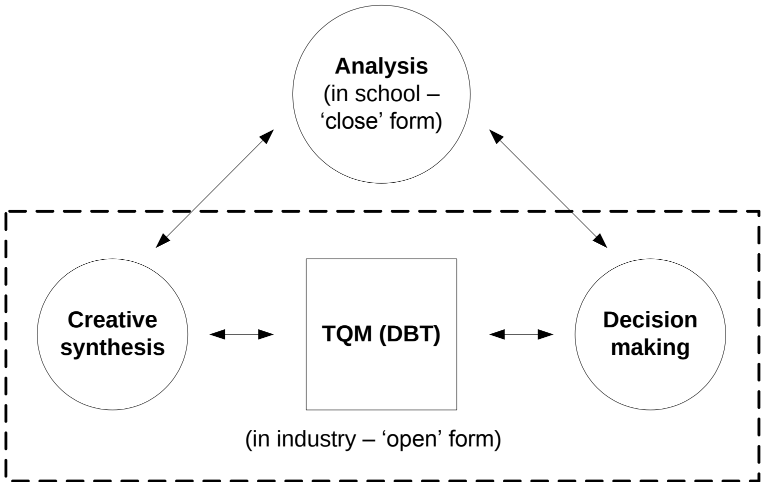

Figure 1. Open- and closed-form education association (DBT = Design Build Teams, TQM = Total Quality Management). Based on Ref. [4].

3.1 Pertinent Literature

An interesting program developed in recent years is the CDIO (Conceiving-Designing-Implementing-Operating) approach [10-12]. This approach was developed by the collaborative efforts of the Royal Institute of Technology (Sweden), Linköping University (Sweden) and the Massachusetts Institute of Technology (USA) [10, 11], which have been running a joint four-year program to develop a model for engineering education, focusing on CDIO skills. The purpose of this program is to provide students with an education that stresses fundamental engineering systems and to sustain productivity, innovation and excellence. The CDIO approach defines the levels of creating a design as follows [12]:

- *Conceive* – defining the need and technology, considering the enterprise strategy and regulations, 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 startup companies do, as well as exercise engineering reasoning to solve problems that are open-ended and ill-defined. In such cases, especially for the latter activity, a systematic approach is needed to gauge to what extent students apply knowledge to solve engineering problems.

A methodical tool developed in recent years that is useful in such evaluation is the ICE (Ideas, Connections, and Extensions) philosophy [13]. In this research, it will be used as a basis for developing a model to evaluate the extent to which students have applied their knowledge for various engineering design projects. 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 [14] versus "shareware" rubrics, the latter of which are poor tools for evaluating students. The ICE rubrics eliminate fuzziness in descriptions between categories, as well as student behaviors and creative expression from evaluating a student's understanding of a given subject.

The ICE rubric methodology may be compared to Bloom's Taxonomy, which has been published in a number of references (see for example [15]) and has been used as an evaluation tool by college and university-level educators. The taxonomy breaks down the range of cognitive development into six levels of achievement, noting that the higher levels may include some of the lower levels of cognition. Table 1 summarizes these levels along with their descriptors, and provides analogous definitions in terms of the ICE philosophy.

Table 1. Bloom Taxonomy with Analogous ICE Levels (based on [15]).

Degree of Cognition	Classification Levels	Descriptors	ICE Equivalent
Lowest	Knowledge	Recalling facts, theories and learned material.	Ideas
	Comprehension	Awareness of what material means (compare, contrast, paraphrase, extend, summarize).	
	Application	Application and understanding of learned facts to answer questions in new environment.	Connections
	Analysis	Breaking down material into constituent parts to understand organizational structure.	
	Synthesis	Recombination of analyzed components into new entities, creatively forming new patterns or structures.	Extensions
Highest	Evaluation	Judging value of material for given purpose using defined criteria and rationale, application to decision-making and selection.	

More recently, a metacompetency model was developed by combining Bloom's Taxonomy with Kolb's Experiential Learning model to more fully utilize higher levels of thinking in fostering greater innovation in engineering problem solving [16].

Several examples of rubrics are described in the literature for a range of subjects, including language comprehension and mathematics [13, 14]. Depending on the nature of the assignment or what learning outcome is required, the rubrics may be written in either quantitative or qualitative terms [13]. Quantitative rubrics are concerned with the amount of information learned at each of three levels of learning, yet are limited in their use as a guide to improve learning. As such, the quality of learning may be the same at each level, but the level of learning is governed by the quantity of information gained. The ICE rubric, however, uses qualitative descriptors. Therefore, from one level to the next, the quality of learning changes and the rubric provides a roadmap for the learning development [13].

4. RESEARCH APPROACH

For the present research, rubrics are used to evaluate students' level of knowledge application. Group design engineering projects assigned through three core design engineering courses with increasing level of difficulty, as well as the fourth-year capstone course, that are respectively scheduled progressively through the four years of engineering studies at UOIT [5-8], were studied to determine to which level of ICE students have carried out and reported on their designs. The rubrics were developed using the actual assigned project requirements by respective faculty (e.g., engineering documentation and written report), which became the "elements" of the project in the ICE context. For each of these elements, a description was provided for each level of ICE as to what is expected for students to have achieved at that particular level of learning.

