International Journal of Engineering Education Vol. 38, No. 1, pp. 25–35, 2022
Printed in Great Britain

0949-149X/91 $3.00+0.00

Development and Implementation of an Integrative and Experiential Design Project: Design, Build and Test a Scanning Tunneling Microscope*

JENNIFER A. COGGAN and CHRISTOPHER RENNICK
University of Waterloo, 200 University Ave., W., Waterloo, ON., N2L 3G1, Canada.
E-mail: jcoggan@uwaterloo.ca; crennick@uwaterloo.ca

This paper describes the implementation of a short duration, design-build-test project for first and second year students where teams were tasked with creating a functioning scanning tunneling microscope. The activity was scaffolded to ensure students could handle the demands of such a complex activity, while making sure that all students could experience some measure of success through specific tasks. This "Engineering Design Day" activity sought to provide experience in engineering design early in students' academic careers as a means to improve their design self-efficacy, show them connections with their classroom learning, and provide an authentic opportunity to work in teams. To evaluate the activity, the Engineering Design Self-Efficacy Instrument was given to students before taking part in the activity, and again at the end of the semester to assess whether there was any growth in student self-efficacy in conducting engineering design. The results showed a statistically significant increase in student confidence and motivation in conducting design, and in their expectations of success at design, while there was no change in their anxiety regarding design. Through examining responses, students enjoyed the activity, they were able to practice working in a team and they were engaged with the design process throughout. These results show that design activities of shorter duration than a typical course project may lead to positive change in students engineering design self-efficacy beliefs.

Keywords: design practice; experiential learning; studio; engagement; self efficacy; teamwork

1. Introduction

An important component of a first year engineering curriculum is to build students' foundation in engineering design. While classroom instruction can be useful in teaching design, students need to be given opportunities to do "deliberate practice" of their design skills, with opportunities to receive expert feedback [1]. Conducting these experiences in a team setting allows the students to learn about design, hands-on building, and how to work through an open-ended problem all while navigating the social complexities they will experience in real engineering practice. Unfortunately, it can be hard to find the time or space within an already crowded schedule to integrate significant and meaningful, hands-on design projects.

The Engineering Ideas Clinic at the University of Waterloo has developed a series of short-duration (typically 2-day), design-build-test activities for each of the 14 programs in the Faculty of Engineering called Engineering Design Days (Design Days) [2]. These high-impact events provide students an open-ended, formative, design project that brings course content together into one project – recognizing that integrating knowledge from across different domains requires practice [3]. Design Days are low or no stakes in terms of grades, as reducing the academic impact of the activity gives students the space to develop their design skills with space for risk-taking, and even failure. Through these activities, we are seeking to provide students with a mastery experience [4] in engineering design that will bolster engineering design self-efficacy as students leave their first year. This paper will describe the implementation of the Engineering Design Day concept in the Nanotechnology Engineering program, and will present an assessment of the activity, with a focus on student self-efficacy in design.

1.1 Self-Efficacy in Engineering

Self-efficacy is one component of Bandura's Social Cognitive Theory [4]. This theory seeks to describe the forces that shape a person's thoughts and actions. Bandura describes three broad categories of forces: behavioral determinants, environmental determinants, and personal determinants (of which self-efficacy is one component). Self-efficacy, then, is a person's self-belief of their capabilities in a specific situation or on a specific task. Self-efficacy has been applied as a lens to investigate many phenomena in the engineering education literature from persistence [5] and academic achievement, to motivation [6], and to the experience of minoritized populations (frequently gender-based, but also ethnicity) within the engineering community, with women and ethnic minorities typically expressing lower self-efficacy believes than their male and/or

---

* Accepted 5 August 2021.

ethnic majority peers [6–9]. In STEM fields, stronger self-efficacy beliefs tend to correlate with better academic outcomes [5–7, 10].

Bandura theorizes there are four sources of self-efficacy beliefs that could be applied to academic interventions [4]:

1. Mastery experiences: achieving success on a challenging task;
2. Social modeling: seeing similar people achieve success;
3. Social persuasion: being convinced by others that one can succeed; and
4. Physical and emotional states.

Reinforcing this, Hutchison et al. [11] in a large study of first-year engineering students found nine categories of factors that students reported as having impacted their self-efficacy: students' ability to understand the course material, drive/motivation to persist in the engineering domain, teaming experiences, technical ability (specifically computing), access to help, ability to complete assignments, general problem-solving ability, and enjoyment/ interest in the course. These nine categories are in general agreement with Bandura's theory.

