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Closing the Design Loop in First-year Engineering: Modelling and Simulation for Iterative Design

Thomas E. Doyle, Jon-Michael J. Booth,
David M. Musson
McMaster University

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1 Yonge Street, Suite 2402
Toronto, ON Canada, M5E 1E5

Phone:	(416) 212-3893
Fax:	(416) 212-3899
Web:	www.heqco.ca
E-mail:	info@heqco.ca

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1 Executive Summary

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. McMaster University's first-year Design & Graphics is a required course for all engineering students. The course has taught hand-sketching, 3D solid modeling, system simulation, 3D rapid prototyping, and culminated in a 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), in which they produced and verified a design using a simulation tool; Prototyping (PRT), in which they used a 3D printer to create a working plastic model of a design; or Simulation and Prototyping (SIM+PRT), in which they used both tools to complete a design.

This study examines student self-efficacy and performance outcomes across these three design project modalities. It is hypothesized that students who complete a design project using the Simulation and Prototyping (SIM+PRT) modality will show the highest scores in both categories.

To measure self-efficacy, a new scale (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 differences was completed using ANOVA.

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 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 to engineering course designers and instructors looking to add simulation or rapid prototyping to first-year engineering design courses.

Based on the results of the study:

1. Experiential learning through a design project involving either simulation or prototyping can promote an increase in self-efficacy.
2. Projects involving Simulation (SIM) had higher project (group and total) performance grades than students in either Simulation and Prototyping (SIM+PRT) or Prototyping (PRT) alone.
3. Prototyping projects (PRT or SIM+PRT) present equal or better visualization performance compared to prior cohorts of the course, with SIM+PRT presenting the best result.

In conclusion, this study has shown that experiential learning through a design project involving either simulation or prototyping can promote an increase in self-efficacy. According to self-efficacy theory, this

greater sense of self-efficacy could lead to improved performance in students. Students who use simulation in their design projects show the highest performance scores in the design project.

2 Introduction

Computer-aided design (CAD) is an important component of every engineer's tool set. While CAD is typically associated with technical drawing software, this definition being extended with the recent introduction of lower-cost rapid-prototyping 'three-dimensional printers.' As CAD continues to advance the modelling of parts and assemblies, the ability to hold and test such models is a fascinating element to which we felt students should be exposed at the earliest stages of their engineering education. The traditional method of teaching the 'Design & Graphics' course to first-year engineers has normally focused on form. By allowing students to take their designs from concept to creation, we can now consider and assess function too.

However, given the investment in resources required to create and support such an addition to the traditional method of teaching Design & Graphics, we first proposed a pilot study to examine the benefits to first-year engineering students of three different types or modalities of design projects:

1) Full simulation (SIM)
2) Full rapid prototyping (PRT)
3) Combined simulation and rapid prototyping (SIM+PRT)

In studying these modalities, we expected to learn how they could improve learning by assessing student perceptions of their experiences with each modality, and student performance in the course.

3 Literature Review

This literature review has been divided into two sections: the first discusses modern trends in engineering design education, while the second covers the literature on self-efficacy as it relates to engineering design education.

3.1 Engineering Design Education: Practice and Theory

Modern engineering design education is increasingly focusing on experiential-style learning. While learning takes many forms (Krathwohl, 2002; Mayer, 2002; Pintrich, 2002), we have restricted our discussion to hands-on and simulation-based experiential learning, as these are most relevant to our project.

3.1.1 Hands-on Experiential Learning

A study completed by researchers at the Rochester Institute of Technology describes how student learning can be 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 (Kolb, 1984).

Students entered the course with various levels of experience and may have attained 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 (Bailey & Chambers, 2004). 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) (Bailey & Chambers, 2002). According to student evaluations, the course appeared to be achieving its learning objectives. Furthermore, it obtained the highest student satisfaction scores of all courses taught in the department, and results for the improved experiential version of the course were higher than for the original (non-experiential) version (Bailey & Chambers, 2004).

A study on educational robotics used an experiential hands-on model to educate technical college, high school and university-level students and to develop their intellectual maturity (Verner & Korchnoy, 2005). The project-based robotics course used a curriculum focused on designing, building and operating autonomous robots. Students used robotics kits with mechanical parts to build various robots with specific tasks in mind, and then programmed their motions and movements to perform 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 (Verner & Korchnoy, 2005). Student assessments of the course indicated that students gained a better understanding of mechanisms and their analysis and of physical modeling. Students were very interested and motivated to study mechanisms in a robotics and CAD environment. The report concluded that activities with digital manipulatives can promote the achievement of learning objectives and that practice designing and operating with robotic kits can improve student understanding of mechanics concepts and the development of skills in spatial imagery and visualization (Verner & Korchnoy, 2005).

According to researchers from the University of Michigan, engineers must be educated as creative innovators. To accomplish this, three complementary learning programs were implemented: a multidisciplinary design program, an entrepreneurship program and an international engineering program. Conger et al. (2010) state that incoming 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. 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 an entrepreneurial mindset in engineering students by offering hands-on activities that would help students see their plans through to fruition. The international program aimed to increase the number of students with international experience by providing study programs, internships, volunteer work and research opportunities outside of the country. These new experiential programs were designed to solidify approaches to empower students with the experience and practice necessary to manifest their solutions to the world's problems (Conger et al., 2010).

Taken together, these three studies demonstrate some of the ways in which experiential learning is being incorporated into postsecondary engineering programs, and highlight that these additions are often met with an increase in student satisfaction.

