Experiential Learning Through Simulation And Prototyping In First Year Engineering Design

EXPERIENTIAL LEARNING THROUGH SIMULATION AND PROTOTYPING IN FIRST YEAR ENGINEERING DESIGN

BY

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To my son Isaac, who taught me I can do anything

Abstract

The act of engineering is synonymous with design. It is a skill that is inherently understood by experienced engineers, but also one of the most difficult topics to teach. For many years, Engineering Design and Graphics has been a required first year course for all engineering students at McMaster University. The course has taught hand-sketching, 3D solid modeling, system simulation, 3D rapid prototyping, and culminated in a design project in gear train design that requires a combination of the core course topics. Students chose their own three-member teams, and lab sections were randomly assigned one of three modalities for completion of the design project: Simulation (SIM) where they produced and verified a design using a simulation tool, Prototyping (PRT) where they used a 3D printer to create a working plastic model of a design, or Simulation and Prototyping (S+P) where they used both tools to complete a design.

The design process used in the project represents Kolb's Experiential Learning Cycle (through Concrete Experience, Reflective Observation, Abstract Conceptualization, and Active Experimentation) as well as Bloom's Taxonomy providing opportunities for Cognitive, Affective and Psychomotor skill development.

This study examines student self-efficacy and performance outcomes between design project modalities that include simulation and 3D printing. It is hypothesized that students who complete a design project using the Simulation and Prototyping (S+P) modality will show the highest scores in both categories.

To measure self-efficacy, a new scale for Engineering Design Self-Efficacy was developed and validated. The project groups were surveyed before and after the completion of the design project. Data collected as part of the study included project individual, project group, and project total grades as well as final course grades. Statistical analysis for survey and performance data was completed using ANOVA to test for differences between the modalities.

Results indicated an overall increase in self-efficacy from the start of term to the end of term for all design project modalities. Performance scores for project group and project total grade were highest for students in the Simulation (SIM) modality. There were no significant differences between the modalities for self-efficacy, project individual grade, final exam or final course grade.

Based on the findings, engineering course designers with the goal of increasing self-efficacy, professional engagement, and performance should consider supplementing courses with experiential learning exercises such as simulation and prototyping. This study will be relevant for engineering course designers and instructors looking to add simulation or rapid prototyping to first-year engineering design courses.

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Notation and abbreviations

3D	Three-dimensional
ANOVA	Analysis of Variance
CAD	Computer-Aided Design
CD	Compact Disc
CD-ROM	Compact Disc Read-Only Memory
DBT	Design-Build-Test
ELM	Experiential Learning Model
ELT	Experiential Learning Theory
ENG	Engineering
IAI	Instructional Assistant Intern
PBL	Project-based Learning
PCC	Pearson Correlation Coefficient
PjBL	Project-based Learning
PLA	Polylactic Acid
PRT	Prototyping modality
RepRap	Self-replicating Rapid Prototyping Machine (3D printer)
S+P	Simulation and Prototyping modality
SBL	Simulation-based Learning
SIM	Simulation modality
TA	Teaching Assistant

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Chapter 1

Introduction

Fundamental to the role of the engineer is the concept of design. This concept can be simple such as when combining ideas in new and different ways, or complex such as when creating a new product or process. First-year university students often struggle with new concepts, such as design, and these struggles can be magnified by the pressures of a new environment with heightened expectations. As educators, it is our duty to be aware of these common stumbling points and provide positive learning experiences that are interest-building and engaging, while delivering practical knowledge and experience to students.

1.1 Design and Graphics Course

In 2012/2013, Engineering Design and Graphics was a required course for all first year engineering students at McMaster University. The incoming class of engineers was approximately eight-hundred students for the whole year, split such that about half of the students were enrolled in the class per term. Course components were taught by the professor and by *instructional assistant interns* (IAIs) which were full-time co-op undergraduate students or recent graduates in an instructor role. Each student attended one hour of lecture, two hours of tutorial, and three hours of lab per week. In lectures led by the course professor, students studied the fundamentals of design such as the design process and introduction to basic gear train design. In tutorials led by IAIs, students were taught hand-sketching, design on paper, and hand-calculations for gear train design. The weekly lab component, also led by IAIs, was where students learned about 3D solid modeling using Autodesk Inventor [9], simulation using Maplesoft's MapleSim software [10], and 3D rapid prototyping using RepRapPro Huxley 3D printers [7].

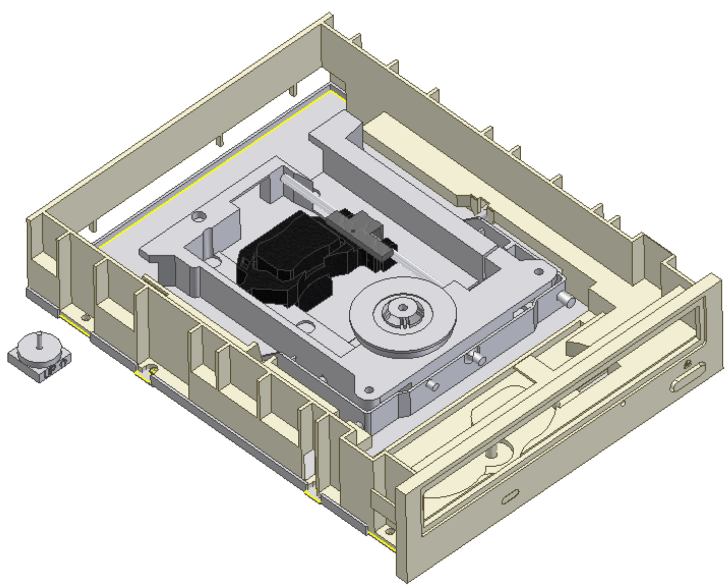


Figure 1.1: CD-ROM file showing chassis and motor to be mounted

The course culminated with a unique design project where students were asked to take on the role of consulting engineers to a fictional company looking to retrofit an existing product. In this school year, students were given a CD-ROM drive (as in Figure 1.1) that had missing components and were asked to design a new gear train to drive the linear motion of the read head at a given speed. Each team was given a unique input parameter (rotational velocity of the motor, based on group number) which resulted in a unique design requirement for each project. The teams were required to research the mechanical operation of the device, model and validate their new design, and submit a technical report with model results and a complete set of engineering drawings.

Students in their final year of undergraduate studies often undertake a *capstone* project, which may represent a culmination of their university engineering knowledge. These projects are often seen as the most rewarding experiences throughout their schooling [11]. The first year *cornerstone* directed design project described above was similar to the capstone projects created in the final year of undergraduate studies in that it gave students a chance to put into practice all of the theoretical knowledge gained throughout the course. The *cornerstone* project was different in that it was scaled to a level that was appropriate for first year students, since incoming first year students were expected to have no previous background in CAD, simulation, or 3D printing [12]. The expectation was that the introduction of experiential learning through simulation and 3D printing made the project more engaging for students, and would provide a more complete education in design.

By providing students with a hands-on design project, they were able to truly experience all aspects of the design process, shown in Figure 1.2 (adapted from [1]). Students were provided with a technical specification that contained a description of the needs of the client. From there, they were required to research the way the product worked using in-class dissection demonstrations and internet resources and

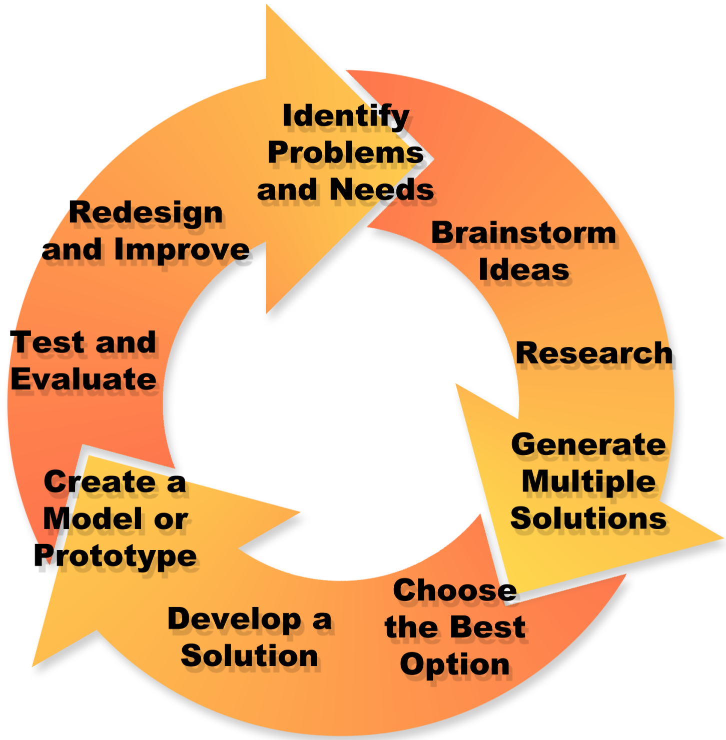


Figure 1.2: Engineering Design Loop (adapted from [1])

brainstorm new ideas for how to replace missing components.

Multiple solutions were generated by the members of the team and the students were able to conceptualize these designs and draw them on paper. An example of one proposed design alternative is given in Figure 1.3. One design was then selected by the team as the best based on its ability to meet the design project requirements.

The hand sketch of the design was translated into a 3D solid model in the computer where students could see how the finished design might appear. A high-quality computer render such as the one in figure 1.4 could also be obtained from the 3D solid modeling software.

In the next stage, the gear models were exported to a simulation package and the

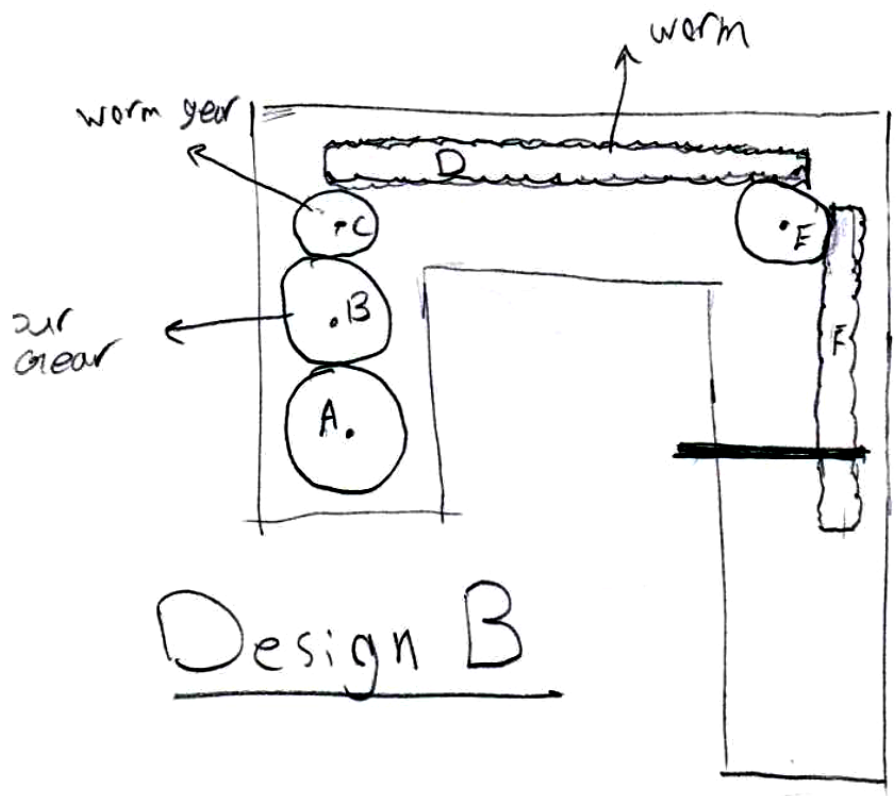


Figure 1.3: Hand sketch of one proposed design alternative [2] (Used by permission)

model was reconstructed by combining ideal gear pairs and inputing the mathematical specifications based on the design on paper and the CAD geometry from the 3D solid model. Students were able to see the design in motion in the 3D viewport, as seen in Figure 1.5(a), and they were able to connect virtual probes to measure simulated output data such as in Figure 1.5(b) for verification and validation of the design.

Finally, students were able to print their model in plastic (as in Figure 1.6) using the rapid prototype printers and hold it in their hands. The process used during the project was iterative, such that the steps could continue around the loop until a final design was achieved and validated using the original design specification.