4.1. Procedure

For this study, the design reports submitted by students taking first- through fourth-year Engineering Design courses between 2003 and 2006 at UOIT have been used. Each design assignment contained various deliverables and requirements students were to submit for a satisfactory grade. Initially, project reports were grouped into categories (exceptional, good, and fair) based on predetermined mark ranges. It is important to note here that no project was previously graded nor has it been assigned based on the ICE approach rubrics that will be presented in this paper. Rather, the already completed, assessed and evaluated design engineering projects that have been previously evaluated using a conventional "one-dimensional" approach were used in this research as the basis on which the respective evaluation rubrics have been built. The reports have then been examined in more detail to determine, based on the ICE-based "three-dimensional" levels of understanding, the extent that students have actually carried out the design requirements. The rubrics developed reflect not only the level of understanding expected for a given project for each element required, but also a progression of the level of understanding required at each level of ICE through the three years of undergraduate study (naturally, as students progress through their undergraduate years, the expectations for a given "element" of a project increase).

5. RUBRICS FOR A 1ST-YEAR DESIGN PROJECT

The first rubric to be developed was a rubric that would help the assessment and evaluation of first-year design engineering projects. In this context, four different group design projects were assigned and evaluated by different instructors to approximately 900 first-year students from 2003 – 2006 with virtually equal levels of difficulty, scope, requested deliverables, and equal marking schemes. These projects were used as the sample project pool for creating this rubric. For example, in 2003 and 2004 the project topic was a hand cart [5, 8], in 2005 it was a tripod, whereas in 2006, an ice skates carrier-related project was assigned.

In the 2006 project, students were asked to design a device capable of carrying ice skates, targeting a market of skaters consisting of those who take up the activity for casual exercise or as a family social activity. A limited amount of background information was provided, including a similar related carrying device for in-line skates (Figure 2) to get students started with their investigation of existing products and their design. The project required students to design a device that would accomplish the following "customer requirements":

- *Requirement 1*: The skate carrying device should allow smooth, safe, and simple operation.
- *Requirement 2*: The skate carrying device should be adjustable to accommodate a variety of skate sizes.
- *Requirement 3*: The skate carrying device should be designed to protect the blade during transport and storage, as well as prevent blades from causing injury.
- *Requirement 4*: The skate carrying device should be designed for compact storage.

With respect to project deliverables, students were required to document accordingly each feature of their design. Further, all required design features were to be incorporated without one feature compromising the functionality of another. The students were asked to create a complete set of engineering documentation describing completely the newly designed skate carrier with the four new features in sufficient detail so that a remotely located manufacturer would be able to produce the device without further intervention. In particular, students were asked to use a 3-D solid modeling CAD (Computer-Aided Design) package to provide: 3-D full assembly (exploded view and motion functionality drawings) accompanied with a tentative bill of materials, 3-D drawings of all its subassemblies, components, and parts as well as multiview part drawings (including dimensions and tolerances) using an appropriate scale for each drawing. In addition, a single-page Owner's Manual and Technical Specification brochure was required to be developed in order to describe the product including, for example, rendered 3-D CAD drawings. Finally, students were required to produce a formal engineering report discussing their design and how it satisfies the requirements and to prepare and give an in-class oral presentation.

Figure 2. Sample carrier for in-line skates [17].

As this was a first-year, first-term design project, simplifications were made in the technical design requirements due to students' limited knowledge of engineering subjects. For example, a structural strength analysis was not required (material makeup of the final design would be assumed infinitely strong) as students would not have had adequate exposure to this area. Also, a working prototype of the final design was not required, though several groups provided animated files with their electronic submissions that showed functionality of the device, as well as using the animations for in-class presentations. Such a project is generally feasible for first-year students, but its open-endedness overwhelms them, as they expect the type of closed-form solution found in mathematics problems. For example, in the 2004 project, students were required to modify or redesign an existing handcart so that it can function as a seat and a ladder and can be used on snow. Figure 3 depicts some of the outcomes of related students' project work on this topic [5].

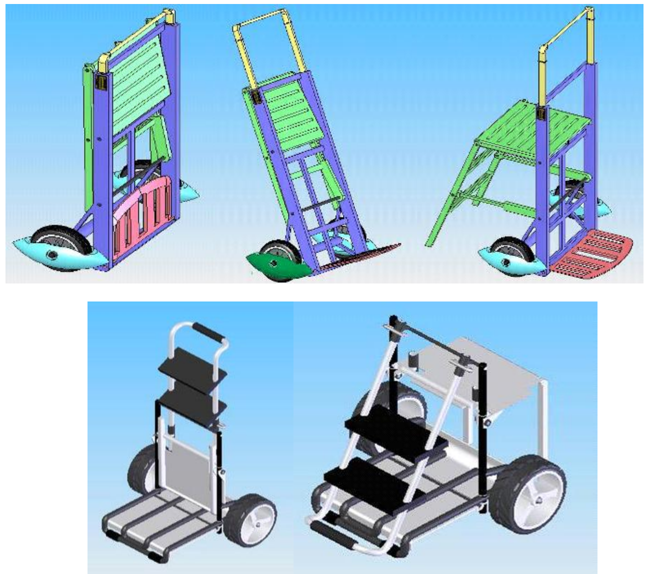

Figure 3. Another first year core design course project sample: Convertible handcart.