3.1.2 Simulation-based Experiential Learning

One way in which experiential education can be built into an engineering course is through the introduction of 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. These models can then be used for experiments in a virtual environment inside the computer. This is particularly helpful in areas 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 relationship 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. Results also indicated that a student's learning outcome is closely associated with the simulation-based learning tool's appeal to the student, and that understanding of the tool and its use are highly correlated with engagement (Lin et al., 2012). A simulation-based learning tool with a higher perceived appeal will thus result in higher student engagement when using the tool, which may in turn produce a better learning outcome (Lin et al., 2012).

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

3.1.3 Project-based Learning and Visualization

The literature on project-based learning (PjBL), not to be confused with problem-based learning (PBL), demonstrates an increasing international adoption of PjBL in engineering education. However, surveys of faculty have found resistance to implementing PjBL until the efficacy of the method is proven. The authors believe that studies such as the one reported here will help guide the use of PjBL in a broader range of engineering topics.

Cölln et al.'s (2012) paper on visual perception found that students who manipulated three-dimensional CAD models performed better than those who only manipulated static three-dimensional CAD or two-dimensional engineering drawings. This result supports the hypothesis that simulation-based learning using interactive three-dimensional models can improve student's visualization performance.

3.2 Self-efficacy

The concepts of self-efficacy and self-confidence are often confused. While self-confidence is a general term that measures an individual's strength of belief in his or her own abilities, self-efficacy refers more specifically to the belief in one's own ability to achieve a certain level of attainment. Self-efficacy can be a strong predictor of behaviour changes and affect the choices that an individual makes, 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 (Stretcher et al., 1986).

Assessing self-efficacy can be a difficult proposition. Albert Bandura, who pioneered the concept of self-efficacy (Bandura, 1977), 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 (Pajares & Urdan, 2006). General purpose scales have limited predictive abilities and explanatory value since they are divorced from the area in which self-efficacy is being measured. For this reason, the creator of a self-efficacy scale must tailor the questions to the particular domain that is being measured (Pajares & Urdan, 2006). It should also be understood that perceived self-efficacy is different from 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. Results can thus allow a program to be tailored to the specific needs of participants (Pajares & Urdan, 2006).

3.2.1 Self-efficacy and Engineering Education

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 enrolment by investing in pre-collegiate engineering programs such as campus tours or summer outreach programs (such as McMaster's Learning Enrichment Advancement Program for high-school students or the Venture Science and Engineering Camp (leap.mcmaster.ca) for students in grades 1 through 8). The long-term effects of pre-collegiate engineering experiences on self-efficacy were 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 (Fantz et al., 2011). 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 (Fantz et al., 2011). Additional study results indicated that students who had pre-collegiate (K-12) experience with engineering concepts had higher engineering self-efficacy scores (Fantz et al., 2011). 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 (Fantz et al., 2011). The findings suggest that pre-collegiate engineering experience may increase self-efficacy and also performance in engineering students and increase retention in engineering programs (Fantz et al., 2011).

Other studies have evaluated factors that can influence students' self-efficacy in technology environments and in an engineering education context. A Canadian study investigated computer use self-efficacy, or more generally individuals' beliefs about their own abilities to use computers in a competent manner. Computer use self-efficacy was found to influence significantly the amount of time and frequency of computer use, the individuals' emotional reactions such as anxiety with computers, and outcome expectancies from computer use (Compeau & Higgins, 1995-1996). Group support, such as the use of computers by others and encouragement from others, was found to have a positive influence on individual computer use self-efficacy and outcome expectancies (Compeau & Higgins, 1995-1996). Participants with high computer use self-efficacy scores also 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 (Compeau & Higgins, 1995-1996).

A survey identifying factors related to student self-efficacy beliefs was administered to first-year engineering students at Purdue University. While the primary 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 (Hutchison et al., 2006), the survey also revealed that students rank the following categories as most important for their success:

- i) drive and motivation for success,
- ii) learning and understanding of the material, and
- iii) abilities in using computers.

The first element on the list is closely related to self-efficacy.

A follow-up qualitative study by Hutchison-Green et al. (2008) at Purdue University explored the engineering self-efficacy beliefs of students enrolled in their first engineering course. Interviews conducted before the start of the semester indicated a 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 a challenging and demanding field (Hutchison-Green et al., 2008). Participants consistently reported previous high school experience in engineering-related concepts as the most influential factor on engineering self-confidence. Self-efficacy scores were influenced by the speed with which students were able to perform various tasks compared to 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 (Hutchison-Green et al., 2008). Students evaluated their confidence levels on certain topics by comparing their beliefs in their own abilities against those of their classmates.

A growing trend in engineering education involves identifying ways in which students learn best, so that teaching methods can be customized to promote more effective learning (Carberry, 2010; Booth et al., 2012, 2013, 2014; Fleming & Mills 1992).

Carberry et al. (2010) developed and validated an instrument for measuring task-specific self-concepts (such as engineering self-efficacy, anxiety, motivation and outcome expectancies). 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, and 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) (Carberry et al., 2010). Finally, their study also found high correlations 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 (Carberry et al., 2010).

Booth et al. (2012, 2013) explored the relationship of self-efficacy to learning outcomes from engineering student design projects. Booth (2104) developed and validated an Engineering Design Self-Efficacy Scale that is employed for this report.

Fleming et al. (1992) developed the VARK (Visual, Aural, Reading and writing, Kinesthetic) learning styles questionnaire to help students identify their learning preferences.

4 Implementation

As the primary instructor of the first-year engineering technical design course at McMaster University, Dr. Thomas Doyle has attempted several iterations of the curriculum motivated by review and reflection on what it means to teach design. Coming from the author's own experience, the course has shifted from a traditional focus on form to a system modelling approach that places emphasis on functionality of design. Given the increasing global trend to incorporate experiential education at all levels of engineering curriculum (Roach, Hussain & Burdet, 2012; Ruth Graham, 2011; Tseng, Chang, Lou & Chen, 2011), the objective was to implement a project-based approach taking students through a complete design cycle.