The iterative nature of the process is reminiscent of Kolb's Experiential Learning

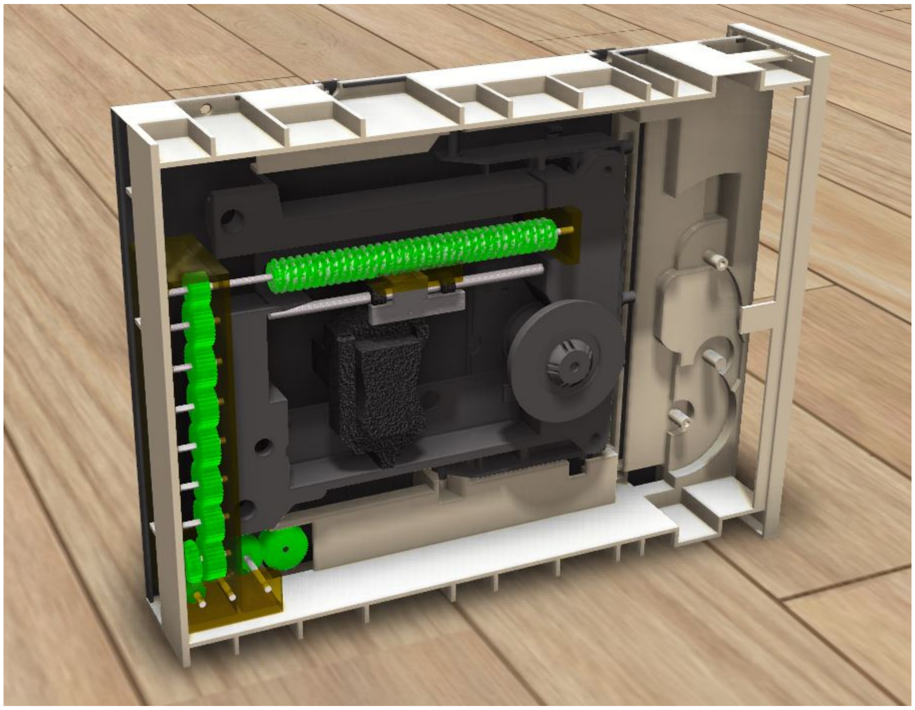
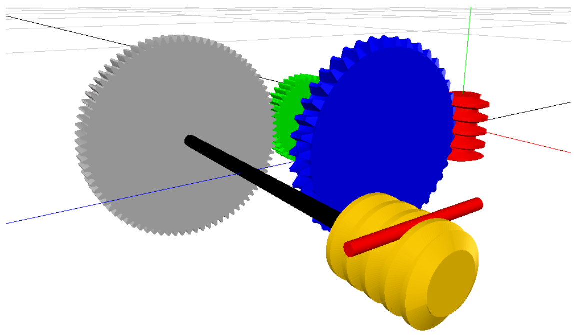


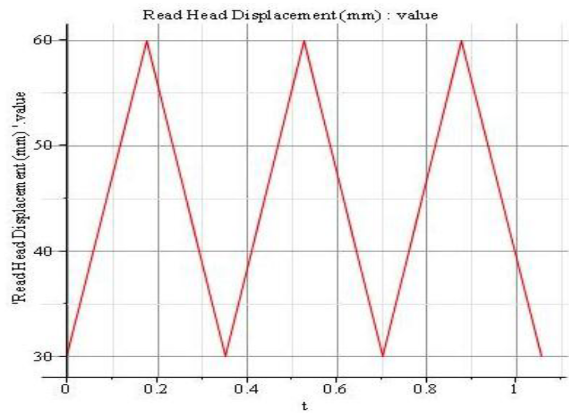
Figure 1.4: Computer render of final design [3] (Used by permission)

Cycle [6]. Kolb theorizes that learning is achieved through a similar iterative process where new knowledge is constructed in the brain through observation of a process, conceptualization of new theories, and experimentation to test those theories. In the design project, this cycle is repeated each time a design alternative is tested and rejected in favour of a better design. A more in-depth discussion of Kolb's Experiential Learning Cycle can be found in Section 2.4.

The domains in Bloom's Taxonomy [5] are fully represented during the design process providing excellent opportunities for Cognitive, Affective and Psychomotor skill development. Cognitive (thinking) skills are developed through the knowledge and mathematics of gear train design. Affective (feeling) learning occurs when students experience satisfaction with a verified design (or disappointment from early



(a) Gear train in the simulator



(b) Output velocity graph

Figure 1.5: Simulation 3D view and sample output graph

iterations) using either simulation results or a physical model with turning gears. Psychomotor (touching) skills are developed through the drag-and-drop interfaces in the solid modeling and simulation software environments, and also through construction of plastic prototypes. More information on Bloom's Taxonomy can be found in Section 2.3.

1.2 Design Project and Modality

The final design project undertaken by students in Engineering 1C03 in the 2012-2013 school year was the culmination of knowledge and skills obtained throughout the course focusing on a gear design retrofit. Students self-selected teams of three and were given a CD-ROM model with missing gear components, as seen in figure 1.1. They were asked to place an ideal motor with an upward facing shaft into a given region and use spur gears, worm/worm gear pairs and a rack-driving worm to

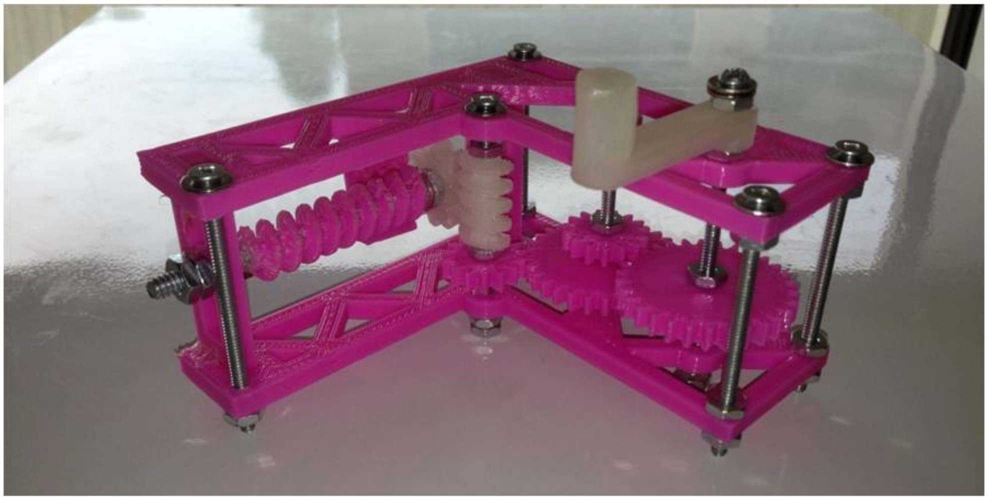


Figure 1.6: Sample final project prototype submission (photo by Omar Boursalie)

translate the rotational motion of the motor into a linear motion on the read head of the CD-ROM drive. The project specification document provided a fixed linear output speed of 30/176 mm/ms (0.170 m/s) for the read head that every team was required to achieve. Each team was given a unique input rotational motor speed based on group number. This made each design unique while unifying the grading process.

Each team was randomly assigned one of three design project modalities for their final project submission; Simulation (SIM), Prototyping (PRT) or Simulation and Prototyping (S+P). Table 1.1 outlines the responsibilities for each of the three modalities. The following subsections provide more detail about submission requirements for each modality.

Table 1.1: Responsibilities and submission requirements for each modality

	SIM	PRT	S+P
Design on Paper	√	√	√
Solid 3D Model	√	√	√
Simulation Software	√		√
3D Printed Model		√	√
Verify Design - Simulation	√		√
Verify Design - Prototype		√	
Validate Design - Simulation	√		
Validate Design - Prototype		√	√
Technical Report	√	√	√
Engineering Drawings	√	√	√
Oral Assessment	√	√	√
Submission of 3D models	√	√	√
Submission of Simulation Files	√		√
Submission of Prototyping Files		√	√
Complete Set of Results	√	√	√

1.2.1 Simulation (SIM)

Teams assigned the Simulation (SIM) modality were expected to create a design on paper, produce a solid 3D model, and create a simulation of their design using simulation software (see section 2.5). These teams were also expected to verify the operation of all parts of the design and validate the design as a whole in the simulator. A technical report was to be submitted along with a complete set of engineering drawings. Each team would be given individual and group oral assessments, and would be expected to submit all 3D models, simulation models and files, and a chapter in the technical report regarding the system modeling and simulation process with results.

1.2.2 Prototyping (PRT)

Teams assigned the Prototyping (PRT) modality were expected to create a design on paper, produce a solid 3D model, and produce a working plastic model of their design using the 3D rapid prototype printers (see section 2.6). These teams were also expected to verify the operation of all parts of the design and validate the design as a whole using the plastic model. The methods for verification and validation were left as an exercise for the students, but one suggestion given was to count the number of turns to the input gear that would produce a fixed output linear motion of the read head and compare that to the original mathematical model. A technical report was to be submitted along with a complete set of engineering drawings. Each team would be given individual and group oral assessments, and would be expected to submit all 3D models, prototyping models and files, and a chapter in the technical report regarding the prototyping process, hardware settings, and results.

1.2.3 Simulation and Prototyping (S+P)

Teams assigned the Simulation and Prototyping (S+P) modality were expected to create a design on paper, produce a solid 3D model, verify their design using simulation software, and produce a plastic model of their design using the 3D rapid prototype printers. These teams were expected to verify the operation of all parts of the design in the simulator, and validate the design as a whole using the plastic model. A technical report was to be submitted along with a complete set of engineering drawings. Each team would be given individual and group oral assessments, and would be expected to submit all 3D models, simulation models and files, prototyping models and files, and a chapter in the technical report regarding the simulation and prototyping processes and results.

1.3 Thesis Problem Statement

This thesis will explore the the differences between the teams assigned to each modality (Simulation [SIM], Prototyping [PRT], and Simulation and Prototyping [S+P]) in terms of self-efficacy and performance.

It is hypothesized that:

1. Students who are assigned a project involving Simulation and Prototyping (S+P) will have higher Engineering Design Self-Efficacy scores.

2. Students who are assigned a project involving Simulation and Prototyping (S+P) will have higher performance scores on the design project.

3. Students who are assigned a project involving Simulation and Prototyping (S+P) will have higher performance scores on the final exam.

4. Students who are assigned a project involving Simulation and Prototyping (S+P) will have higher final course grades.

The expected outcome of the research in this thesis is that Simulation and Prototyping (S+P) can be shown to be a more effective learning paradigm than pure Simulation (SIM) or Prototyping (PRT) alone in a design project involving experiential learning.

1.4 Scope

Experiential Learning is part of a larger philosophy known as Experiential Education [13]. Experiential Education is concerned with the interactions between teacher and student, the construction of experiential exercises for use in the classroom, and broader topics such as educational structure and expected outcomes. Experiential Learning on the other hand is concerned only with the individual student's learning process. This work will focus on the student, and as such the term Experiential Learning will be used.

During the data collection stage of this project the surveys that were administered to participants included questions which identified interest in simulation, interest in rapid prototyping (3D printing), academic motivation, learning preference, self-efficacy, and confidence levels in simulation, prototyping, and gear train design. For the purposes of this study only the survey data pertaining to self-efficacy will be analyzed.

1.5 Significance of the Results

This thesis is designed to provide engineering educators and education researchers with insight into the ways in which new learning tools (such as simulation software and 3D printing) can be implemented to enhance student learning, improve self-efficacy, increase engagement, and boost performance. The results obtained in the study could also be generalized to include any number of new technologies introduced to first year students. By studying student reactions to course technologies we can more completely understand and respond to student needs. This thesis will be useful specifically to instructors of engineering design and graphics courses and early introductions to mechatronics in first year and additionally will have value to anyone involved in course creation or curriculum development related to design in engineering.

1.6 Thesis Organization

The first chapter of this thesis has provided a general introduction to the core concepts which will be further explored throughout the thesis such as the Engineering Design and Graphics course and the design project, as well as design project modalities, the thesis hypotheses, scope, and significance of the results.

Chapter 2 will explore the theoretical background for the project, including the concepts of design, the design process, Bloom's Taxomony, Kolb's Experiential Learning Theory, simulation, and rapid prototyping.

Chapter 3 presents a review of literature related to the topics in this thesis including previous work by the author, first year design, Bloom's Taxonomy, experiential learning, simulation-based learning, and self-efficacy.

Chapter 4 provides an overview of the methods used to obtain the data used in this study including the development of a self-efficacy scale, reliability and validity testing for the scale, data collection through self-efficacy and performance assessments, and data analysis methods.

Chapter 5 contains a complete set of the results of the statistical analysis of the data including population, self-efficacy scale reliability and validity, self-efficacy difference over time, and performance.

Chapter 6 presents a discussion of the results and their significance including population, self-efficacy, and performance.

Chapter 7 delivers conclusions and discusses potential future areas of research as well as providing recommendations for the future of engineering courses and the use of experiential learning.

Chapter 2

Theoretical Background

In this chapter, a theoretical background is given for the topics explored throughout this study.

2.1 Design

The Oxford Dictionary defines the word *design* [14] as a noun as in:

> *a plan or drawing produced to show the look and function or workings of a building, garment, or other object before it is made*

or as a verb as in:

> *to decide upon the look and functioning of (a building, garment, or other object), by making a detailed drawing of it*

Design may be a union of art and science, a combination of ideas, creation of new products or processes, or simply a doodle in a notebook.

2.2 The Design Process

In the world of engineering, *design* takes on a more formal meaning, most often referring to the series of steps that one must take to move from idea to finished product. These steps are commonly known as the *design process*.

The steps of the design process vary slightly depending on the source material but generally follow the same basics which include defining the problem, doing research into existing solutions or previous approaches, generating a series of design alternatives and selecting the best, creating a model or prototype of the design, testing the design to ensure it meets the original requirements, and looping back to the beginning to refine the design. The particular version used in the Engineering Design and Graphics course is adapted from Dym and Little [4] and is shown in Figure 2.1.