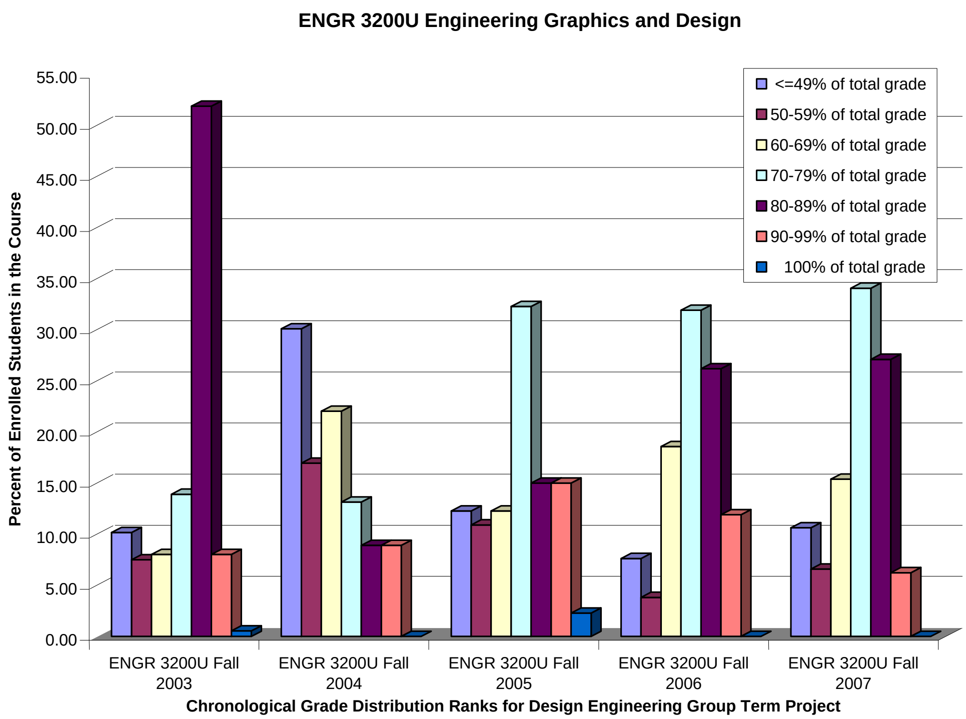

Figure 4. Distribution of design project grades in the first year core design course.

Although statistics show that the number of students receiving failing (<49%) and poor grades (50-59%) in first-year design projects has improved each year, as shown in Figure 4, it is necessary, however, for students to learn early in their undergraduate studies what is expected to produce satisfactory project deliverables so that they can better handle upper year design projects, where standards are raised higher. By using rubrics as a roadmap, instructors can provide better guidance to students as to the project expectations and levels of understanding, as well as a fair and consistent grading scheme, resulting in future shifts in grade distributions towards the "good" (75-85%) and "exceptional" (>85%) range. Evaluating the students' ability to apply knowledge gained from their engineering curriculum to an open-ended design problem has to also be aligned with the identified Engineering Design Competency [1, 2]. Here, the desired outcome would be a feasible design of an ice-skate carrier. Figure 4 also shows the grade distribution for the project grades of Fall 2007, the first time rubrics were introduced as a means of evaluation, where the distribution shows a tendency towards the "good" grades or better.

To develop a suitable rubric as a roadmap for evaluating student performance on first-year design projects, one could consider that for mathematics learning as well as that of a science report [13], both from which elements may be used in constructing a basic framework. The project itself contains technical aspects and methodologies, as well as communication (report writing, etc.) requirements. In this context, fifteen elements were identified to base the evaluation of the students' design and reporting. The descriptors presented for each level of learning in ICE were based on a review of the previously evaluated first-year project reports. The grade that the reports received would place them in one grade range overall; however, the projects did not necessarily exhibit just one learning level in every element given. For example, a report receiving 7/10 may exhibit **I**deas level of learning under Background Search and Report Write-up, but under the categories related to the technical drawings, it may exhibit characteristics of the **C**onnections level. It should be noted that some of the descriptors are project specific, but may be altered for different projects, or for generality. Using all these components, a respective rubric suitable for evaluating first-year projects has been developed, as shown in Table 2.

6. RUBRICS FOR A 2ND-YEAR DESIGN PROJECT

Similar to the development of the rubric for assisting with the evaluation of first-year design projects, a rubric can be developed to guide the evaluation of second-year design projects. For this rubric, project work from three second-year core design courses from 2004 to 2006, where two projects were assigned per term, were considered. Such projects are intended to emulate real-world assignments. Thus, for example, the first design project in 2004 required the design of a "Free Choice Type of Vehicle Based on a Common Platform Concept Supporting Interchangeable Vehicle Bodies", whereas the second project required students to design a "Bi-axial Rotating Mechanism for Single Charge Fabrication of Integral-Skin Polyolefin Foams [6, 8]." Related sample student works are presented in Figure 5.