To achieve this transformation, Doyle modified a mechanical dissection project (Doyle, 2009) that had previously been part of the curriculum into one requiring the reverse engineering retrofit of an existing gear train (Doyle, Smith & Ieta, 2011). The evolution of the course from 2006 to 2012 is presented in Table 2. To effectively analyze and assess such a project, the course adopted a multi-domain physical modelling software application (MapleSoft, 2013) that permitted first-year students an experiential interaction with a three-dimensional simulation of their designs. The real-time interaction gave students the ability to close the design loop through verification of theory and intermediate design steps, with the complete validation of the system function. However, at this point the resultant design was still digitally abstract and for some students difficult to visualize. It was hypothesized that by incorporating rapid prototyping 3D printing, all students could bring the abstract digital into the physical (Doyle, 2013) and benefit from improved perception, performance and visualization of the final product. The physical models were manufactured using three-dimensional printers available to the first-year students in McMaster Engineering 1's Experiential Playground and Innovation Classroom (EPIC) (McMaster University Engineering 1, 2013).

Table 1: First-year Technical Design Course Progression: 2006, 2009, 2011, 2012

Course	2006	2009	2011	2012
Topics	•Solid Modeling CAD •Hand Sketching •Engineering Drawings	•Solid Modeling CAD •Hand Sketching •Engineering Drawings •Dissection Project •Course Competition	•Solid Modeling CAD •Hand Sketching •Engineering Drawings •Mechanisms/Gear Trains •Directed Dissection •Simulation Based Design Project •Course Competition	•Solid Modeling CAD •Hand Sketching •Engineering Drawings •Mechanisms/Gear Trains •Directed Dissection •Assigned Project Modality •Course Competition
Year 1 Enrolment	857	1083	1304	850
Sections	8	4	4	4
Final Exam	2h	2h	3h	3h
Final Exam Content	•Multiple Choice (visualization) •Isometric sketch •Multiview sketch	•Multiple Choice (visualization) •Isometric sketch •Multiview sketch	•Multiple Choice (visualization) •Multiple Choice (gear train design) •Isometric sketch •Multiview sketch	•Multiple Choice (visualization) •Multiple Choice (gear train design) •Isometric sketch •Multiview sketch
Instructor(s)	Doyle/Elkott	Doyle	Doyle	Doyle

As an introductory engineering design course, we assume no prior knowledge on the part of students. They are first exposed to the concepts of solid modelling and, just prior to the midpoint of the course, when students have basic solid modelling assembly skills, the course focus becomes the understanding and application of simple mechanisms. The team design project is introduced and, as the course progresses, teams are able to apply new material to their project immediately. The topics and project unfold in the following order to form a complete design loop:

1. Simple mechanisms
2. Ideal gears and gear pairs (calculations and solid modelling)
3. Gearing ratio and standards (solid modelling tools for gear design – Autodesk Inventor's Design Accelerator)
4. Simulation of gear pairs (real-time, interactive 3D simulation – Maplesoft's MapleSim)
5. Multistage gear train design
6. Validation and verification of design
7. Manufacturing (3D printing)

4.1 Form vs. Function

While most students become adept at using Computer Aided Design (CAD) software, the traditional assessment focus on the form of a design results in many students having little functional understanding of the parts and assemblies they are modelling. This result highlights the problem with many traditional graphics courses: the emphasis of assessment is based on the mechanical form and not on the function.

In part, this is the result of increased class sizes, limited resources and insufficient tools. The incorporation of a system modelling tool for visualization and simulation into traditional design and graphics courses allows students to gain insight into the mechanical function of the mechanisms they are creating. A system modelling software application would also facilitate the evaluation of the function of a mechanical assembly.

4.2 Mechanisms

To refocus the course, students are introduced to simple mechanisms and shown how such assemblies are found in all technology domains. First-year students are intrigued to learn that a simple slider-crank mechanism (Kinematic Models for Design Digital Library, 2013b) concept is easily observed in the firing of a piston and crankshaft motion in the common internal combustion engine (Kinematic Models for Design Digital Library, 2013a). Providing the tools to harness and drive this intellectual curiosity gives students the ability to experiment with different designs.

The mechanisms introduced are the combinations of spur gears, worm gears and rack gears. The discussion quickly transitions from intuition into the theory of simple mechanisms for the translation of motion. Once the basics of hand calculations and design parameters (e.g., gear ratio, diametral pitch, etc.) are introduced, the student can create the CAD solid model. Figure 1 illustrates the iterative process the student follows in designing the functional mechanism.

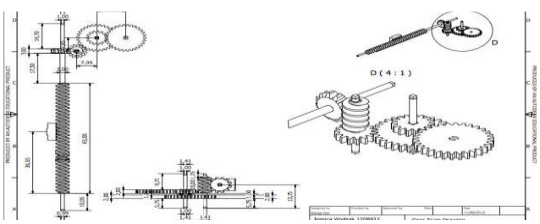
4.3 Systems Approach and Modelling

The system modelling process merges the design form and function into a real-time interactive tool that grants the student the ability to close the design loop through iterative verification. This approach allows the student to experiment and gain confidence by using their course knowledge for a practical application.

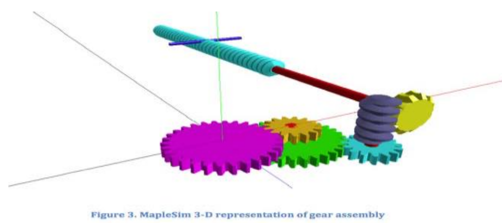
The complexity of a system modelling and simulation software application is non-trivial, and its inclusion in a first-year design course was not without serious consideration. The objective was not to add another tool that would distract from the course objective of teaching functional design. To remain focused on solving the problem, students are given generic gear-pair modules (spur-spur, worm-worm, worm-rack) that are to be customized with hand calculation and solid model geometries. With these modules, the instructor provides the scaffolding necessary to focus on solving the design problem, rather than starting at the ground level of the software application. Solving the design problem requires the cascading of the provided modules to create a much more complex gear train with specific space and time constraints.