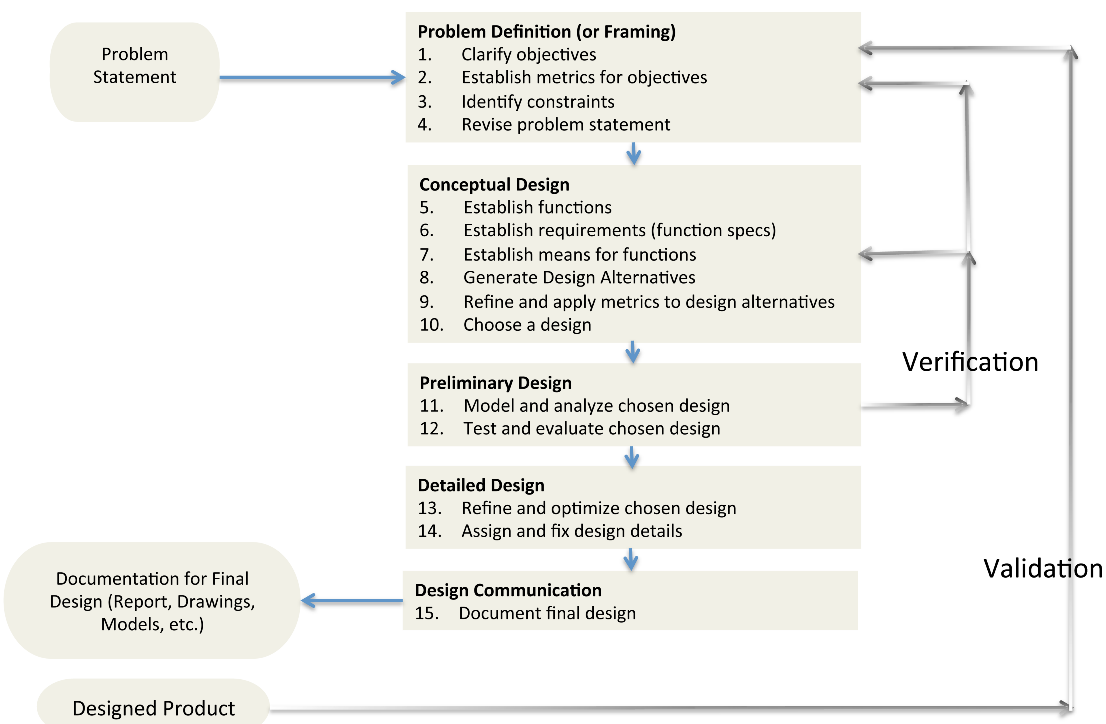


Figure 2.1: The Design Process (adapted from [4])

This model, showing a series of blocks where the steps are further divided, also clearly shows the iterative nature of the process. Verification of the design is done periodically between the blocks and if the product or process being designed does not pass the verification then the earlier steps can be repeated. The final designed product is validated against the original requirements and can also be moved back to the beginning of the process for redesign or improvement.

2.3 Bloom's Taxonomy

In 1956, a committee of educators led by American educational psychologist Benjamin Bloom created a theoretical framework for classification of student learning objectives. This framework, known today as Bloom's Taxonomy [5], divides educational objectives into three domains. The Cognitive domain refers to knowledge and thinking, and represents the most traditional method of education. The Affective domain refers more to the feelings and emotions that accompany learning. The Psychomotor domain refers to physical skills and learned actions. Bloom's Taxonomy inspires educators to focus on all three domains and create a more complete and holistic form of learning.

2.3.1 Cognitive

The Cognitive domain refers to knowledge, thinking, understanding, and the use of the brain in the learning process. The subcategories in the cognitive domain underwent a minor revision in 2001 [15] and are now given in the form of levels starting with *Remembering*, then *Understanding*, *Applying*, *Analyzing*, *Evaluating*, and *Creating*. In the design project, the cognitive domain was represented through the technical knowledge of gear train design. Students were asked to *recognize* and *recall* types of gears and mathematical formulae related to gear train design. They had to *interpret* and *explain* the use of the various gear types, and *implement* formulae to *understand* the behavior of gears in given designs. They had to *organize* the given designs, *applying knowledge* of the parts into a complete system of gears. They had to *evaluate* what had been done and *critique* the methodology which prepared them for the final part which was *creating* a new design by *combining* all the elements.

2.3.2 Affective

The Affective domain refers to the feelings and emotions that accompany learning, and is symbolized by the heart. This domain also contains levels which were characterized by the emotional responses that students had to the technologies that were employed in the final design project [16]. Most students had little to no experience with simulation or rapid prototyping when they entered the course, and this lack of experience may have produced excitement, discouragement, or any number of other positive or negative effects. Affective learning began with *passive listening*, either to an instructor or to their peers and team members about new project ideas. Students *responded* and shared their own views and opinions. *Valuing* occurred when a student placed a value on a process, item, or new piece of information and began to internally weigh the relevance of certain information against some others. All of this relevant information was then *processed* and *organized*, *combined* and *compared* with other internal ideas. Finally, new *ideas and beliefs were formed*.

2.3.3 Psychomotor

The psychomotor domain is about learned physical skill and dexterity [17]. Like the other domains, the psychomotor domain consists of a series of progressive steps which were represented throughout the design project. First, students used their *perception* to observe gears moving and could *form ideas* about how creating a rotation on one gear would cause a reactive change in another. Students prepared themselves by entering a *mindset* for working with gears. Students used simulation software or 3D printers to create models of designs *guided by an instructor* through course work and lab instruction and assignments. After some *experimentation* (and inevitable failures) students began to understand and could *successfully perform the task* of creating a gear train. Mastery of these skills by continuous, repetitive tasks could eventually lead to *automatic response* such as assembly-line pre-programmed behaviors where an individual could perform a task so easily that they do not have to think about it while they are doing it, *adaptation of materials* for tasks for which they were not originally designed, or creative new ways of thinking about gears and combinations, but these psychomotor levels were beyond the scope of the design project.

2.3.4 Overlapping Domains

Figure 2.2 illustrates a theoretical overlap between the Cognitive, Affective and Psychomotor domains. By focusing on this overlap and providing students with exercises that encompass aspects from each domain it was hypothesized that a more complete learning experience could be achieved. Engineering Design and Graphics provided students with Cognitive, Affective and Psychomotor domain skills through the various elements of the design project. The goal was to provide a more complete model

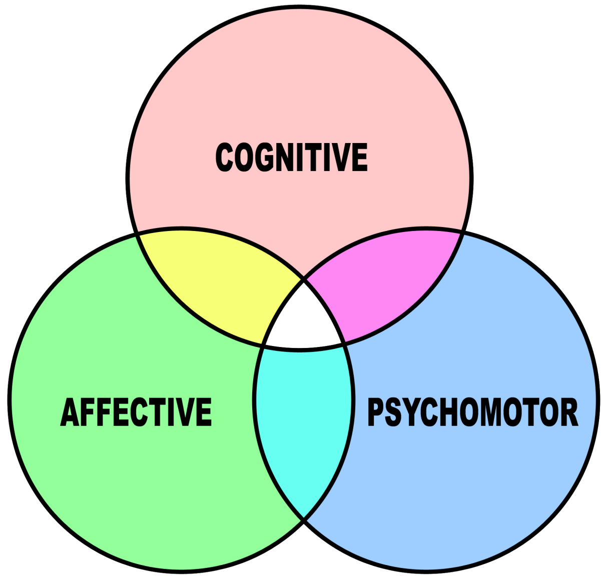


Figure 2.2: The overlapping domains of Bloom's Taxonomy (adapted from Bloom [5])

for learning and thereby increase engagement, retention, and performance.

2.4 Kolb's Experiential Learning Theory

The word *experiential* is derived from the root word *experience*. One obvious definition of Experiential Learning then is *learning through experience*. This experience can

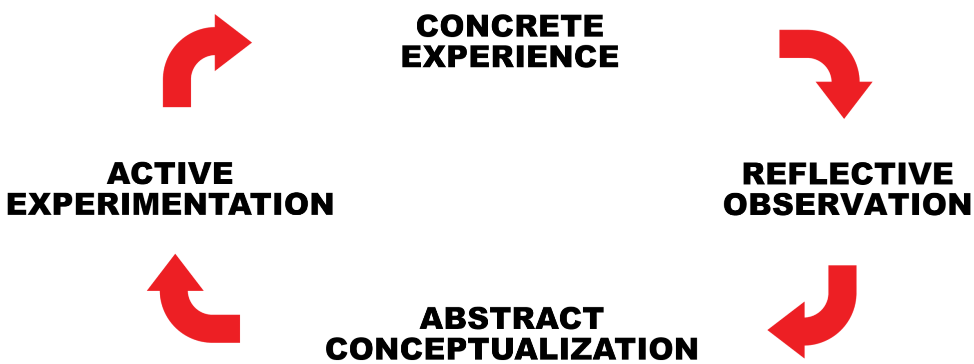


Figure 2.3: Kolb's Experiential Learning Cycle [6]

be gained in the classroom, in the laboratory, or on-the-job. It is not uncommon to find many different definitions for the term depending on the source material. Some will use the basic definition above while others choose to enhance the definition to *hands-on learning* or *learning by doing*. This study chooses to use the more formal reference to Kolb's Experiential Learning Theory (ELT) [6] which emphasizes the importance of active, hands-on experience in the learning process. The theory describes the cycle in which new knowledge is formed within the individual.

Kolb's learning cycle, fundamental to ELT [6], is shown in figure 2.3. The cycle consists of four discrete steps. Typically the loop begins with Concrete Experience, but according to the theory it can start at any of the four steps.

Concrete Experience Concrete experience refers to the knowledge that an individual or group has obtained from some form of exercise or doing (rather than watching). This is the foundation for each of the following steps.

Reflective Observation Reflective observation is a period of non-doing and thinking about the exercise or what has been experienced. This stage involves questioning and reviewing the knowledge obtained in the previous step.

Abstract Conceptualization Abstract conceptualization is where the individual or group begins to understand and interpret the information and the relationships between events. New theories are formulated about what will happen under certain conditions of change.

Active Experimentation Active experimentation is where theories are put to the test.

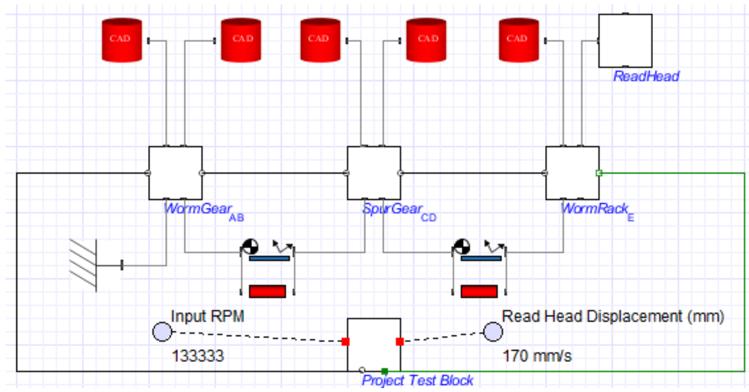
> Predictions are made and then proven or disproven through a detailed plan. The experimental results form the basis for new concrete experience, and the cycle continues.

By providing students with a hands-on design project, they were able to experience all aspects of the design process described in Section 2.2. They were able to conceptualize a design, draw the design on paper, and translate the design into a 3D solid model in the computer. They could translate the 3D model to a visual simulation package and see it move and obtain virtual instrument measurement data for design validation. Finally, they could fabricate their model using the rapid prototype printers and hold it in their hands.

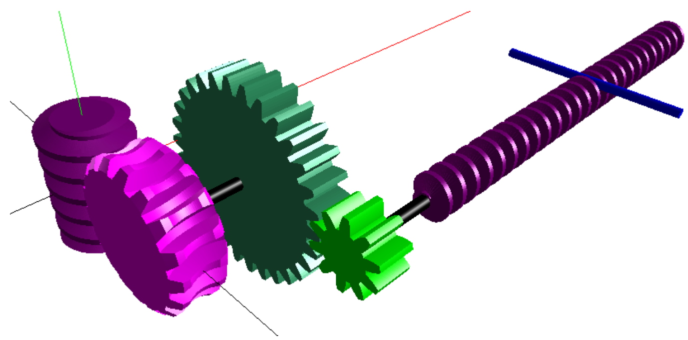
This process encompassed all parts of Kolb's Experiential Learning Cycle. Concrete experience was obtained through the use of 3D solid modeling software, simulation software, and 3D printers. Reflective observation occurred at the end of each stage of development, where students could reflect on what they had accomplished and some of the limitations of their design. Abstract conceptualization occurred when students theorized about how they might have made design changes to improve their design in future revisions. Active experimentation occurred when students built their designs using the software or hardware and implemented proposed changes. Finally, new concrete experience was obtained when the design had been completed.

2.5 Simulation

The Oxford Dictionary defines the word *Simulation* as the noun form of *Simulate* [18], which means:



(a) 2D simulation view



(b) 3D simulation view

Figure 2.4: Example student submissions for simulated gear train

to pretend to have or feel (an emotion)

or, more suited to our purposes:

to produce a computer model of.

Simulation can be used in places where it is dangerous or impractical to work (such as in medical simulations), or where resources are limited (since software can be less expensive for students than complete sets of gears and tools, for example).

In the Engineering Design and Graphics course, simulation was used to verify and validate gear train designs. The software allowed the user to create a chain of gears as in Figure 2.4(a) and enter a rotational input velocity to induce movement. Gear orientation and rotation could be visually observed on screen in the 3D viewport as in Figure 2.4(b). Virtual probes could be attached to measure and plot intermediate and output velocities as in Figure 2.5.