Hutchison-Green et al. [12], in their investigation of the first year engineering student experience concluded that first-year students base their self-efficacy primarily on social modeling because few have mastery experiences to draw on; ending their paper with the recommendation that instructors provide students with mastery experiences, and with the feedback necessary for them to realize they have actually achieved mastery. There is significant evidence from the engineering domain that ill-structured, team-based experiences (typically a significant mastery experience) can lead to measurable increases in student self-efficacy [13–18]. An important distinction for this paper, however, is that unlike Design Days which have a short duration (typically two days), these experiences are typically multi-week long [15], or in many cases, semester-long projects [14, 16–18].

This paper seeks to conduct an assessment of the impact of a high-intensity, short-duration, design-build-test activity on student design self-efficacy. To date, there is very little research into the effects of short-duration design experiences like hackathons on engineering design self-efficacy (see [19] for a recent review of hackathons as a pedagogical tool in engineering). Telenko et al. [20] reported some improvement in student self-efficacy after taking part in "Designettes" which typically lasted between 1 and 5 days in length, however little detail was given regarding how these data were collected. A past evaluation study of multiple Design Days activities has shown some growth in student self-efficacy development during the term where it took place [21]; however, many previous Design Days implementations occurred alongside additional design instruction and/or design projects, and so it is difficult to assess the impact of the Design Days activity itself. The Nanotechnology Engineering Design Days ("Nano Days") activity described in this paper is the only design instruction present in the term, and so represents an ideal place to rigorously assess the impact of a 2-day design activity on student self-efficacy development.

2. Nano Engineering Design Days

2.1 Motivation

The Nanotechnology Engineering (NE) program at the University of Waterloo is a multi-disciplinary engineering program where students are taught a broad knowledge base from the interface of science and engineering in first and second year. They use concepts from biology, chemistry, electronics, math, and quantum physics to research, design and manipulate systems measured in billionths of a metre in upper year courses. One challenge in the early years of the NE program is that the students have difficulty seeing how the content fits together while they are being taught the fundamental background on many different topics. It isn't until upper years when content converges and the students can begin to understand how the fields are inter-connected through nanotechnology. Student feedback showed that engagement with the content, and the program in general, can be low at the beginning due to the perceived disparate content. It was important to engage the students through a creative, hands-on activity that could bring together the topics they were learning in the first year courses and increase the forward thinking of content.

Another intended outcome for the project was to clearly introduce the steps used in engineering design and create an immersive design experience. Feedback from NE students revealed that they wanted more integrative projects in the lower years where much of the time is spent teaching engineering science – typical of engineering programs [22]. It was therefore important to engage in the building and testing of a physical object or system which would allow the students to "practice" engineering design and enhance their professional portfolio of engineering projects.

Many of these students have had little to no exposure to what engineering, and in particular what engineering design, entails. This project has taken the best practices of the previously run Design Days activities (see [21, 23–25]) and developed an ambitious project of having the students design, build, and test a scanning tunneling microscope (STM). This project was selected due to the fact that it contained numerous elements from courses that the students had learned in first year such as basic circuits, chemistry (electrochemistry), materials (piezoelectric materials), and physics (spring constant); and is directly applicable to nanotechnology. With little room in the first year curriculum to add a new design course, the Design Days format was easily adaptable for the NE program.

2.2 Activity Structure

A scanning tunneling microscope is generally comprised of a scanning head assembly that contains a piezoelectric tube or disc that moves an atomically sharp tip across the surface of a conductive material in order to produce an image. This assembly must be contained in a vibration isolation system to shield it from external mechanical vibrations since the tip must be kept within 1 nm of the sample to allow for consistent tunneling of electrons. The final components of the STM are the electronic circuitry to control the microscope, an amplifying circuit to produce a readable signal from the tunnelling current, and software to capture the image. These elements were emphasized as they represent topics of interest to Nanotechnology Engineering (viz. the piezoelectric disc), or they represent topic areas in the program (e.g., electronics, electro-chemistry, nano-scale imaging). The development of a "home-built" STM had already been described previously [26, 27].

Based on prior experience implementing Design Days in first year, the project was broken down into smaller activities with milestones/checkpoints. These milestones aid students in structuring their work time and provide a mechanism for the teaching team to monitor student progress. Day 1 of Nano Days consisted of an introduction to the overall activity, an activity to prepare the piezoelectric disc, time to design the vibration isolation system (including CAD drawings of any custom laser-cut parts), and preparation of the amplifying circuit. By the end of the first day, students constructed and demonstrated the amplifier circuit for the tunneling current as well as the preparation of the piezo disc for the scanning head (with any mistakes corrected before the second day).