(a) 

(b) 

Figure 5. Second year core design course project sample using Meccano 50 ™ Design kits.
Figure 5(a) Various vehicles based on a common platform. Skateboard approach.
Figure 5(b) Biaxial mechanism for rotational molding. Mold = Unopened pop can

Figure 6 shows summative mark distributions for the two projects over each of the three years the course has been offered, similar to the ranges used for the first-year project. For these projects, students were given detailed background information to help them understand the industrial applications of the issues involved and establish a need for the stated design of the platform/mechanism. In 2005, the first design project required students to design landing gear for a small aircraft, while the second project was the design of a rickshaw mechanical walker. In 2006, the first project was a variation of that assigned in 2004, whereas the second was the same as that assigned in 2005. For all second year projects the general deliverable requirements were similar to those for the first year design projects. However, some additional requirements to be delivered included: an organized logbook of all the group's activities, interactions, and decisions made for their design (with justifications and rationale) and a functioning prototype using a Meccano 50® design kit that was provided to each project group. As the level of complexity of the required device to be designed has now increased compared to a first-year project, with the number of parts having increased, the use of subassemblies to provide required functions increase and this is stressed in developing the respective rubrics. Also, expectations of students' learning increased from year 1 to year 2 of the engineering program. A resulting rubric is proposed for the second-year design projects, as shown in Table 3. Progression in the ICE level of understanding of a common element is notable. For example, one can look at the element "Background Search." At the **I**deas level, first-year students may well restrict themselves to just listing a small number of existing products, or just repeating the examples provided in the project outline. By second-year, students should at least be able to understand key features and functions of the existing product when their level of understanding is **I**deas. Introducing the rubric in Fall 2007 to guide students in their design requirements resulted in a greater shift of grades to the 70% or better range, an improvement from previous years. In 2007, the two design projects were the Vehicular Platform, and a new second project, Autonomous Mechanical Walking Mechanism of a Free Choice Animal.

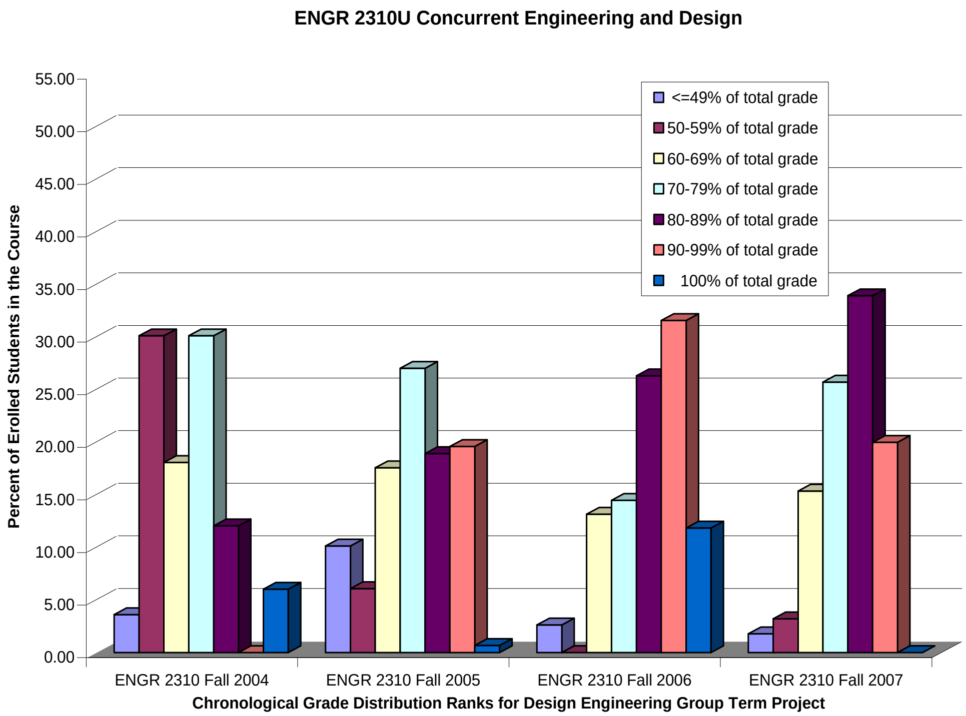

Figure 6 Distribution of design project grades in the second year core design course.

7. RUBRICS FOR A 3RD-YEAR DESIGN PROJECT

Here, a rubric for the evaluation of students' learning level is developed for a third-year design project. By this time in an undergraduate engineering training program, learning expectations of students are much higher than in earlier years. The resulting rubric reflects this in the common categories between it and those of first- and second-year design projects. The scope of a typical third-year integrated project is provided using the project assigned in 2005 (the 2006 design project was a modification of this project) [7, 8]. The third-year students were required to design a manipulator system that performs the following tasks:

- *Requirement 1:* Grasps a tire from one of three input conveyors at a height of 1 m.
- *Requirement 2:* Rotates tire 180° (in 2006, the rotation was 90°, as the tires were to be standing upright on the input conveyor).
- *Requirement 3:* Places tire on an output conveyor at a height of 1.5 m.
- *Requirement 4:* Repeats procedure for a second tire and stacks second tire on top of first.
- *Requirement 5:* Is capable of completing process for three different sizes of tires.

At the third-year level, students were required to analyze their design by mathematical/numerical means (that is, using Finite Element Analysis) to provide structural strength analysis for consideration of material selection. Finally, students were required to build a functioning prototype using LEGO Mindstorms® design kits. Figure 7 illustrates a sample of respective student project work.

The obtained grade distribution is as shown in Figure 8. Note that grade distributions are also included for the Fall 2007 offering of the design project, where the rubric was first introduced. As a result, a greater trend is seen in the grade distributions to the higher ranges (70% or better). From the reports, a possible rubric, as shown in Table 4, is developed, which also includes elements such as Physical Prototype and Maintenance Manual. Again, using the element of "Background Search" as an example, by their third year, the progression at the **I**deas level of learning is now that students should also demonstrate that they understand the scope of the existing product; for example, what kind and how many technologies are embodied.