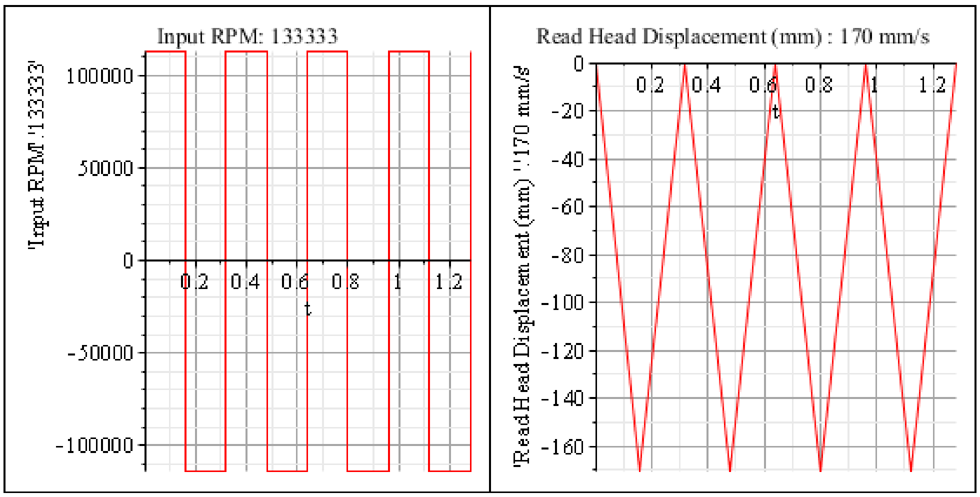


Figure 2.5: Sample input and output graphs

Using simulation allowed the students to quickly and easily verify and validate their designs by comparing the simulated outputs to their hand calculations. They were also encouraged to investigate design alternatives by making modifications to parameters such as gear size, number of teeth, or input velocity.

2.6 Prototyping

The word *Prototype* [19] is defined by the Oxford Dictionary as:

> *a first or preliminary version of a device or vehicle from which other forms are developed; the first, original, or typical form of something; an archetype.*

In the Engineering Design and Graphics course, a prototype was a plastic model created using a 3D printer (a type of rapid prototyping machine) such as the RepRap-Pro Huxley 3D printer shown in Figure 2.6. Prototyping was the process of creating the model.

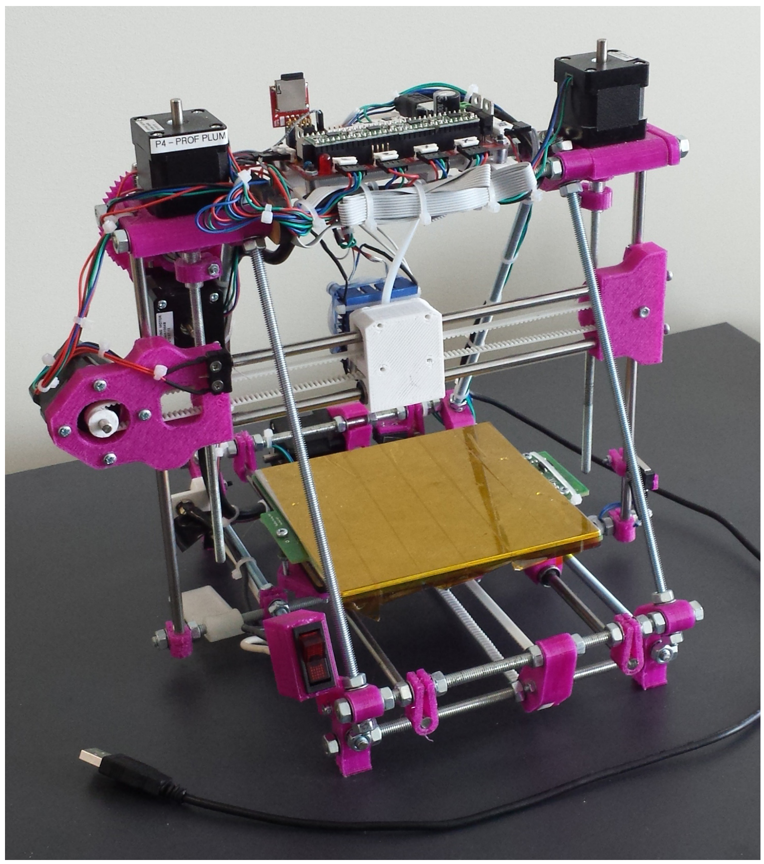


Figure 2.6: RepRapPro Huxley 3D printer [7]

Rapid prototyping machines can use either additive or subtractive processes. In additive-type machines such as 3D printers, material is added to a work area and built up layer-by-layer until the model is complete. Subtractive-type machines such as computer numerical control (CNC) routing and milling machines start with a large piece and remove unwanted material by cutting or drilling. Subtractive machines can use metal tools, lasers, or even high-pressure water to remove material.

The Engineering Design and Graphics course utilized nine (9) RepRapPro Huxley 3D printers. These additive-type prototyping machines employed a corn-based plastic called Polylactic Acid (PLA). PLA, shown in Figure 2.7, was found to be ideal for printing because it was low-cost, non-toxic, biodegradable [20], and produced high quality printed parts. PLA was purchased in a variety of colours for use in the course.

Figure 2.7: PLA printing filament

Chapter 3

Literature Review

This chapter presents a review of existing literature relating to the topics in this thesis.

3.1 Previous Work By The Author

Self-efficacy is the belief in one's own ability to achieve a certain level of attainment. Self-efficacy is a self-concept, like confidence, only more specific in that it adds a directed goal. In a 2012 study, our research found that increasing self-efficacy should be a primary concern for engineering educators as self-efficacy can be important to student retention, involvement, and performance in engineering and technology fields [21]. The research in the paper builds on self-efficacy research by Albert Bandura who created the concept in 1977 and established four main sources for self-efficacy: (a) Mastery experiences, which are the individual's personal beliefs about their own performance, (b) Vicarious experiences, which are perceptions of the performance of others, (c) Social persuasions, which include judgment by peers and superiors, and

(d) Physiological states, which refers to the enjoyment, interest, and satisfaction that one feels for the topic [22]. Drive and Motivation was used as a fifth source and these categories were used in a pilot study to create a self-efficacy inventory which we administered to first-year engineering students in March 2012. We found that students who had completed a design project in Engineering Design and Graphics had higher self-efficacy and involvement scores than students who were enrolled in the course but had not yet completed the project. In addition, a correlation between self-efficacy and involvement (a sense of belonging to the engineering community) was found for both groups, with a higher correlation for those who had completed the project. We concluded that students feel more confident in their engineering abilities and feel a greater sense of belonging when their abilities have been put to the test through a design project [21].

Students have preferences for the way they learn, and our research has shown that these preferences have an effect on self-efficacy and performance [23]. Students in the Fall 2012 term of Engineering Design and Graphics were given the VARK learning styles inventory by Fleming [24] which provides a means to identify and quantify preferences for Visual, Aural/Auditory, Read/Write, and Kinesthetic learning preferences. These preferences are identified by the tools by which students feel they are most comfortable using.

Visual Preference for maps, charts, and symbols

Aural/Auditory Preference for lectures, group discussion, and radio

Read/Write Preference for books, internet searches, and printed material

Kinesthetic Preference for a more hands-on approach with simulation, video, and live demonstrations

VARK was chosen because it clearly identifies Visual and Kinesthetic learning preferences, which best aligned with the introduction of 3D printers to the course. Students were given two surveys: one at the beginning of term which included 10 self-efficacy questions, and one at the end of term which included the same 10 self-efficacy questions and the 16-question VARK survey [25]. Performance data was also collected from 15 gear design calculation questions taken from the final exam. Results were sorted by the modality of design project that the student had completed. Our results indicated an increase in self-efficacy for all learning preference categories in all modalities. Visual learners showed the highest increase in self-efficacy by learning preference. The Prototyping (PRT) modality students showed the highest increase in self-efficacy by modality. Visual learners given a Prototyping project (V-PRT) showed a statistically significant largest self-efficacy increase than other combinations. Our results for performance indicated the highest scores for Visual learners by learning preference and Simulation and Prototyping (S+P) students by modality. For combinations, Kinesthetic learners assigned a Simulation project (K-SIM) had the highest overall grades. Our research concludes that there are some combinations of learning preference and design project modality which are well or poorly suited for combination. One such poor combination might be Read/Write learners with a hands-on prototyping project (R-PRT), while a well-suited combination would be Kinesthetic learners with a purely simulation design project (K-SIM) [23].

3.2 First Year Design

Design is one of the most important components to all disciplines of engineering. It is often heard that engineering is fundamentally about design. Researchers from the University of Calgary examined and evaluated the strengths and weaknesses of design education and the various approaches used throughout North American by institutions offering engineering courses. Veltman et al. state that getting a first year design course *right*, that is using the proper educational approach, can have a significant positive impact on the first year experience and potentially increase student retention [26]. The first approach that was studied consisted of lectures and seminars with topics on design methodology and cases studies. This approach was common since it was the least resource-intensive in terms of instruction and testing, but the lack of opportunities for students to apply theoretical knowledge may have reduced the effectiveness of students to provide true engineering analysis and design [26]. The second approach used experiential learning though small-scale and reverse-engineering projects. Here there were many opportunities for students to put theory into practice, but often the limited resources available for projects would make it difficult to cover the entire design process within the course and project constraints. The third approach used full-scale (often industrial or community) projects which despite being the most resource-intensive did provide students with the most complete design process experiences. This approach did however limit students' opportunities to learn from their own design failures through iteration. The study concludes that students tend to have a keen desire to see and (ideally) do engineering which makes first year design experience particularly important [26].

Building on previous work developed in the early 1990's, a new course was introduced to freshman engineers at Federal University of Santa Catarina (UFSC) in Brazil in 1999. The course was designed to introduce the real world of control engineering to first-year students with the goal of developing an initial understanding about engineering knowledge and improving professional skills. Practical exercises were found to increase motivation and a sense of professional belonging [27]. Concepts used in the creation of the course included that new knowledge is based on previous learning, and that students act as mediators of knowledge for each other. In this way, students can solve problems in groups that could not otherwise be solved alone [27]. In addition, problems that are put in a competitive context can increase motivation. Vallim et al. state that the core of the creative process is the design project which should be introduced early in the undergraduate curriculum and not withheld until upper years [27]. Specific technical knowledge should be balanced with abstract thinking, and professional skills such as group work, communication, and leadership should be developed. Professors should be responsible for passing on engineering technical and cultural knowledge to students, and students should be provided with support resources [27]. In the UFSC course, students were given practical design projects involving LEGO-based robots where they were challenged with solving a series of design problems. Students worked with the professor as client and consultant, learning about designing a complete system from parts. Vallim et al state that multiple solutions exist for any problem, and that the term *project* refers to the process of looking for solutions among several alternatives. They conclude that real-world skills are developed through the design projects presented in first-year, and should continue to be enhanced and practiced using similar projects at all levels of study [27].

Researchers at the University of Arizona studied the effect of different hands-on course models on first-year student design process knowledge [28]. Ernst et al. state that engineering design is one of the most important, yet one of the most difficult concepts for students to understand, and that universities are opting for a hands-on approach to promote learning [28]. They also suggest that the solid understanding of design created in first-year can promote a stronger context in upper years. Topics studied included needs/requirements identification, idea generation, analysis and decision-making, building and testing, design process iteration, time allotment, and documentation. In their paper only minor or non-significant differences in design process knowledge were found between the groups of students in different hands-on projects, yet previous research had found some significant (unstated) differences between students taking hands-on projects and students with non-hands-on projects. The research suggests that students learn more through the use of hands-on design projects in first year, though the specific nature of the hands-on project does not seem to matter [28].

The School of Engineering and Applied Science (SEAS) at Miami University has adopted a common first-year curriculum for all incoming engineering students which has provided an opportunity to expose students to engineering fundamentals such as the design process. One course, *Computing, Engineering, and Society* has recently changed from using a week-by-week introduction to each engineering discipline to a more complete and holistic educational model that demonstrates the entire design process loop by having students design a model train layout. Students completing the course using each course model were evaluated and students who participated in the model train version of the course were found to be more familiar with the design process and be more willing to engage in project-related discussions [29]. Students in the new model could recite the elements of the design loop, but had difficulty applying those elements to new problems and indicated a disconnect between traditional course work (homework, exams, math) and problem solving [29]. One identified major issue was the wide variance in the amount of time that students spent on the project, with some students carrying teams, making decisions, building the layout, and even spending more time than expected for a one-credit course while other less-motivated students allowed them to carry the workload. Another identified issue was a need for more mathematical analysis such as scale calculations for train speed and scenery sizes. Troy et al. believe that offering students a realistic engineering design experience is an effective approach to introduce first-year students to the various disciplines of engineering [29].