Once the students complete their iterative verification of functioning stages of their designs, the finalized design and full validation can be conducted. Figure 1a, b and c present a student submission of a CAD assembly model, system model simulation, and an example virtual probe measurement of linear displacement *vs.* time. With this feedback, students can then proceed to the rapid prototyping of their physical model.

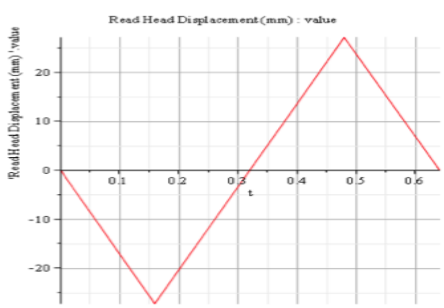
Figure 1: Example of Student Design and Prototype



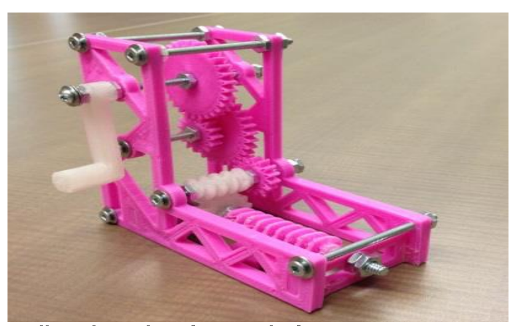
a) CAD Solid Model



b) System Model & Simulation



c) System Simulation Validation



d) Physical Model Prototype

4.4 Rapid Prototyping

The final stage of the course design project is the fabrication of the model using a rapid prototyping three-dimensional printer. This brings the abstract model out of the digital simulation and into the hands of the student. The advent of low-cost rapid prototyping printers (Bowyer, Giacalone & Howyer, 2013) allows students to interact directly with the machines. Figure 5d is a photo of the final physical model after the solid and system modelling.

4.5 Research Questions

Based upon the intervention of rapid prototyping in engineering design, we have studied the pedagogical benefit (measured based on student perception and performance) of incorporating rapid prototyping (3D) printers in project-based learning. By structuring the course in this way, we give the new engineering student the opportunity to experience a complete design loop from concept to creation.

Our research questions for this study were as follows:

(1) Will students assigned to the Simulation and Prototyping (SIM+PRT) project modality score higher than those assigned to the SIM or PRT conditions on:

- engineering design self-efficacy?
- design project performance?
- the final examination?
- final course grades?
- most improved visualization performance?

(2) Will students who are assigned to Protoyping (PRT, SIM+PRT) have the most improved visualization performance compared to prior cohorts?

5 Methodology

In order to collect self-efficacy data that were specific to the course context, we developed and validated a self-efficacy scale, which is included as Appendix 1. Anonymized course performance data were also compared to determine if a particular modality offered a pedagogical advantage.

5.1 Participants

All students enrolled in the first-year Engineering 1C03 Design & Graphics course at McMaster were eligible for the study. The course registered approximately 400 students per term (Fall 2012 and Winter 2013), for a total of 800 students.

5.2 Data Collection

The graduate student investigator, Jon-Michael Booth (who is not a TA or otherwise affiliated with the course), introduced the self-efficacy survey to students during the lab sessions. The survey data were collected using an online form. Performance data (grades) were collected from the Engineering 1 department.

McMaster Research Ethics Board (MREB) approved this study (#2012039).

5.2.1 When Were Data Collected?

Two self-efficacy surveys were run per term (2 terms, total of four surveys) during ENG 1C03, one before the submission of the project and the other after submission. Each student was invited to take part in two surveys. There was no difference between what students in each term were asked to do.

The first survey took place during the first week of labs. While labs normally run for three hours, this first session was exceptional, primarily including demonstration of introductory material, and only ran for 90 minutes. During the extra time, students were free to leave or stay to listen to a talk by the student researcher on the proposed study and to complete the first survey online using the computers in the lab.

The second survey was announced on the course web site and a reminder email was sent to all eligible participants. The survey was available online for students to complete on their own time during week 12 of ENG 1C03 after the design project had been completed but before the final exam.

Two data sets were collected, both containing the same information and differing only in the time at which the survey was administered. Data set 1 was collected in Term 1, with the first survey happening in September 2012 and the second survey happening in December 2012. Data set 2 was collected in Term 2, with the first survey happening in January 2013 and the second survey happening in April 2013. Additionally, performance data (grades) were collected throughout the course. These data were obtained from the professor and with the permission of the Engineering 1 department (already obtained). Performance data collected consisted of the evaluation of assignments, labs, exams and in-class i-clicker responses. Permission from the students was obtained in the letter of information/consent.

5.2.2 How Were Data Collected?

Online surveys: Both surveys were administered online. They consisted of approximately 25-30 closed-ended Likert scale questions and 3-5 short-answer questions. Students accessed the survey through McMaster’s online learning management system. The online system also hosted the letter of informed consent.

Administrative data: Additionally, performance data (grades) and administrative data were collected throughout the course. For the purposes of the study, identifying information was stripped and replaced with a code number. This process was automated, done on the server at the time of submission.

Performance data collected consisted of the evaluation of assignments, labs, exams and in-class i-clicker responses. These data were obtained with the permission of the student through the letter of informed consent. These data were linked with the survey data through the same code number described above.