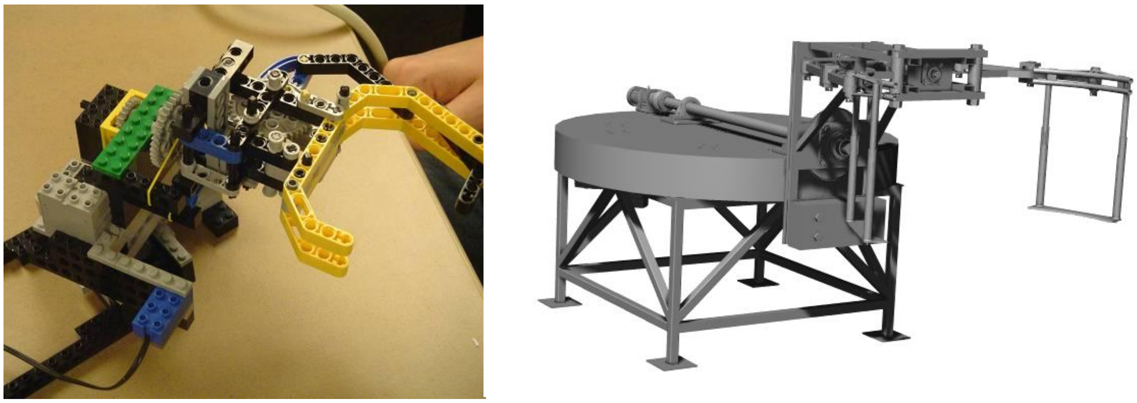

Figure 7. Third year core design course project sample using LEGO Mindstorms ™ design kits.

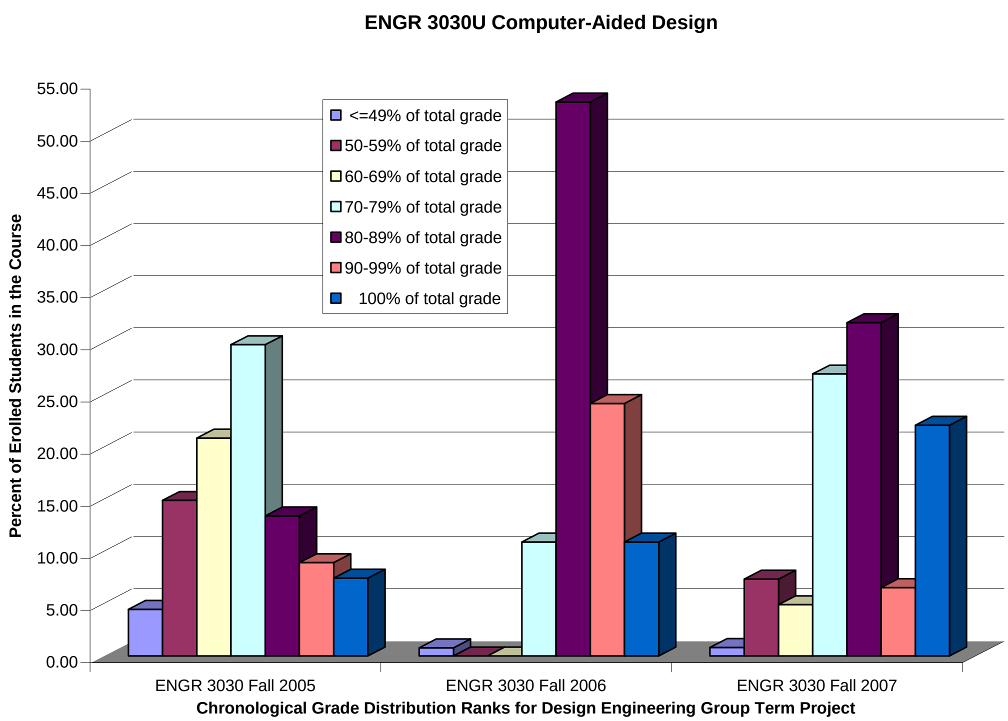

Figure 8 Distribution of design project grades in the third year core design course.

8. RUBRICS FOR A 4TH-YEAR DESIGN PROJECT (CAPSTONE COURSE)

Finally, a rubric is presented for the fourth-year capstone design project for projects undertaken in 2006. The capstone design course serves as one of the final preparations for students before entering the industry, eager to assume the role of the new kind of preferred "hybrid" design-ready engineering profile. Detailed descriptions of the requirements for capstone design projects are available in Pop-Iliev and Platanitis [18], but a summary of the project scope is provided. In this course, students are divided into teams to undertake different design projects that allow them to apply knowledge and technical skills gained in previous years of study to a design problem. In manufacturing, for example, students are required to develop manufacturing systems and/or processes intended for the fabrication of the newly-designed product, providing detailed analyses of whether or not the design meets the requirements, which also includes a functioning prototype of the product. Students choose their design project from several predetermined projects, or they may use their own ideas for design projects. The sample description below 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.*