Engineering schools throughout Canada and the United States use different approaches to first year engineering design education that can generally be classified into three categories: Traditional education, Project-based learning, and Simulation-based learning. Schools that opt for a more traditional approach focus on the fundamentals of math and science and provide little or no practical design experience for first year students. Project-based learning (PjBL) schools will assign design projects, with either the course instructor or an outside agency working as the client. This approach is most in-line with the experiential learning concepts discussed throughout the thesis and has been adopted by many schools. Simulation-based learning (SBL) employs computer-aided design tools to create complex mathematical models of real world structures and mechanisms that can be used for experiments in a virtual environment inside the computer. Simulation can be used for simple assignments or as part

Table 3.1: First year engineering design educational approach

Institution	Country	First Year Design	Enrollment
California Institute of Technology	USA	Traditional [30]	265
Dartmouth College	USA	Traditional and PjBL [31]	269
Harvey Mudd College	USA	Traditional and PjBL [32]	198
Massachusetts Institute of Technology	USA	Traditional [33]	1141
McGill University	Canada	Traditional [34]	771
McMaster University	Canada	Traditional, SBL and PjBL [35]	1230
Queen's University	Canada	Traditional and PjBL [36]	650
Rose-Hulman Institute of Technology	USA	Traditional and PjBL [37]	561
Simon Fraser University	Canada	Traditional [38]	150
Stanford University	USA	Traditional [39]	2209†
University of Alberta	Canada	Traditional [40]	770
University of British Columbia	Canada	Traditional [41]	852
University of California - Berkeley	USA	Traditional [42]	≈1600
University of Toronto	Canada	Traditional and PjBL [43]	1339
University of Waterloo	Canada	Traditional and SBL‡ [44]	≈1590

Traditional refers to math and science fundamentals, with little or no design
PjBL refers to Project-based Learning, SBL refers to Simulation-based Learning
† Total freshman enrolment - Engineering declared as major in second year
‡ Dependant on the engineering program choice, not offered in all

of a larger design project. Table 3.1 lists some high-rated schools for engineering education in Canada and the United States and the approach used for first year engineering design education.

3.3 Bloom's Taxonomy

Benjamin Bloom was the head of a group of educational psychologists who in 1956 developed a classification for the various levels of intellectual behaviors required for learning. Although the document describes three domains of learning (cognitive, affective, psychomotor) only the cognitive domain was fully described. The formal document referring to the cognitive domain has come to be known as Bloom's Taxonomy [5]. In the 1990's a new group led by one of Bloom's former students updated the taxonomy and made the language more modern [15].

The cognitive domain of the original taxonomy contains the categories of knowledge, comprehension, application, analysis, synthesis, and evaluation. Each category (except application) also contained subcategories. The understanding was that mastery of each category would be necessary before moving to the next, more challenging category. For example, a students should be given a good working knowledge of a topic before they can move on to more challenging topics such as comprehension and application [8].

The revised taxonomy updates the categories to remembering, understanding, applying, analyzing, evaluating, and creating [45]. Figure 3.1 shows the complete mapping from the old version to the new version. The first four categories of the revised taxonomy map closely to the first four in the original taxonomy. The last two map to the last two of the original taxonomy but in the reverse order, as more modern

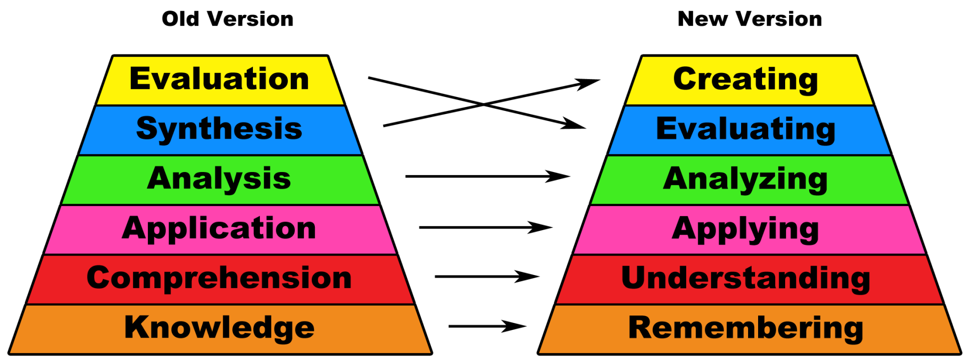


Figure 3.1: Bloom Levels (adapted from [8])

thinking promotes evaluation of criteria coming before creation of new material. The revised taxonomy also includes a second dimension to the knowledge domain, where specific types of knowledge can be called upon in each category.

Metacognitive knowledge has been added to the revised taxonomy in the knowledge category, and refers generally to knowledge about learning and thinking that a student may have [46]. Strategic knowledge is knowledge about strategies for learning and thinking, knowledge of tasks refers to types of cognitive tasks and common classroom and cultural conventions, and self-knowledge (which is critically important) refers to knowledge about the specific methods of learning that work best for the individual. Metacognitive knowledge is generally linked to improved student learning and should be explicitly taught to students [46].

There are several methods for acquiring knowledge, and some are better than others. The authors of one paper [47] discuss some of these methods and evaluate them using the revised taxonomy, focusing on the cognitive processes. Many methods place emphasis on *remembering* to promote retention of knowledge, but adding the cognitive processes associated with the other categories can promote true learning. Analysis of all of the cognitive processes can help educators to build better assessment tools that go beyond recognition and recall of facts [47].

3.4 Experiential Learning

A study completed by researchers at the Rochester Institute of Technology describes how student learning has been improved by the incorporation of an experiential learning model into a third-year Thermodynamics course. The methodology used in the study was based on Kolb's experiential learning model which consists of four stages including concrete experiences, reflective observations, abstract conceptualization, and active experimentation. Students entered the course with various levels of experience and may have accomplished the first and/or second stages of the model. The classroom became an ideal venue to deliver information about the first and second stages and to bring students to similar experience levels [48]. Students created various physical devices relating to course topics which allowed them to experiment (stage four) and reflect (stage two) rather than simply listening to a lecture or discussion. Ideally, students would become able to anticipate possible outcomes (conceptualization, stage three) [48]. The course had a high student satisfaction score and appeared to be achieving its learning objectives according to student evaluations [48]. The course obtained the highest score of all courses taught in the department, and results for the improved experiential course were higher than the original (non-experiential) version of the course [48].

A study on educational robotics used an experiential *hands-on* model to effectively educate technical college, high school, and university level students and stimulate intellectual maturity [49]. The paper contains an explanation of a project-based robotics course with a curriculum focused on designing, building, and operating autonomous robots. Students used robotics kits with mechanical parts to create various robots with specific tasks and then program their motions and movements for performing those tasks. The course aimed to integrate physics and technical mechanics in a general context and robotics provided a possible approach. Students gained experiences in machine control, practice in synthesis and analysis of mechanisms, development of spatial imagery and visualization capabilities, as well as development of creativity, technical, and practical skills [49]. Student assessments of the course indicated a contribution to understanding of mechanisms and their analysis and physical modeling. Students were very interested and motivated to study mechanisms in a robotics and CAD environment. The experiences gained indicated that activities with *digital manipulatives* promote the achievement of learning objectives and that practice designing and operating with robotic kits can improve understanding of mechanics concepts and skills in spatial imagery and visualization [49].

According to researchers from the University of Michigan engineers must be educated as *creative innovators* [50]. To accomplish this, three complimentary learning programs were implemented: a multidisciplinary design program, an entrepreneurship program, and an international engineering program. Verner et al. state that arriving students were typically excited about engineering and design work and the potential future impact it would have, yet they often struggled to understand the connection between classroom knowledge and their future profession [50]. Rather than focusing on traditional engineering and science programs, these new experiential programs focused on the creative side of engineering. The multidisciplinary program integrated real-world experiences as part of traditional capstone design experience courses and promoted multi-semester experiences that covered the complete design-build-test (DBT) cycle. The entrepreneurship program was focused on engagement programs and developing the entrepreneurial mindset in engineering students by offering hands-on activities that would help students implement their endeavors. The international program aimed to increase the number of students with international experience by providing study programs, internships, volunteer work, and research out of the country. These new experiential programs were designed to solidify approaches to empower students with experience and practice necessary to manifest their solutions to the world's problems [50].

3.5 Simulation-Based Learning

Simulation-based learning (SBL) involves the use of computer-aided design tools to create complex mathematical models of real world structures and mechanisms that can be used for experiments in a virtual environment inside the computer. Simulation can be used in places where it may be too expensive or too dangerous to create a real-world model or prototype.

A study investigated students' perceptions of simulation-based learning and its relationships to learning outcomes. Researchers found that of all computer-aided pedagogical methods, simulation-based learning (SBL) was generally regarded as one of the most flexible and effective [51]. Lin et al. state that many studies have addressed specific designs and functionalities of SBL tools, however few have examined how the learner feels about using these tools. The findings imply that teaching is an interactive process and that the learner's perception of the instruction tools may influence the usage of the tools and the learning outcomes [51]. A simulation-based learning tool with a higher perceived appeal will result in a higher student engagement in using the tool which may produce a better learning outcome [51]. Results indicated that a student's learning outcome is highly associated with the simulation-based learning tool's appeal to the student, and that understanding of the tool and its use is highly correlated with engagement [51]. Further, students were divided by learning outcome and students with high learning outcomes were found to have higher appeal scores for the SBL tool [51]. The results suggest that simulation-based learning in this context could promote a deeper engagement and more frequent interaction with the tool to seek a better understanding, which could lead to a better learning outcome [51].

Supplementing traditional educational processes with virtual laboratories using interactive 3D simulation can have substantial benefits, according to a 2010 study [52]. Self-directed learning in this forum can improve student motivation and engagement, can reduce resource and space requirements, and can offer a reduction in costs over non-virtual laboratories [52]. Simulated environments can closely replicate a real-world environment, and offer the advantage of providing opportunities to investigate situations which would be difficult, unsafe, or impractical to otherwise explore. Simulation-based learning could increase student competence and promote autonomy and self-directed learning, and computer-based simulation which provides first-hand, interactive learning experiences could also improve student motivation and enhance skill mastery [52]. Findings suggest that basic student needs for competence, relatedness, and autonomy support were met, and also indicate that simulation-based learning can potentially enhance self-regulation of motivation and increase understanding and application [52]. Additional findings indicate that the effects of simulation-based learning in this way varied according to students' educational background, gender, and familiarity with the technology, and that the effectiveness of the strategy may be reduced by such factors.

3.6 Self-Efficacy

Self-efficacy is the belief in one's own ability to achieve a certain level of attainment. The concepts of self-efficacy and self-confidence are often confused. Self-confidence is the more general term that measures the individual's strength of beliefs in his or her own abilities. Self-efficacy adds a specific level of attainment and refers to the strength of the individual's belief in his or her own ability to achieve that specific goal.

A survey designed to identify factors related to student self-efficacy beliefs was administered to first-year engineering students at Purdue University. The findings suggest that science and engineering programs should take responsibility for filling the technology workforce needs of the future by ensuring high retention of students [53]. Additional results of the Purdue survey revealed a number of categories of classification of student responses, including drive and motivation for success, learning and understanding of the material, abilities in using computers, the availability of help and associated resources, course enjoyment, interest and satisfaction, course grading, student abilities for problem-solving, group and teamwork issues, and issues related to completion of assignments. The top three categories as ranked by students were drive and motivation for success, learning and understanding of the material, and abilities in using computers [53].

A follow-up qualitative study by Hutchison-Green et al at Purdue University explored engineering self-efficacy beliefs of students enrolled in their first engineering course. Interviews conducted before the start of the semester indicated and high level of engineering confidence for incoming students, which is consistent with self-efficacy theory since these students had chosen to pursue a career in the challenging and demanding world of engineering [54]. Previous high-school experience in engineering-related concepts was consistently reported as most influential basis for engineering self-confidence among participants. Some of the results were influenced by the speed with which students were able to perform various tasks compared with other students, the level of perceived individual contribution when working in a group environment, the amount of prerequisite material that the individual had mastered, and the individual's incoming grades [54]. Students consistently rated their confidence levels in certain topics by comparing their beliefs in their own abilities against those of their classmates.

Student success is largely due to the experiences they have in the classroom [55]. Specifically, increased learning and student persistence in an engineering course or discipline may result from a greater understanding of how teaching practices can influence student self-perceptions [55]. A multi-university study of undergraduate engineering courses looked at classroom practices and student perceptions of themselves both as students and as future engineering professionals. For example, students who engage in active, hands-on learning experiences are more likely to gain experience from their own accomplishments than students attending and listening passively to lectures [55]. Also, group collaborations provide students with opportunities to observe and model the behaviors of other students. Several topics in self-perception were studied including outcome expectations, students' responsibility for self-learning, students' belief in their abilities to complete an engineering program, motivation to become a professional engineer, and confidence in the abilities to work and perform as a professional engineer. Results show that classroom practices can have more significant influences on student self-perceptions such as self-confidence, academic responsibility, belief in the ability to complete the program, and motivation to become an engineer than other background characteristics of the student [55]. Additionally, clear course and assignment structure, clear instructions and timely and relevant feedback from instructors paired with group projects and peer collaboration produce high gains in student self-perception [55].

Albert Bandura, who pioneered the concept of self-efficacy [22], also created a guide for developing self-efficacy scales which states that there is no all-purpose or *one-size-fits-all* measure for perceived self-efficacy [56]. General purpose scales of this type have limited predictive abilities and fail in explanatory value since they have no relevance to the domain to which they are attached. For this reason, the creator of a self-efficacy scale must tailor the questions to the particular domain that is being measured [56]. It should also be understood that perceived self-efficacy is different than other constructs such as self-esteem (self-confidence, self-worth), outcome expectancies (perceived outcome of a particular path of action rather than the belief in the ability to follow the path), and locus of control (the belief that a circumstance is within the realm of control of the perceiver and not the result of outside forces). A properly designed self-efficacy scale will measure the strengths and limitations of perceived capability in the domain of functioning, and can provide a high level of predictability of outcomes as well as providing a means to tailor a program to the specific needs of the participants [56]. The value of a scale can be measured in terms of reliability and validity, which will be discussed in Section 4.1.2.