5.2.3 Compensation

Participants were asked in each survey if they wished to be entered in a draw to win a 3D printer identical to the ones used in the course. Participants who answered 'yes' on either survey were entered once to win the prize. Students who completed both surveys were entered twice and had two chances to win the prize. The prize was a 3D printer kit (not assembled) valued at $669.00.

As required per the McMaster Research Ethics Board, students who started either survey were entered into the draw regardless of whether or not they completed the survey.

5.2.4 Participant Withdrawal

Participants were told during the initial study presentation that they were not obligated to complete either of the surveys. If students chose to withdraw from either of the surveys, they could click the 'Clear the survey and exit without submitting' button online. Once the survey was completed, withdrawal was no longer possible.

Students who did not wish to have their data included could withdraw by simply not completing the survey. There were no penalties or marks deducted for withdrawal or non-completion of the survey, as this research was not connected to course work. Students were informed that they could only be entered in the draw if they answered 'yes' on the associated survey question on either survey.

5.2.5 Confidentiality

Participant data were stripped of identifiers and replaced with a unique code.

Students entered their MACID and student number with the survey. When the student submitted their survey, the student number and MACID were checked against a master list to ensure that students completing the survey were enrolled in the course.

Once this verification was completed, a 'hash' code was generated by the server and stored in the database along with the survey responses. This 'hash' code uniquely identified each survey respondent but could not be decoded to identify either the student number or MACID of the participant. The ‘hash’ code itself was created using the SHA-1 hash algorithm, designed to securely store banking information.

Participant data were stored in a secure database administered by the Engineering 1 department. Participant marks and survey responses were available only to the graduate student investigator, who kept all information confidential. Only aggregate data are reported here and no identifiers are used.

5.3 Self-efficacy Scale

One of the principal goals of this study was to determine the effects of design project modality on self-efficacy. To that end, it was 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 (Schwarzer & Jerusalem, 1995), 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 of self-efficacy.

5.3.1 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 items in the scale were made up of domain factors representative of Bandura's identified four areas of self-efficacy, which include mastery experiences, vicarious experiences, social persuasions and physiological states, and the fifth often-included area, drive and motivation.

The identified domain for first-year engineering design was the cornerstone design project (Doyle, 2011), which focuses on the retrofit and redesign of a gear train.

According to Bandura, a good understanding of the domain material is essential for the development of a good self-efficacy scale (Bandura, 2006). 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 when working to achieve a specific task.

A Likert-style (Likert, 1932) 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 1. 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.

5.4 Justification of the Scale

The new scale was tested for both reliability and validity. 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.'

5.5 Instruments

Design & Graphics is a required course for all first-year engineering students. About half of the students take the class in each of the Fall and Winter terms. Any difference in the data collected between the terms was negligible.

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

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 10 classes over the course of the week. A scripted presentation with slides was delivered to each of the 10 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. 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 survey, again delivered online, after they had completed the course design project oral presentation. The survey 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 survey included confidence in simulation, confidence in prototyping, self-efficacy, professional engagement and learning preference.

5.6 Performance Data

Performance data from consenting participants were collected and analyzed for use in the 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 were final course grade using the 12-point GPA scale at McMaster.

5.7 Data Analysis Methods

For this study, an alpha value of 0.05 was chosen to test for significance.

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 are not quite normal.

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 (Tukey, 1977) 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.

6 Results

This section will present the results of the data analysis completed on the survey and performance data obtained from the Fall 2012 and Winter 2013 terms of Design & Graphics.

6.1 Population

Due to the survey response rate and subsequent number of full 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 a total of 170 respondents.

Table 2: Population Statistics by Term

	Total Students in the Class	Completed the Survey	
Term 1	427	93	21.78%
Term 2	373	77	20.64%
TOTAL	800	170	21.25%

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, six were assigned Simulation (SIM), two were assigned Prototyping (PRT), and two were assigned Simulation and Prototyping (SIM+PRT). Table 6 shows the total number of students who were assigned to each modality and the total who voluntarily completed the surveys.

Table 3: Population Statistics by Modality

	Total Students by Modality	Completed the Survey	
SIM	468	90	19.23%
PRT	181	50	27.62%
SIM+PRT	151	30	19.87%
TOTAL	800	170	21.25%

6.2 Self-efficacy Instruments

A 10-item self-efficacy instrument developed for this study was administered to the participants at the beginning and end of the course. With 167 responses, reliability of the Time 1, 10-item self-efficacy instrument provided a good inter-item correlation and indicated a good level of reliability with a Cronbach's alpha value of 0.74. Reliability of the Time 2, 160 response, 10-item self-efficacy instrument presents a similar result with $\alpha = 0.72$.

The scale can be validated using content validity and face validity (Bandura, 1977) 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 appeared to measure engineering design self-efficacy. From this we can suggest that the scale is valid.

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

6.3 Start and End of Term Instruments

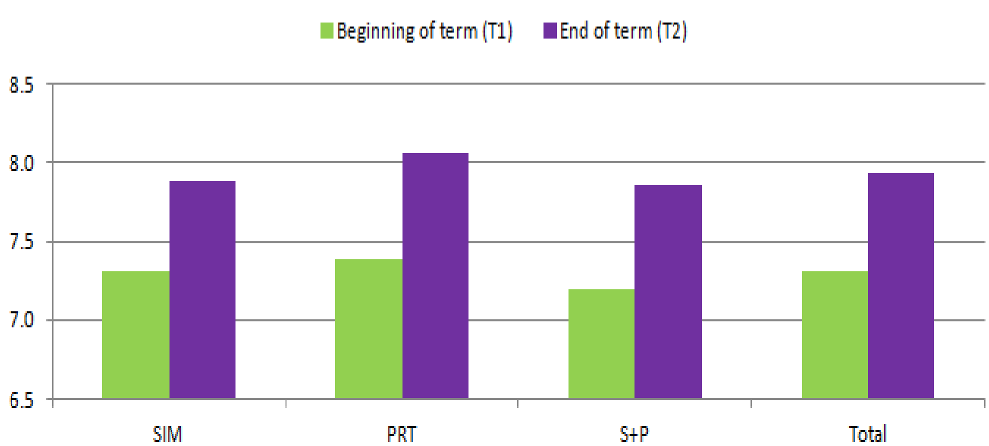
The 10-item instrument was administered at the beginning of the course and again at the end of the course. The results of both assessments as well as the average differences in the scores are shown in Table 7.