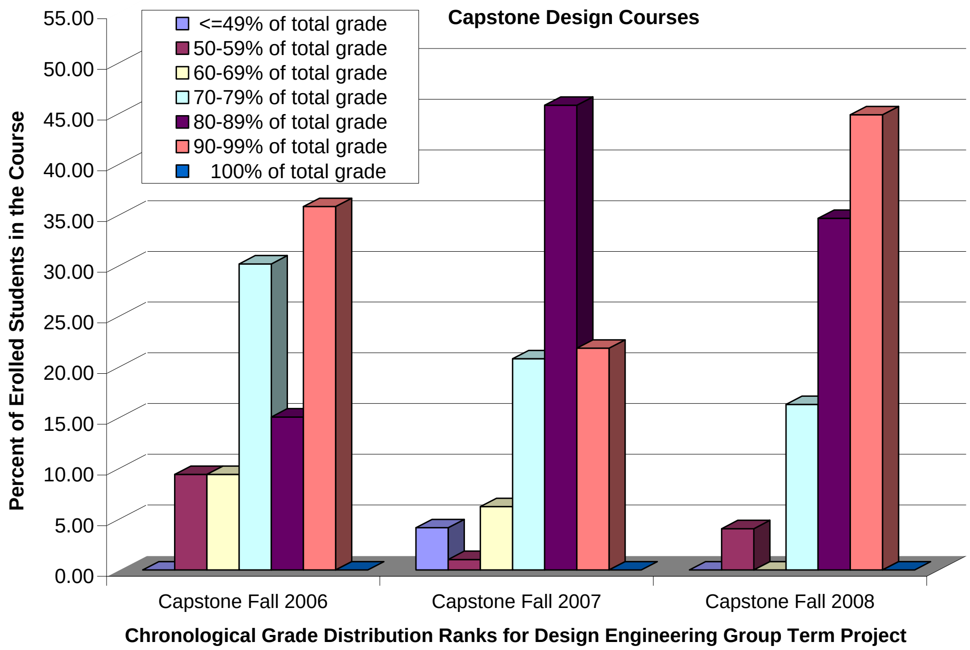

Figure 9. Distribution of design project grades in the fourth year capstone design course.

Figure 10. Capstone design project – Automatic Door Opening Device (Courtesy of: Mike McLeod, Matt Van Wieringen, Ben Fagan, Mark Bernacki).

Figure 11 Capstone design project – Hybrid Bike (Courtesy of: Theodora Biney, Zak Dennis, Pierre Hinse, Adam Kraehling, Samveg Saxena).

Figure 9 depicts the variations of students' performance in a fourth year capstone design engineering course. The critical percentage of marginally performing students on design engineering projects is showing a decreasing trend (Figures 3-5) in all core engineering courses while achieving about 15% of "sub-standard" (<70%) student performance in the graduating year. Such a trend has been attributed in part to the development of digital learning modules to assist students with gaining the necessary skills to be applied to the design project. Rubrics were introduced to the capstone design courses from Fall 2007 (as with all the core design courses). Grade distribution data is provided for Fall 2007 and Fall 2008, and shows improved grade distributions as a result of using the rubric. Figures 10 and 11 show examples of capstone design projects.

The rubric developed for evaluating students' work in future offerings of this course, as well as to what level students apply their knowledge and skills in each of the design project requirements for this and similar fourth-year engineering design courses, is shown in Table 5.

9. CONCLUSION

At UOIT, we are strategically aiming towards igniting the engineering curiosity of our students and finding new methodologies to focus innovation efforts so they foster innovative design engineering ideas that employ the synergistic effect between design and innovation as the key for sustaining corporate performance and competitiveness. Through assigning design projects, we are striving towards embedding innovation in design engineering while ensuring that the educative design engineering cases are industry driven and realistic, follow modern methods, and focus on real time and new products and processes.

This paper reviewed the performance of students on design projects assigned progressively through their four undergraduate years in the engineering program. Using these projects, students' levels of understanding in the different areas required throughout the design process, from conception to final design (and development of working prototypes for years 2 through 4), were evaluated. The obtained results include comprehensive rubrics which can be used as roadmaps for evaluating design projects in future course offerings at each year. Each rubric outlines the fundamentals of the expected level of understanding in a number of elements based on the ICE methodology. Also, for each ICE level, a progression of understanding through years 1-4 (years 2-4 for skills introduced starting in year 2) is shown to increase each subsequent year, given the increase in expectations for the design projects in each year. Using such a roadmap, instructors can clarify expectations to students for maximum grade results, as well as provide themselves with a "three-dimensional" approach to grading final project submissions. The rubrics are continually under development and refinement, and ongoing research is taking place in the development of multiple dimension rubrics which assign a grade to a given element based on the skill level an element is introduced and the rank (level of learning) at which the student applies that skill [19]. The usefulness of these multidimensional rubrics has been demonstrated in fourth year design courses, including Advanced Mechatronics, and capstone [20]. In order to maximize the utility of the proposed rubrics, the authors are open to and would welcome feedback and suggestions for new inputs, further refinement, modifications, improvements and/or customization.

10. ACKNOWLEDGMENTS

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 has been implemented in support of this research work. The authors are also grateful for the hardware and software provided by PACE (Partners for the Advancement of Collaborative Engineering Education).

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Table 2. Rubric Developed for Evaluating a First-Year Engineering Design Project.