Self-efficacy can be a strong predictor of behavior changes such as healthy living [57]. Health behavioral education is particularly interested in the concept of self-efficacy expectation which involves an individual's beliefs about his or her capabilities of achieving specific situational goals. Individuals should not be characterized simply as having a *high* or *low* self-efficacy without reference to a specific circumstance with which the score is associated. Self-efficacy can affect the choices that an individual may make, the amount of effort they will expend on a task, and the amount of time they will continue with a task when faced with obstacles [57]. Self-efficacy expectations can be categorized according to theory set forth by Bandura [22]. Mastery experiences refer to learning though personal experiences and achieving master over feared or difficult tasks. Vicarious experiences include learning by observation of events and people and watching as others master feared or difficult tasks which increases the belief that the individual can overcome the same difficulties. Verbal persuasion refers to verbal judgments by peers or mentors. Physiological state takes into account that individuals may be more likely to expect failure when they are agitated or tense. Self-efficacy appears to be a consistent predictor of short- and long-term successes in all health-related research studied, and a consistently-positive relationship was found between self-efficacy and health behavior change and maintenance. Many health-related programs that are designed to enhance healthy living and practices are implicitly enhancing self-efficacy expectations, and the conclusion of this study is that these types of programs could be further improved if they are designed to directly target increasing self-efficacy.

A Canadian study investigated *computer-use self-efficacy*, or more generally the individuals' beliefs about their own abilities to use computers in a competent manner. Computer-use self-efficacy in those individuals was found to significantly influence the amount of time and frequency of computer use, the individuals' emotional reactions such as anxiety with computers, and outcome expectancies from computer use [58]. Group support such as the use of computers by others and encouragement by others was found to have a positive influence on individual computer-use self-efficacy and outcome expectancies [58]. Individuals' behaviors and feelings were also highly influenced by computer-use self-efficacy. The results showed that participants with high computer-use self-efficacy scores derived the most enjoyment from computer use, experienced less anxiety toward computers in general, and used computers for more time and with greater frequency than individuals with lower scores [58].

A growing trend in engineering education involves understanding the ways that students learn and improving and customizing teaching methods to promote more effective learning. An instrument for measuring task-specific self-concepts (such as engineering self-efficacy, anxiety, motivation, and outcome expectancies) was developed and validated for this purpose by Carberry et al [59]. The authors define a *task-specific self-concept* as any variable concerning the understanding an individual has of him or herself for a given task. They also suggest that the desire or lack of desire to perform any given task is dependent on self-understanding. Findings indicate that the steps in the design process can be used as levels of attainment for the purpose of measuring perceived task-specific self-concepts (such as self-efficacy) [59].

The researchers state that previous engineering experiences play a large role in engineering design self-efficacy. This effect was shown by significant differences in self-efficacy scores between participants in groups with low, intermediate, and high levels of engineering experience. High correlations were also found between engineering self-efficacy, anxiety, motivation, and outcome expectancy for engineering design which goes a long way to confirming the theoretical concepts of self-efficacy theory [59].

Early experience with engineering concepts can create a high level of interest in pursuing engineering as a course of study, and as a result many colleges and universities aim to increase enrollment by investing in pre-collegiate engineering programs such as campus tours or summer outreach programs (such as McMaster's Learning Enrichment Advancement Program [60] for high-school students or the Venture Science and Engineering Camp [61] for grades 1 through 8). The long-term effects of pre-collegiate engineering experiences on self-efficacy was studied in various engineering disciplines with the hypothesis that self-efficacy related to engineering studies would increase with a greater amount of pre-collegiate engineering experience [62]. Sources of exposure to engineering concepts included toys and hobbies that the student may have experienced and related to some engineering discipline, such as LEGO® and Lincoln Logs™ to civil engineering, Erector Sets® for mechanical engineering, Estes Rockets® and model airplanes for aerospace engineering, microscopes for biological engineering, electronic hobby kits for electrical engineering, or video game production for computer engineering.

First-year engineering self-efficacy provides a good indication of the long-term effects of pre-collegiate engineering experience and can be used to gauge how prepared students feel for studying engineering at the university level [62]. Additional results of the study indicated that students who had pre-collegiate (K-12) experience with engineering concepts had higher engineering self-efficacy scores [62]. In particular students who had taken engineering or technology classes in high school or with hobbies in programming, electronics, producing video games, robotics, or model rockets had significantly higher engineering self-efficacy scores [62]. The findings suggest that pre-collegiate engineering experience may increase self-efficacy and also performance in engineering students and increase retention in engineering programs [62].

Chapter 4

Selected Methodology

This chapter will provide an overview of the methods used to obtain the data used in this study including the development of a self-efficacy scale, reliability and validity testing for a scale to provide justification of its use, data collection through self-efficacy and performance assessments, and data analysis methods.

4.1 Self-Efficacy Scale

One of the principal goals of this study is to determine the effects of design project modality on self-efficacy. To that end, it is first necessary to establish an instrument with which to measure self-efficacy. Several existing self-efficacy scales were investigated, including the General Self-Efficacy Scale [63], but discarded due to their lack of specificity to the research objectives.

Self-efficacy is considered to be domain-specific, meaning that any scale must be tailored specifically for the area of study it intends to measure. Self-efficacy scores between domains may vary significantly since people are not masters of all domains.

As such, there is no *one-size-fits-all* measure for self-efficacy.

4.1.1 Engineering Design Self-Efficacy Scale Development

Since self-efficacy is highly specific to the outcome expectations of the course it was determined that a custom scale should be developed.

The identified domain for first year engineering design was the *cornerstone* design project [64], which focuses on the retrofit and redesign of a gear train (see sections 1.1 and 1.2).

According to Bandura, a good understanding of the domain material is essential for development of a good self-efficacy scale [65]. Questions should be directly related to the domain, and should target factors that have a direct impact on the domain. Scales should include various levels of challenge, such as those defined below.

Ingenuity The measure of how different a project is from other similar projects

Exertion The measure of how much effort has been put into a project

Accuracy The measure of how close a project comes to achieving one or more target parameters

Productivity The measure of how much can be produced and how quickly

Perseverance The measure of how long an individual sticks to a project under pressure

Self-efficacy should measure the level of difficulty that an individual believes they can overcome toward a specific task.

The items in the scale were chosen by domain factors representative of Bandura's identified four areas of self-efficacy which included mastery experiences, vicarious experiences, social persuasions, and physiological states, and the fifth often included area, drive and motivation. A Likert-style [66] response scale was chosen for the questions and ranged from 0 to 10, with 0 being *I strongly disagree*, 5 being *I am impartial or do not care* and 10 being *I strongly agree*. The complete Engineering Design Self-Efficacy Scale is given in Appendix A.

4.1.2 Justification of the scale

In order to justify the use of the new scale, it was tested for both reliability and validity. The results of the reliability and validity tests can be found in Section 5.2. It is important to note that both reliability and validity are a matter of degree. Both reliability and validity can be measured and quantified, but there are some varying opinions on what can be considered *reliable* or *valid*.

4.1.3 Reliability

The Oxford Dictionary defines *Reliable* [67] as:

> *consistently good in quality or performance; able to be trusted.*

Reliability tests if the measurement is dependably consistent and not random, meaning that it would produce the same results under the same circumstances. Most forms of reliability can be computed using correlation, meaning that scores from one set of items is compared to scores from another set of items. Table 4.1 lists the various types of reliability.

Table 4.1: Reliability

Test-Retest Reliability	Measures the degree to which scores are consistent over time, or consistent between testing sessions. Participants are typically given the same test two or more times with some time between the testing sessions. Problems occur when the participants remember the original test, or grow in maturity or learning between tests.
Equivalent-Forms or Alternate-Forms Reliability	Measures the degree to which scores are consistent between different forms of the same test. Participants are given two tests which are equivalent except for the actual items included which may have been reworded or substituted with equivalent items. The problem here would be the difficulty in creating a second unique instrument.
Split-Half Reliability	Measures the degree to which scores are consistent between halves of the items. Participants are given a long test, and the results are split using the odd-even strategy. This is a form of Internal Consistencies Reliability.
Internal Consistencies Reliability	Measures the degree to which item scores relate to each other and to the total of all items. All items are correlated to each other and to the total. This is equivalent to the average of the Split-Half Reliabilities computed for all possible halves.

4.1.4 Validity

Validity [68] is defined as:

> *the degree to which evidence and theory support the interpretations of test scores entailed by proposed uses of tests.*

Validity tests if the scale measures what it is supposed to measure and not some other phenomenon. It is typically computed by calculating a correlation coefficient between the item being measured and some predicted quantifiable outcome. Table 4.2 lists the types of validity.

Table 4.2: Validity

Content Validity	The degree to which the entire domain is represented. Typically logical rather than empirical. Asks if only a subset of the domain is being measured.
Face Validity	The degree to which an instrument appears to measure what it purports to measure. Asks if the instrument looks like it is measuring something other than what was intended.
Criterion-Oriented or Predictive Validity	The degree to which the instrument predicts another quantifiable measure. Asks how well the instrument scores correlate with the scores from the other measure.
Concurrent Validity	The degree to which test scores correlate with another established instrument or valid criterion administered or available at the same time. Asks how well the instrument scores correlate with the scores from the other instrument.
Construct Validity	The degree to which an instrument measures an abstract or hypothetical construct. Asks if the construct can be used to predict some result.

4.2 Assessments

Engineering Design and Graphics is a required course for all first year students. About half of the students take the class in the first term (Fall), and the remaining half take the class in the second term (Winter). This study required data from the full set of first year students so the procedure described here for one term was duplicated in the second term. Any difference in the data collected between the terms was negligible.

The majority of student data was collected through surveys. Two similar but distinct instruments (per term) were created which included the self-efficacy scale from Section 4.1 as well as additional interest points.

The scale given in Appendix A lists the 10 statements chosen to assess self-efficacy. Items 1 and 2 are used to assess self-efficacy based on Mastery experiences, which are beliefs based on things that the participant has done. Items 3 and 4 are used to assess self-efficacy based on Vicarious experiences, which are beliefs based on things that others have done. Items 5 and 6 are used to assess self-efficacy based on Social persuasions, which are beliefs based on the verbal judgments of peers. Items 7 and 8 are used to assess self-efficacy based on Physiological state, which are beliefs based on the mental state of the participant. Items 9 and 10 are used to assess self-efficacy based on Drive and Motivation, which are beliefs based on the desire to better oneself.

The first instrument was administered during the second week of the course. This was the second week of lectures but the first week of labs and tutorials. The instrument was introduced at the end of the lab for each of ten classes over the course of the week. A scripted presentation with slides was delivered to each of the ten classes to maintain the uniformity of the instructions. After explaining the purpose of the study to the students, they were given the choice to participate in the assessment which was delivered online. Students were free to complete the assessment during their weekly lab session, or at any time over the following week when convenient for them. Since the assessment was delivered online, students could use lab computers, laptops, or even their home computers to complete it. Data collected from the first assessment included interest in simulation, interest in rapid prototyping (3D printing), self-efficacy, professional engagement, and academic motivation.

The second instrument was administered during the twelfth week of the course. This was the second-to-last week of lectures and the final week of labs and tutorials. Students were asked to complete the second assessment, again delivered online, after they had completed the course design project oral presentation. The assessment web site remained open for a period of two weeks leading up to the final exam but was closed before the exam itself. Data collected from the second assessment included confidence in simulation, confidence in prototyping, self-efficacy, professional engagement, and learning preference.

The assessment process developed in the first term was repeated for the second term.

4.3 Performance Data

Performance data from consenting participants completing Engineering Design and Graphics was collected and analyzed for use in this study. The performance data collected included project individual grades, project group grades, project total grades, and final exam grades, all using a percentage value. The other performance data collected was final course grade using the 12-point grading scale.

4.4 Data Analysis Methods

Statistical analysis of data was performed using the Statistics Package for Social Sciences (SPSS) by IBM Corp. [69] Data were analyzed using arithmetic mean and standard deviation for basic statistics, and Analysis of Variance (ANOVA) to compare the data for inter-correlations and statistical significance.

In a statistical analysis, the numerical value of *alpha* serves as the significance level of the study. It represents the probability that a given result happens due to an actual observed phenomenon and not by random chance. Social science studies typically use an alpha of 0.05 which means that the data can be considered non-random if the same results would be obtained 95 times out of 100. Alpha is typically chosen by the researcher, and probability constants can be computed for each analysis which can be compared to alpha. Computed probability constants less than alpha indicate statistical significance in the results, meaning that the results are not likely to have occurred by random chance. For this study, an alpha of 0.05 was chosen to test for significance.

Analysis of Variance is the primary tool for making statistical inferences about two or more sets of data [70]. ANOVA compares the variance from the mean of the entire population to the variances from the means when the data is separated into groups. If the variance of the groups is much lower than the variance of the entire population (computed using a ratio and providing a probability or *p-value*), it can be said that there is a statistically significant difference in the variance between the groups.