Table 4: Self-efficacy Scores at the Beginning and End of Term

Project Modality	N	Time 1		Time 2		Average Difference
		Mean Avg.	Std. Dev.	Mean Avg.	Std. Dev.	
SIM	80	7.30	1.098	7.88	0.84	0.60
PRT	47	7.39	1.248	8.06	0.99	0.72
SIM+PRT	30	7.19	1.197	7.86	1.04	0.66
Total	157	7.31	1.156	7.93	0.92	0.65

At the beginning of the 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 the 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 9.

Figure 2: Self-efficacy at the Beginning and End of Term



A statistical analysis was performed on the entire population to compare the mean self-efficacy at Time 1 and Time 2. The descriptive statistics are given in Table 5. 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 Pearson correlation coefficient was 0.437 with p=0.0001 (N=157), which also indicates a statistically significant correlation between the scores.

Table 5: Average Self-efficacy between Time 1 and Time 2

	Mean	Std. Dev.	N
Average SE at T1	7.31	1.16	167
Average SE at T2	7.93	0.92	160

Table 6: One-way ANOVA Test Results for Self-efficacy

		Sum of Squares	Df	Mean Square	F	Significance
Avg. SE at T1	Between Groups	0.72	2	0.36	0.27	0.77
	Within Groups	221.22	164	1.35		
	Total	221.95	166			
Avg. SE at T2	Between Groups	1.12	2	0.56	0.65	0.52
	Within Groups	134.23	157	0.86		
	Total	135.35	159			
Avg. Diff	Between Groups	0.46	2	0.23	0.18	0.84
	Within Groups	196.61	154	1.28		
	Total	197.07	156			

To test the significance of the scores between modalities, a one-way ANOVA was completed. The results shown in Table 6 indicate no statistical significance between groups for self-efficacy at Time 1, Time 2 or the average difference between the times.

6.4 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 7, and the final exam and final course performance results are shown in Table 8. Only data from consenting participants were collected and analyzed.

Table 7: Project Performance Scores (Percent)

	N	**Project Individual Grade**		**Project Group Grade**		**Project Total Grade**	
		Mean	St Dv	Mean	St Dv	Mean	St Dv
SIM	90	84.94	13.17	94.04	8.27	92.22	7.51
PRT	50	85.60	10.72	88.04	9.32	87.55	7.94
SIM+PRT	30	83.67	12.99	89.42	8.87	88.27	7.89
Total	170	84.91	12.41	91.46	9.08	90.15	7.97

Table 8: Final Exam and Final Course Performance Scores

	N	**Final Exam Grade**		**Final Course Grade**	
		Mean	St Dv	Mean	St Dv
SIM	90	72.69	15.08	10.01	2.18
PRT	50	70.67	12.17	9.54	2.03
SIM+PRT	30	72.09	9.14	9.90	1.37
Total	170	71.99	13.34	9.85	2.02