Elements	Ideas	Connections	Extensions
Background Search	- uses examples given in outline - lists ideas found in the textbook	- compares/relates ideas to a variety of existing devices found in immediate surrounding environment -attempts to understand how related devices operate and identifies underlying physical concepts	- considers needs for product design - compares/relates ideas to those found in archive journals and patent literature - identifies deficiencies of existing devices and suggests strategies for improvement - identifies possible target markets for a redesigned or newly designed product -identifies possible competitors
Brainstorming	- comes up with sufficient ideas to barely satisfy design requirements - generates concepts with questionable feasibility	- relates existing ideas to create new feasible concepts that satisfy function - exhibits some creativity in satisfying customer needs	- uses variety of studies to design improved concepts - provides new, useful features beyond the basic requirements - provides innovative design concepts that satisfy both function and form - identifies interfaces between various components - identifies optional design concept implementations
Sketching Ideas	- provides basic rough sketches	- shows how each requirement fits together - labels components to identify key features	- uses axonometric and/or perspective views in sketching concepts - provides accurate and realistic 3-D visualization - shows approximate dimensions - clearly describes features and functions
Screening /Selection/Evaluation of Generated Design Concepts	- compares existing concepts, deriving new design from best one	- compares ideas generated and refines best one - selects appropriate reference concept	- explores combinations of ideas to improve design before making final selection - justifies design decisions - considers material factors in concepts - somewhat considers elements of manufacturability
CAD Package Proficiency	- understands basic commands and creates simple shapes	- manipulates shapes and creates assemblies of moderate complexity	- creates complex shapes and creates realistic renderings and assemblies
Motion Simulation Package Proficiency	- creates simple linkage motions	- relates dynamic elements of design to key device functions	- develops animations of design showing realistic device functionality
Assembly Drawings	- shows components assembled in 3-D drawing	- provides component labels - uses exploded views to show assembly of parts	- shows sizes and material makeup of components - draws components in functional positions - uses exploded views to show how components fit together and relates them to functions
Bill of Materials	- lists parts used for assembly	- provides part numbers, quantities, and corresponds each to assembly	- provides sizes and material, identifies custom and standard parts, understands relationships of parts with product function - identifies and lists standard parts
3-View Drawings	- provides 3 views of each part designed - shows some dimensional information	- adheres to ANSI standards - applies adequate dimensioning to build parts properly	- dimensions are clear, units and tolerances applied accordingly - understands how drawings are related and parts fit together
Tolerances	- provides generalized tolerances	- considers specific tolerances to components - relates tolerances to parts fitting	- understands different types of tolerances with respect to functionality of components (clearance, interference, etc.)
3-D Renderings of Final Design	- provides basic picture showing form of design	- identifies significant features and relates to functions - provides rendered device drawings - attempts to improve appearance by appropriately choosing different colors	- exports basic files into programs specifically designed for rendering to create almost absolutely realistic imagery - creates background and realistic surrounding appropriate for device implementation
Brochure	- provides brief description of device in English	- provides language independent user-friendly instructions with adequate 3-D renderings and use of symbols only	- effectively combines written information with 3-D renderings to highlight key features and functions - advertises product adequately for target markets

Oral Presentation	- summarizes overall design - random approach	- addresses target market - highlights identified need for design - shows how requirements are met with design	- uses animations and videos with sound effects to demonstrate key device functions and advantages - demonstrates additional features
Progress Reports	- summarizes brainstorming ideas and meeting minutes	- shows progressive steps, logically coming up with design to meet requirements and target market needs	- shows necessary background research to relate existing ideas to new designs - shows how target market needs are met
Report Write-up	- outlines basic categories/sections - provides activity summary	- uses proper format and language - connects categories throughout report - provides coherent descriptions	- provides design process proficiency justification - provides detailed explanations about used rationale - expands ideas to new ways of thinking - draws conclusions and suggests further research

Table 3. Rubric Developed for Evaluating Second-Year Engineering Design Projects.

Elements	Ideas	Connections	Extensions
Logbook	- summarizes briefly group activities and results	- coherently logs daily activities and emails logged - outlines intended goals to achieve	- discusses design ideas generated and rationale of decisions made for final design
Background Search	- describes existing products and patents	- discusses pros and cons of existing patents and products - identifies and reinforces design need	- relates existing products to needs of new design - improves design based on merits and deficiencies of existing patents and products
Brainstorming	- provides descriptions to sketches - relates required functions to needs	- relates existing ideas to create new concepts - effectively uses screening charts to compare, eliminate, or redevelop ideas	- considers additional features to improve device - considers needs of customers and design requirements
Sketching Ideas	- presents freehand sketches with a degree of neatness and comprehension of requirements	- creates relationships between requirements and features sketched	- shows progression/evolution of designs through sketches - provides realistic drawings with key technical information
Concept Development and Screening	- derives design with adequate creativity using existing concepts	- considers appearance, ease of use and assembly - provides detailed information on scope of design - somewhat understands use of House of Quality	- considers functional flexibility and failure modes - considers complexity of parts and assembly with respect to manufacturability and function -uses House of Quality to generate engineering specifications
3-View Drawings	- provides 3 views of each part designed using correct angular view - shows some dimensional information with redundancy	- adheres to ANSI standards - supplies adequate, clear notation, relating part and drawing numbers to BOM - dimensions features without ambiguity	- organizes drawings to relate to 3-D views of components - demonstrates relationships of components to final assembly - labels drawings by appropriate identification showing relationships between drawings
3-D Renderings of Final Design	- shows adequate 3-D renderings of components	- shows key features and functions - displays appropriate view for most 3-D details to show	- provides realistic drawing with color and material rendering - develops comprehensive functional drawings
CAD Package Proficiency	- shows knowledge of many commands and creates moderately complex designs	- manipulates shapes of various complexities into assemblies and understands design constraints	- creates detailed designs of mechanisms showing realistic renderings and understands motion/dynamics of design
Motion Simulation Package Proficiency	- demonstrates basic understanding of moving components with respect to design	- correlates dynamics of moving components and their constraints	- uses motion simulation to identify design problems and improve design
FEM Package Proficiency	- understands discretization methods to calculate structural properties	- associates computed stresses and strains to constraints on moving components	- identifies potential structural failure modes - identifies remedial measures - implements remedial measures in an iterative fashion
Assembly Drawings	- shows components assembled in 3-D drawing with adequate clarity	- shows subassemblies and relates each to key features and functions	- provides exploded views with appropriate callouts to relate assembled components to parts lists - provides notes for assembly purposes
Bill of Materials	- lists parts used for assembly	- accurately provides part numbers, quantities, standards and corresponds each to assemblies	- distinguishes subassemblies and BOMs provided at subassembly level as well