For the correct use of ANOVA, it is assumed that the data sets consist of two or more independent groups (in our case we use the design project modality as the separator) and one dependent variable (for example, self-efficacy or performance), and that the dependent variable is approximately normally distributed. ANOVA is quite robust, and can usually be used even if the data is not quite normal [71].

ANOVA typically reports the statistical significance of the difference between the groups in terms of *p-value* or probability of randomness, however it cannot determine which groups have the statistically significant difference when there are more than two groups. For this purpose, a Tukey [72] post-hoc test was used to identify the statistically significantly different groups. The Tukey test consisted of a number of simple comparison tests to isolate the groups.

Chapter 5

Results

This chapter will explore the results of the data analysis completed on the survey and performance data obtained from the Fall 2012 and Winter 2013 terms of Engineering Design and Graphics.

5.1 Population

There were a total of 800 students who completed Engineering Design and Graphics in the 2012/2013 school year. Table 5.1 shows the distribution of students by term, the number of students who voluntarily completed the surveys, and the percentage of students that completed the surveys.

Table 5.1: Population Statistics By Term

	Total Students In The Class	Completed The Survey	Percentage
Term 1	427	93	21.78%
Term 2	373	77	20.64%
TOTAL	800	170	21.25%

Due to the low survey response rate and subsequent low N (number of participants) for each term, the decision was made to combine the results from both terms into a single large data set. All results that follow will use the combined data with an N of 170 students.

Students were randomly assigned lab sections by the registrar. Lab sections were randomly assigned one of three modalities such that of the 10 possible lab sections per term, 6 were assigned Simulation (SIM), 2 were assigned Prototyping (PRT), and 2 were assigned Simulation and Prototyping (S+P). Table 5.2 shows the total number of students who were assigned each modality and the total who voluntarily completed the surveys.

Table 5.2: Population Statistics By Modality

	Total Students By Modality	Completed The Survey	Percentage
SIM	468	90	19.23%
PRT	181	50	27.62%
S+P	151	30	19.87%
TOTAL	800	170	21.25%

5.2 Self-Efficacy

As discussed in section 4.1, a developed 10-item self-efficacy instrument was administered to the participants at the beginning and end of the course. The complete Engineering Design Self-Efficacy Scale is given in appendix A.

5.2.1 Scale Reliability

Bandura's work on creating scales to measure self-efficacy [65] suggests using Internal Consistency reliability testing (see section 4.1.3). This form of reliability testing measures how the items relate to each other and to the total.

The most commonly used form of Internal Consistency reliability is Cronbach's Alpha [73] which provides a score based on how well each item compares to each other item as well as to the total when all items are combined. Ideally, all items on the self-efficacy scale should measure the same thing, but by increasing the number of items we ensure that there are no erroneous results that may arise due to confusion or misinterpretation of any single item. Cronbach's Alpha generally increases as the inter-correlations between test items increase, meaning that the overall score will be highest when all items are measuring the same construct.

Cronbach's Alpha is scored on a scale of 0 to 1, with values less than 0.6 providing poor or no inter-correlation (not measuring the same thing), values from 0.6 to 0.7 providing acceptable inter-correlation, values from 0.7 to 0.9 providing good inter-correlation, and values above 0.9 providing excellent inter-correlation.

The first test on the 10-item self efficacy scale based on 167 valid respondents at Time 1 produced a Cronbach's Alpha score of 0.744 which provided a good inter-item correlation and indicated a good level of reliability. The second test based on 160 valid respondents at Time 2 produced an Alpha of 0.722 which also indicated a good level of reliability. The tests suggested that Cronbach's Alpha and reliability could be marginally increased if one or more of the items were removed. The statistical package SPSS provides *Item-Total Statistics* which compares each item in the scale to the total when that item is either included in the total or excluded from the total.

Using this method it was determined that item-total correlation was low (<0.3) at Time 1 for questions 5, 6, and 8. The item-total correlation was also low (<0.3) at Time 2 for questions 5 and 6. Removing these items may have increased the Alpha as high as 0.757 but this minor increase did not seem to warrant the change in scale as was therefore not implemented.

5.2.2 Scale Validity

Bandura also suggests using Predictive and Construct validity testing (see section 4.1.4). By self-efficacy theory, students who score high on self-efficacy tests should perform better at the tasks for which the self-efficacy scale was designed [22]. A correlation that is found between self-efficacy and an outcome indicates the predictive abilities of the construct, and will support its validity.

To test for correlation, the Pearson Correlation Coefficient (PCC) was computed. This value ranges from 0 to 1 with significant correlation values given at 0.3 or higher. Significant correlation refers to the indication that low scores on one measure correspond to low scores on another, and likewise high scores on one correspond to high scores on the other.

The highest correlation found was between the scale and the project individual grade. The Pearson Correlation Coefficient (PCC) was 0.133 with $p=0.087$ ($N=167$) which is not statistically significant at the $p<0.05$ level.

The scale can be validated using Content Validity and Face Validity since all domains of Bandura's self-efficacy theory (mastery experiences, vicarious experiences, social persuasions, and physiological states) are represented. The scale was reviewed by four members of the Engineering faculty at McMaster as well as a social scientist from McMaster's faculty of Health Sciences. All agreed that the scale appears to measure what it purports to measure, being Engineering Design Self-Efficacy. From this we can say that the scale is valid.

5.2.3 Difference over time

The 10-item instrument was administered at the beginning of the course and again at the end of the course. The results of both assessments as well as the average differences in the scores are shown in Table 5.3.

Table 5.3: Self-efficacy scores at the beginning and end of term

	N	Time 1		Time 2		Avg. Diff.
		Mean Avg.	Std. Dev.	Mean Avg.	Std. Dev.	
SIM	80	7.304	1.098	7.882	0.841	0.600
PRT	47	7.390	1.248	8.056	0.985	0.723
S+P	30	7.193	1.197	7.857	1.039	0.663
Total	157	7.310	1.156	7.929	0.923	0.649

At the beginning of term (Time 1) there is no statistically significant difference between the scores for each design project modality, which indicates no self-efficacy bias before the modality was assigned. At the end of term (Time 2) all of the modalities show an increase in mean average self-efficacy scores and a decrease in standard deviation. These results are presented visually in Figure 5.1.

A statistical analysis was performed on the entire population to compare the mean average self-efficacy at Time 1 and Time 2. The descriptive statistics are given in Table 5.4. A dependent t-test (paired-samples t-test) was used to compare the self-efficacy means at Time 1 and Time 2 and indicated a statistically significant increase in self-efficacy from Time 1 to Time 2 (t-value = -7.236, N=157, $p<0.0001$). The

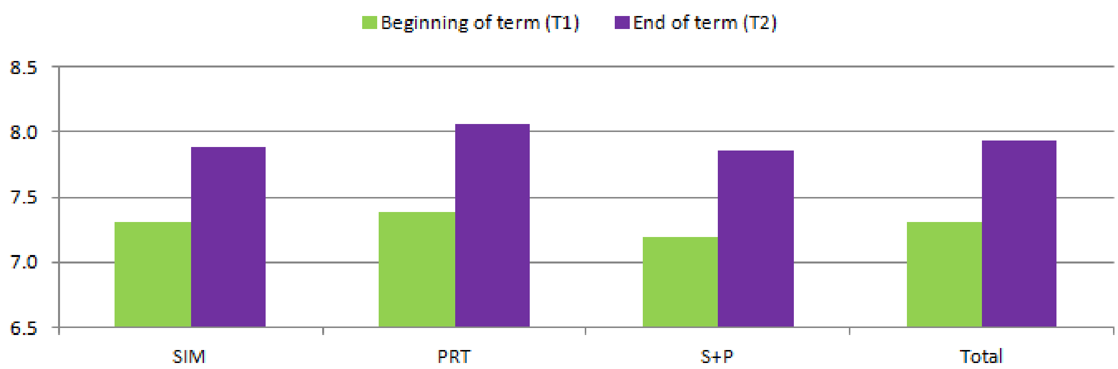


Figure 5.1: Self-efficacy at the beginning and end of term

Pearson Correlation Coefficient (PCC) was 0.437 with p<0.0001 (N=157) which also indicates a statistically significant correlation between the scores.

Table 5.4: Average Self-Efficacy Between Time 1 and Time 2

	Mean	Std. Dev.	N
Average SE at T1	7.31	1.156	167
Average SE at T2	7.93	0.923	160

To test the significance of the scores between modalities, a one-way ANOVA test was completed. The results shown in table 5.5 indicate no statistical significance between groups for self-efficacy at Time 1, Time 2, or the average difference between the times.

5.3 Performance

Performance data collected from participants included design project individual grades, project group grades, project total grades, final exam grades and final course grades. The project performance results are shown in Table 5.6 and the final exam and final course performance results are shown in Table 5.7. Only data from consenting

Table 5.5: One-way ANOVA test results for self-efficacy

		Sum of Squares	df	Mean Square	F	Significance
Avg SE at T1	Between Groups	0.723	2	0.361	0.268	0.765
	Within Groups	221.222	164	1.349		
	Total	221.945	166			
Avg SE at T2	Between Groups	1.118	2	0.559	0.654	0.522
	Within Groups	134.234	157	0.855		
	Total	135.352	159			
Avg Diff	Between Groups	0.458	2	0.229	0.180	0.836
	Within Groups	196.614	154	1.277		
	Total	197.072	156			

participants was collected and analyzed.

Table 5.6: Project performance scores

	N	Project Individual Grade		Project Group Grade		Project Total Grade	
		Mean	St Dv	Mean	St Dv	Mean	St Dv
SIM	90	84.944	13.165	94.041	8.269	92.222	7.509
PRT	50	85.600	10.721	88.043	9.321	87.554	7.942
S+P	30	83.667	12.994	89.417	8.868	88.267	7.894
Total	170	84.912	12.409	91.461	9.079	90.151	7.974

The project performance results are shown visually in Figure 5.2. Students who completed a design project using the Simulation (SIM) modality had higher project group grades and higher project total grades, both with the lowest standard deviation. For project individual grades, students who completed the design project using the Prototyping (PRT) modality had the highest grades and lowest standard deviation.

The final exam performance results are shown visually in Figure 5.3. Students who completed a design project using the Simulation (SIM) modality had the highest

Table 5.7: Final exam and final course performance scores

	N	Final Exam Grade		Final Course Grade	
		Mean	St Dv	Mean	St Dv
SIM	90	72.689	15.084	10.011	2.180
PRT	50	70.674	12.169	9.540	2.032
S+P	30	72.089	9.139	9.900	1.373
Total	170	71.991	13.337	9.853	2.017