Figure 3: Project Performance Data Collected from 170 Students

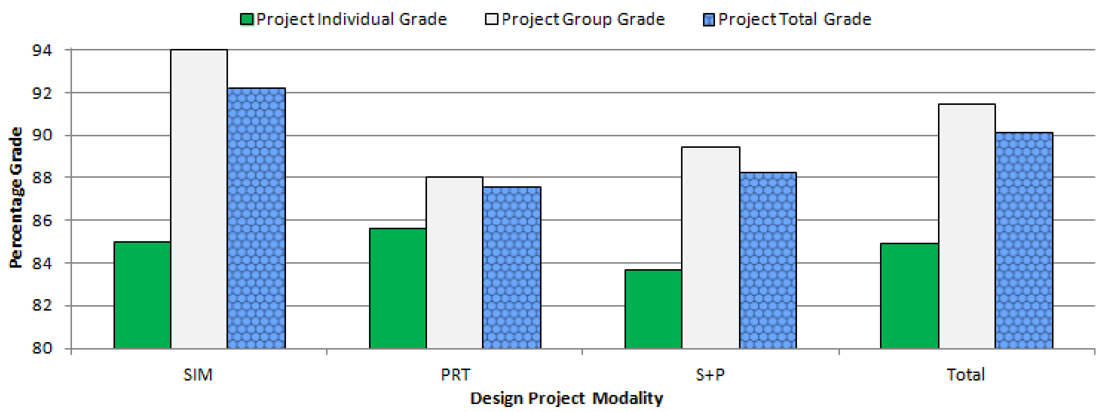


Figure 4: Exam Performance Data Collected from 170 Students

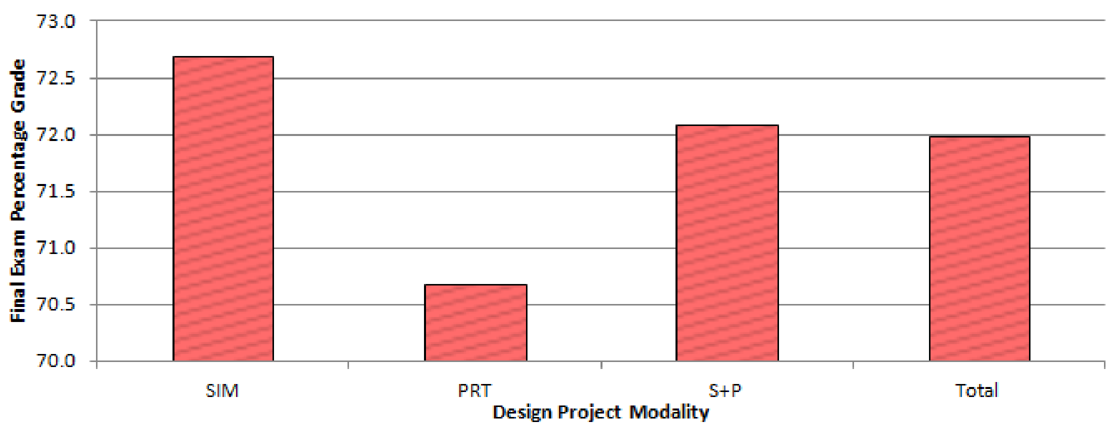
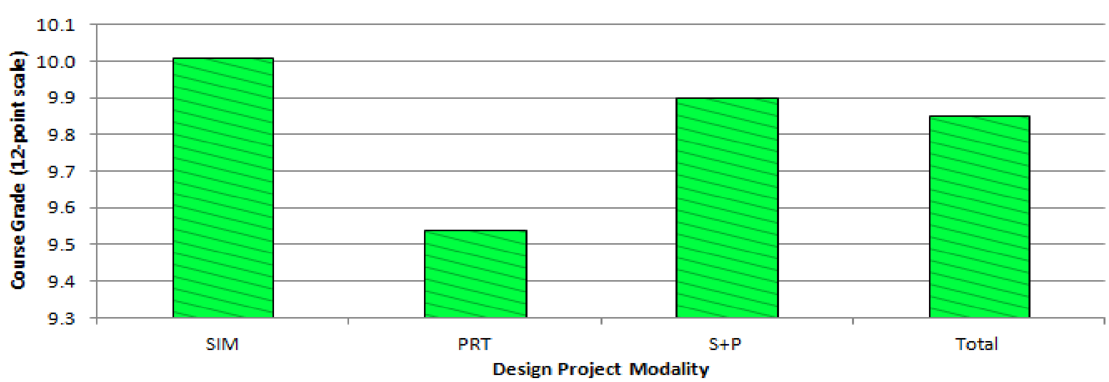


Figure 5: Course Performance Data Collected from 170 Students



The project performance results are shown visually in Figure 3. 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 4. Students who completed a design project using the Simulation (SIM) modality had the highest exam grades, but 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. 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 9 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 10 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 (SIM+PRT) modalities for both project group and project total grades.

Table 9: One-way ANOVA Test Results for Performance Scores

		Sum of Squares	df	Mean Square	F	Significance
Project Individual Grade	Between Groups	70.28	2	35.14	.23	.80
	Within Groups	25953.39	167	155.41		
	Total	26023.68	169			
Project Group Grade	Between Groups	1308.72	2	654.36	8.66	.00
	Within Groups	12622.75	167	75.59		
	Total	13931.46	169			

		Sum of Squares	df	Mean Square	F	Significance
Project Total Grade	Between Groups	829.61	2	414.81	6.99	.00
	Within Groups	9916.51	167	59.38		
	Total	10746.12	169			
Final Exam Grade	Between Groups	130.91	2	65.46	.37	.70
	Within Groups	29929.40	167	179.22		
	Total	30060.32	169			
Overall Course Grade	Between Groups	7.22	2	3.61	.89	.41
	Within Groups	680.11	167	4.07		
	Total	687.32	169			

Table 10: Post-hoc Tukey Test on Performance Scores

			Mean Difference	Significance	95% Conf. Int.	
					Lwr Bnd	Upr Bnd
Project Group Grade	SIM	PRT	6.00*	0.00	2.37	9.63
		SIM+PRT	4.62*	0.03	0.29	8.96
	PRT	SIM	-6.00*	0.00	-9.63	-2.37
		SIM+PRT	-1.37	0.77	-6.12	3.37
	SIM+PRT	SIM	-4.62*	0.03	-8.96	-0.29
		PRT	1.37	0.77	-3.37	6.12
Project Total Grade	SIM	PRT	4.67*	0.00	1.45	7.88
		SIM+PRT	3.96*	0.04	0.11	7.80
	PRT	SIM	-4.67*	0.00	-7.88	-1.45
		SIM+PRT	-0.71	0.92	-4.92	3.50
	SIM+PRT	SIM	-3.96*	0.04	-7.80	-0.11
		PRT	0.71	0.92	-3.50	4.92
*. The mean difference is significant at the 0.05 level.						