Tolerances	- applies generic tolerances to each dimension	- considers part fitting - understands use of tolerances for dimensioning and manufacturability	- effectively uses GD&T methods for accurate part fits in assemblies
User Manual	- highlights main functions of design	- demonstrates knowledge of assembly and provides step instructions	- gives thorough operational detail - supplies significant 3-D renderings to complement explanations
Physical Prototype	- builds reasonable scale presentation of design	- understands function of device and working environment	- applies constraints and builds robust functioning device - supplies automation codes and interfaces
Oral Presentation	- maintains time restriction - summarizes design activities	- shows attention to details of functions and key features - demonstrates functioning prototype	- follows logical order in explaining design background, requirements, and progress of design - maintains professionalism
Report Write-up	- outlines basic categories/sections - gives superficial explanations under each category	- provides subcategories and connects explanations by referring to figures, data, drawings, etc. - shows coherence in information flow throughout report	- organizes sections in suitable order - provides table of contents and gives detailed explanations of design - gives conclusions adequately justifying results for design

Table 4. Rubric Developed for Evaluating Third-Year Engineering Design Projects.

Elements	**Ideas**	**Connections**	**Extensions**
Logbook	- Provides chronological order of meetings and assigned tasks to members	- clearly outlines steps to show design progression - outlines intended goals to achieve	- includes email correspondence with step-by-step, daily log - provides daily learning and application
Background Search	- lists products and available patents - provides general pictures of designs - demonstrates scope of existing product	- 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	- 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 - 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	- provides realistic visualization - shows approximate dimensions - clearly describes features and functions
Concept Development and Screening	- compares existing concepts - derives new design from best one - demonstrates poor 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 - chooses the best concept using appropriate tools
3-view Drawings	- provides 3 views of each part designed - shows some dimensional information	- adheres to ANSI standards - applies adequate dimensioning and tolerances to build parts properly - labels individual parts and associates them with assembly and BOM	- displays clear dimensions and understands tolerance and GD&T application - understands how drawings are related and parts fit together - uses additional views to provide clarification details, scaled adequately
3-D 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 them to functions - provides functional views with components positioned accordingly
CAD Package Proficiency (NX4)	- demonstrates ability to create realistic 3-D renderings	- shows proficiency in designing key features and associates them with required functions	- manipulates shapes of varying complexities to create fully functioning virtual models

Motion Simulation Package Proficiency (MSC Visual Nastran)	- creates motion simulation to validate design requirements	- identifies problems in design of moving parts as related to fixed components and suggests design improvements	- 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	- determines failure modes and considers modes such as bending and twisting of components in dynamic analysis
Assembly Drawing	- shows components assembled in 3-D 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 - somewhat 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
Maintenance Manual	- lists basic warnings and general maintenance guidelines	- relates functions of device to regular maintenance activities	- organizes maintenance activities according to frequency required to perform them for maximum operational life
Physical Prototype	- builds reasonable scale presentation of design	- builds working model capable of essential functions	- develops working model capable of robust functionality for range of environments
Oral Presentation	- discusses ideas for final design - outlines methodology used	- provides highlights of key features and functions - uses 3-D renderings to present functions	- makes use of animations to show assembly and function - demonstrates functioning prototype
Report Write-up	- outlines basic categories/sections - provides activity summary	- connects categories throughout report - provides coherent descriptions	- provides detailed explanations and expands to new ways of thinking - draws conclusions regarding design and suggests further research - provides design justification

Table 5. 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 and requirements information	- 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 - Applies learned lessons to new idea generation and design improvement
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 and researches methods for optimal incorporation
Project Management	- Provides project schedule of events and submissions	- Organizes plan/schedule by milestone deliverables - Provides additional organizational (PERT, etc.) identify task dependencies	- Considers consequence of late submissions and plans for advanced completion of deliverables (margin of error) - Includes Critical Chain analysis and explores alternative paths for task completion
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 - Evaluates merits of existing design and incorporates feasible	- Demonstrates preliminary results of final design - Identifies plan for further design refinements - Relates results to original requirements

		attributes to new concepts	
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 - Incorporates features having merit in new concepts generated	- 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 - Chooses 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 to product functionality and manufacturability - 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 - Explores various mesh sizes and compares solutions obtained for each mesh density to identify consistencies between solutions
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