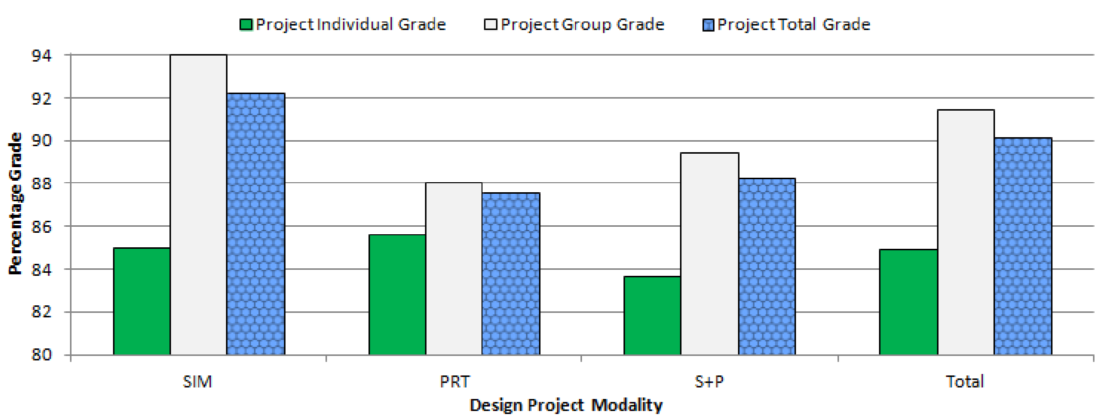


Figure 5.2: Project performance data collected from 170 students

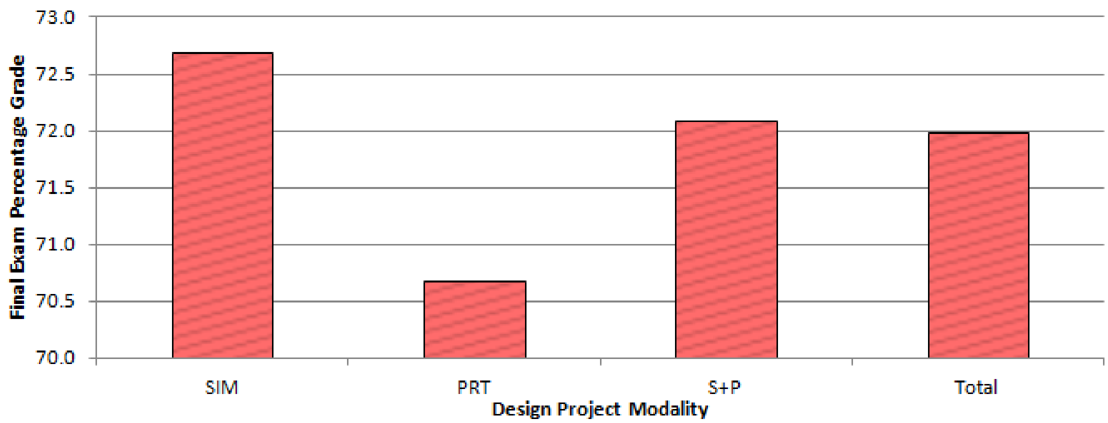


Figure 5.3: Exam performance data collected from 170 students

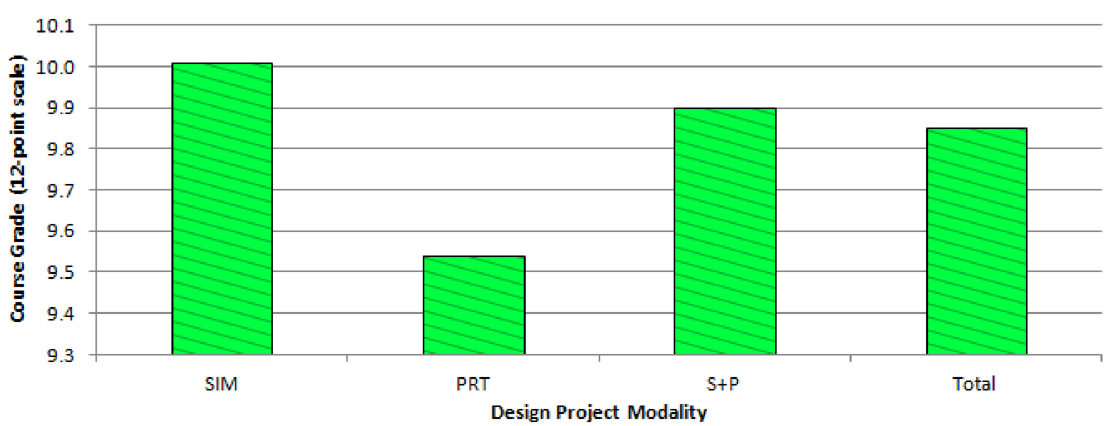


Figure 5.4: Course performance data collected from 170 students

exam grades, however they also had the highest standard deviation. Students who completed a design project in the Prototyping (PRT) modality had the lowest exam grades.

The final course performance results are shown visually in Figure 5.4. Students who completed a design project using the Simulation (SIM) modality had the highest course grades with the highest standard deviation. Students who completed a design project in the Prototyping (PRT) modality had the lowest course grades.

To test the significance of the scores between modalities a one-way ANOVA test was completed for the collected performance data. The results shown in Table 5.8 indicate a statistical significance between the modalities for project group ($p<0.001$) and project total ($p=0.001$) grades.

A post-hoc Tukey test was performed on the project group and project total grades to determine the categorical differences that show statistical significance. The results shown in Table 5.9 indicate a statistical significance ($p<0.05$) between the Simulation (SIM) and Prototyping (PRT) modalities as well as between the Simulation (SIM) and Simulation and Prototyping (S+P) modalities for both project group and project total grades.

Table 5.8: One-way ANOVA test results for perfomance scores

		Sum of Squares	df	Mean Square	F	Sig.
Proj. Ind. Grade	Between Groups	70.288	2	35.144	.226	.798
	Within Groups	25953.389	167	155.410		
	Total	26023.676	169			
Proj. Group Grade	Between Groups	1308.716	2	654.358	8.657	.000
	Within Groups	12622.746	167	75.585		
	Total	13931.462	169			
Proj. Total Grade	Between Groups	829.611	2	414.805	6.986	.001
	Within Groups	9916.512	167	59.380		
	Total	10746.123	169			
Exam Grade	Between Groups	130.910	2	65.455	.365	.695
	Within Groups	29929.404	167	179.218		
	Total	30060.315	169			
Course Grade	Between Groups	7.215	2	3.607	.886	.414
	Within Groups	680.109	167	4.073		
	Total	687.324	169			

Table 5.9: Post-hoc Tukey test on performance scores

			Mean Difference	Sig.	95% Conf. Int.	
					Lwr Bnd	Upr Bnd
Proj. Group Grade	SIM	PRT	5.998*	0.000	2.372	9.625
		S+P	4.624*	0.033	0.290	8.959
	PRT	SIM	-5.998*	0.000	-9.625	-2.372
		S+P	-1.374	0.773	-6.122	3.374
	S+P	SIM	-4.624*	0.033	-8.959	-0.290
		PRT	1.374	0.773	-3.374	6.122
Proj. Total Grade	SIM	PRT	4.667*	0.002	1.453	7.882
		S+P	3.955*	0.042	0.113	7.797
	PRT	SIM	-4.668*	0.002	-7.882	-1.453
		S+P	-0.713	0.915	-4.921	3.496
	S+P	SIM	-3.955*	0.042	-7.797	-0.113
		PRT	0.713	0.915	-3.496	4.921

*. The mean difference is significant at the 0.05 level.

Chapter 6

Discussion

This chapter will present a discussion of the results obtained from the statistical analysis.

6.1 Population

The information presented in Section 5.1 shows that the surveys were offered in the Fall and Winter terms of the 2012/2013 school year to 800 first-year Engineering students. The surveys were voluntary, and as such received 170 valid respondents who completed both surveys and were eligible for inclusion in this study (21.25%).

The chance to win a 3D printer of the same model used in the course was offered to all students as an incentive to participate in this study. There were 521 entries received for the draw (representing 65.12% of the population), however the McMaster Research Ethics Board did not allow the lottery to be restricted to only those students who completed the survey. As a result, participation in the survey was much lower than anticipated.

The decision was made to combine the data from two terms into one larger data set. This survey and performance data collection techniques were identical between the terms and as such did not introduce any bias of results. Data collected from second term may indicate slight variances since students have had an additional four months of schooling, but since all results are averaged and we are not drawing any conclusions between terms the small differences are negligible.

The low number of survey participants may cause some unknown bias in the results, and in future studies it may help to generate new ideas and methods for ensuring a more complete level of participation by the class.

6.2 Self-Efficacy

One of the primary expectations of this study was that assigned design project modality would have an effect on self-efficacy. According to the results in Section 5.2 there was a large statistically significant increase in average self-efficacy from the beginning of term (Time 1) to the end of term (Time 2) for all modalities. This result is justified because students learn about the topics of simulation, prototyping, and gear train design throughout the course. Students have a better understanding of these course topics at the end of term which leads to a higher confidence in their abilities to work and answer questions in those topics.

The average increase in self-efficacy when divided by modality shows no significant difference between the modalities. This was interesting since the 3D printers were the newest addition to the course and as such might have generated a great deal of excitement with the students.

Students who completed the design project in the Simulation (SIM) modality were not required to use the 3D printers for the design project and, due to the time constraints of the project and the limited lab time available toward the end of the course, were generally unable to access the 3D printers after the initial two-week printing unit during weeks 4 and 5. One predicted result was that these students may have felt left out when they were assigned a project that did not require the use of the printers, and this would account for a lower self-efficacy increase.

It was expected that students in the Simulation and Prototyping (S+P) modality would have the highest increase in self-efficacy since they had a more complete exposure to the core course technologies through a requirement in the design project specification. There was little restriction on the use of the simulation software since it was available in the lab to all students and most students had also purchased a copy. Many of the groups assigned a Prototyping (PRT) project also used the simulation software for verification of their designs even though it was not required by the project. Additionally, all students in the course were taught the basics of simulation and prototyping before the design project was assigned. This could also account for the lack of significant findings for self-efficacy.

6.3 Performance

The expectation was that students who completed a design project in the Simulation and Prototyping (S+P) modality would have higher performance scores than students completing a design project in another modality. The results in section 5.3 indicate the highest project individual grades for students in the Prototyping (PRT) modality (by a very small margin), highest grades for project group, project total, final exam, and final course grade for students in the Simulation (SIM) modality.

The project individual grades are very similar, and show no statistical significance for their differences. The result is satisfactory since any significant difference between the groups may have indicated a modality bias in project requirements or marking rather than a knowledge difference between the students in the different modalities. The questions administered during this part of the oral assessment were somewhat general and contained elements of all course knowledge relating to gear design, simulation, and prototyping, but since the examiners were able to choose questions based on the individual's strengths it makes sense that all students would perform strongly regardless of modality.

Project group and project total grades show a statistically significant performance difference with Simulation (SIM) students leading the way. This result may have been influenced by the necessary difference in marking scheme used for students using the 3D printers (both the Prototyping (PRT) and Simulation and Prototyping (S+P) modalities). It may also indicate that students who did not have to spend time using the 3D printers were more free to experiment with the simulation software and could devote more time to it. Future work on this topic could include a qualitative assessment using open ended questions to allow the students to express any strong feelings they may have on the inclusion of the 3D printers on the course and the fairness of the marking between modalities.

Exam grade and final grade, although not significant, show higher performance scores for Simulation (SIM) and Simulation and Prototyping (S+P) compared to Prototyping (PRT) alone. If this result was significant it could show that students with the most exposure to the simulation software were able to more fully understand the course material, and gear design principles in general. The largest number of students who completed the survey also came from the Simulation (SIM) modality, with more than half of all participants (52.9%) completing a project in pure Simulation (SIM) and this fact could also help to explain the results.

From the whole class, again more than half (58.5%) completed the project in the Simulation (SIM) modality. Students who were working in that modality would have the most access to help from other students since more were available. If we include the Simulation and Prototyping (S+P) students, the total available access to peer assistance would have been 77.4% of the population for simulation, and only 41.5% of the population for prototyping.

Additionally, more time was spent in lecture, lab, and tutorial learning about simulation than 3D printing. Most of the prototyping knowledge gained was obtained from trial and error with the 3D printers after a quick lesson in getting started. This would have meant a steeper learning curve for 3D printing students. This would include the Prototyping (PRT) modality as well as the Simulation and Prototyping (S+P) modality, although students discouraged by setbacks with the printing may or may not have been able to step away to another part of the project (ie. simulation) for encouragement depending on their assigned modality which could further explain some of the differences between the Prototyping (PRT) and Simulation and Prototyping (S+P) modality.

Self-efficacy theory suggests that students with the highest self-efficacy will have the highest performance [22]. Students in the Simulation and Prototyping (S+P) modality showed the highest increase in self-efficacy, but did not show the highest performance in any category. Further work is required in this area, where the focal points should be ensuring a proper alignment between self-efficacy and performance measures, and increasing the population of survey respondents so that a fair analysis between the modalities can be completed.

Chapter 7

Conclusions

This thesis has explored the impact of simulation and prototyping introduced to students in Engineering Design and Graphics over the course of the term as well as the differences between the teams assigned to each design project modality in terms of Engineering Design Self-Efficacy and performance.

Based on the results of the study:

1. Students who completed a project in the Simulation and Prototyping (S+P) modality did not have higher Engineering Design Self-Efficacy than students in either Simulation (SIM) or Prototyping (PRT).

2. Students who completed a project involving Simulation (SIM) had higher project group performance grades than students in either Simulation and Prototyping (S+P) or Prototyping (PRT) alone.

3. Students who completed a project involving Simulation (SIM) had higher project total performance grades than students in either Simulation and Prototyping (S+P) or Prototyping (PRT) alone.

4. Students who completed a project in the Simulation and Prototyping (S+P) modality did not have higher project individual performance grades than students in either Simulation (SIM) or Prototyping (PRT).

5. Students who completed a project in the Simulation and Prototyping (S+P) modality did not have higher final exam performance grades than students in either Simulation (SIM) or Prototyping (PRT).

6. Students who completed a project in the Simulation and Prototyping (S+P) modality did not have higher final course performance grades than students in either Simulation (SIM) or Prototyping (PRT).

In conclusion, this thesis has shown that experiential learning through a design project involving either simulation or prototyping promotes an increase in self-efficacy. By self-efficacy theory, this greater sense of self-efficacy could lead to higher performance in students. Students who use simulation in their design projects show the highest performance scores in the design project.

As a recommendation, all first-year engineering design classes should seek to include design projects involving experiential learning such as simulation and prototyping to increase self-efficacy and increase performance scores.

Appendix A

Engineering Design Self-Efficacy Scale

As part of this study, a new self-efficacy scale was developed for use by students in Engineering Design and Graphics at McMaster University (see section 4.1). The items in the scale were chosen by domain factors representative of Bandura's identified four areas of self-efficacy which included mastery experiences, vicarious experiences, social persuasions, and physiological states, and the fifth often included area, drive and motivation. A Likert-style [66] response scale was chosen for the questions and ranged from 0 to 10, with 0 being *I strongly disagree*, 5 being *I am impartial or do not care* and 10 being *I strongly agree*. The complete 10-item instrument is given here.

1. I have sufficient computer skills to create a visual model of any design.
2. I am confident I can deal with any problems I encounter during a design project.
3. Knowing that a project has been successfully completed by others makes me believe I am capable of completing the same project.

4. If I am on the right team, I can accomplish anything.
5. Encouragement from my professor, teaching assistant (TA) or instructional assistant intern (IAI) is important to my ability to complete a project.
6. In general, I often seek the advice of friends (non-team members) when completing a project.
7. Being interested in a course is important to my success in course projects.
8. I am more likely to succeed in a course project if I already have a good mark in the course.
9. I want to succeed, so I will succeed.
10. The desire to better myself is a strong motivation in course work and projects.

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