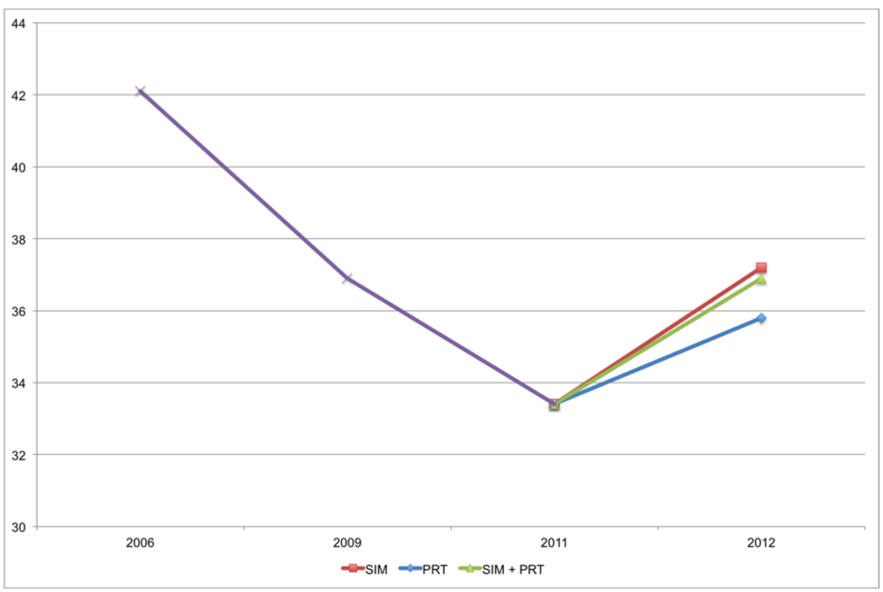
6.5 Visualization

The selected methodology examined student performance on two standard visualization types: isometric and multiview sketches. The mean of aggregate score (isometric + multiview = score /57) taken from final examinations was used to compare the performance of first-year cohorts in 2006, 2009, 2011 and 2012. Referring back to Table 2, the course evolution has a traditional offering of an engineering first-year technical design course in 2006, a dissection in 2009, simulation-based learning in 2011 and the three modalities in 2012. The mean visualization performance decreased from 2006 to 2011, with a steady increase in the cohort variance. As of 2012 the performance in all three modalities had improved visualization performance, with a notable decrease in variance.

Table 11: Visualization Performance across Cohorts

Year	Mean	Standard Deviation
2006	42.1	6.9
2009	36.9	7.3
2011	33.4	10.6
2012 (SIM)	37.2	8.6
2012 (PRT)	35.8	9.1
2012 (SIM+PRT)	36.9	8.7

Figure 6: Aggregate Visualization Scores across First-year Cohorts



7 Discussion

While the survey was offered to 800 students, participation was voluntary and drew 170 valid respondents (21.25%) who completed both surveys and were eligible for inclusion in this study. The decision was made to combine the data from both terms into one data set. As the survey and performance data collection techniques were identical between the terms, this did not introduce any bias of results. Data collected from the second term may indicate slight variances as students had 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.

7.1 Perception

One of the primary expectations of this study was that assigned design project modality would have an effect on self-efficacy. There was a large statistically significant increase in average self-efficacy from the beginning of the term (Time 1) to the end of the term (Time 2) for all modalities. This result is understandable 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 higher confidence in their abilities to work and answer questions in those topics.

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

It was expected that students in the Simulation and Prototyping (SIM+PRT) modality would have the highest increase in self-efficacy, as they had 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, as 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.

7.2 Performance

The expectation was that students who completed a design project in the Simulation and Prototyping (SIM+PRT) modality would have higher performance scores than students completing a design project in another modality. The results in Section 6.4 indicate the highest project individual grades for students in the Prototyping (PRT) modality (by a very small margin), and the 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 in their differences. The result is satisfactory, as any significant difference between the groups may have indicated a modality bias in project requirements or marking rather than a difference in student knowledge across 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 well 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 (SIM+PRT) modalities). It may also indicate that students who did not have to spend time using the 3D printers were freer 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 (SIM+PRT) compared to Prototyping (PRT) alone. 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). 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 as more were available. If we include the Simulation and Prototyping (SIM+PRT) 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 on how to get 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 (SIM+PRT) 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 (i.e., simulation) for encouragement depending on their assigned modality. This could further explain some of the differences between the Prototyping (PRT) and Simulation and Prototyping (SIM+PRT) modality.

Self-efficacy theory suggests that students with the highest self-efficacy will have the highest performance (Bandura, 1977). Students in the Simulation and Prototyping (SIM+PRT) 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.

7.3 Visualization

Further analysis of the visualization results revealed that the progressive decline of visualization mean and increase in variance was disproportionately due to the poorer students struggling with increased course content and possibly the abstractness of simulation software. The overall low response and format of the study do not provide sufficient data to assess whether working on a prototyping project (PRT or SIM+PRT) improved visualization for the previously struggling students. However, the trend indicated that the strongest results come from the combination of simulation and prototyping (SIM+PRT).

8 Conclusion

This report has explored the impact of simulation and rapid prototyping implemented during the execution of a design project for first-year engineering students in Design & Graphics. Projects were assigned in three modalities: Simulation, Prototyping, and Simulation and Prototyping. The authors studied the differences between the teams assigned to each design project modality in terms of their engineering design self-efficacy and performance.

1. Experiential learning through a design project involving either simulation or prototyping can promote an increase in self-efficacy in first-year engineering students.
2. Students who completed a project involving simulation (SIM) had higher project (group and total) performance grades than students in either Simulation and Prototyping (SIM+PRT) or Prototyping (PRT) alone.
3. Students who are assigned Prototyping (PRT or SIM+PRT) present equal or better visualization performance compared to prior cohorts of students, with SIM+PRT presenting the best result.

Self-efficacy theory tells us that this increase in self-efficacy could lead to better performance in students. Students who use simulation in their design projects (SIM, SIM+PRT) show the highest performance scores in the design project.

The increase in exam and visualization performance from prototyping experience is encouraging because students demonstrate the capability to synthesize as much or more course content with both an increase and self-efficacy with equal or better performance.

Study limitations include the lower response rate and slight differences in submission requirements between project modalities (e.g., simulated model vs. prototyped model).

As a result of this study, McMaster University first-year engineering expanded its rapid prototyping recourses (epiclab.mcmaster.ca) and the Design & Graphics course's design project is now modeled on the SIM+PRT modality.

Future work will study the traditional method of teaching visualization and the role of rapid prototyping in acquisition of visualization skills.

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