During day 2, students prepared their tip through electrochemical etching, constructed their vibration isolation system, and conducted final testing by imaging a DVD. Constructing their system required students to integrate their custom laser cut parts with the supplied standard components to build the physical system of the STM (see Fig. 1 for a sample of student work). Sometimes this would require some additional refining, but virtually all groups were able to assemble the physical box that will suspend the scanning head. Students also verified that their tip worked by observing a tunneling current on an oscilloscope.

In some cases, this division of tasks was chosen for logistical reasons: the CAD drawings of any custom laser-cut parts needed to be submitted by the end of day 1 so they could be checked and manufactured before the second day; and the electro-chemically etched tips are not stable long term (they oxidize and are quite fragile) and so need to be manufactured close to when they will be installed in the final machine. Additionally, care was given to the selection and order of these tasks to ensure that students could experience successes throughout the activity such as a working piezo disc setup, amplifier circuit and the observation of a tunneling current with the

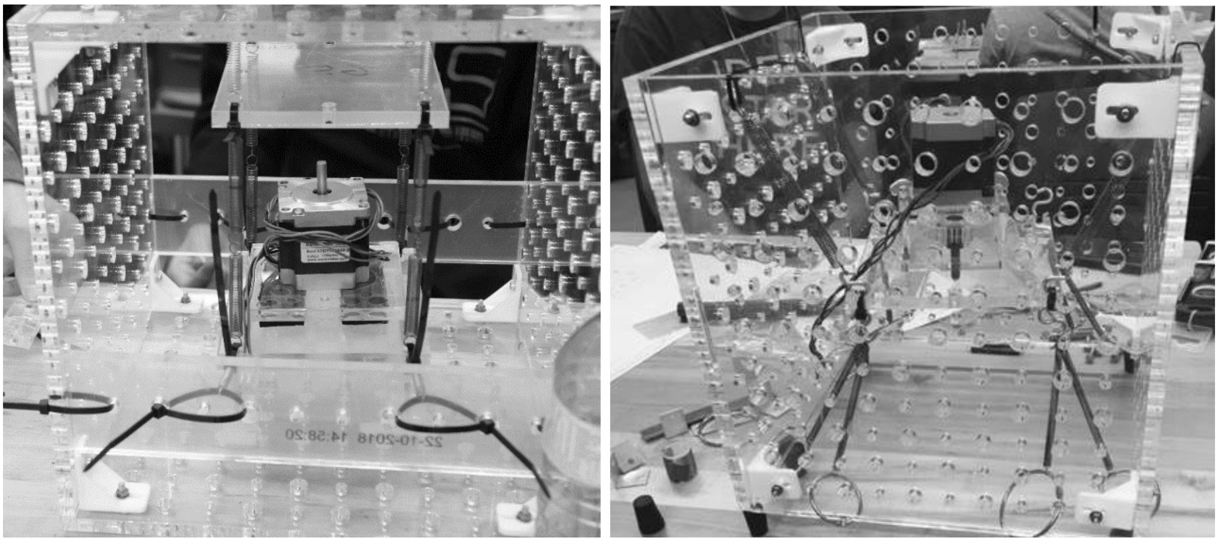

Fig. 1. Examples of student-design vibration isolation systems.

tip they manufactured. These small successes in a large, complicated activity are crucial for their self-efficacy development and work to maintain their motivation to persist through the challenge.

In order to complete a full design project with ~120 first year students it was determined that holding the event as a 2-day activity was the best option. Previous Design Days activities with other engineering programs at UW had shown that this structure provides the necessary time, focussed concentration, teamwork and hands-on work that make them highly successful events. For this implementation in NE, the students were placed into teams of 5 by the instructor. It was not necessary for an activity to be completed during a specific timeframe or before moving onto the next activity. Activities would be introduced at a specific time, and it was left to the team to determine how to complete all activities and milestones by the end of the day.

Specific instructions were given for most of the activities including the piezoelectric disc, circuit building, and tip preparation with worksheets designed to prompt students, similar to a short assignment or lab activity. The major design component to this project was the vibration isolation system. A short background presentation was given on the sources of vibration; the concepts of resonance frequency, harmonic and damped oscillators; and some general ways to create passive vibration isolation in a system. A list of potential supplies that the students could use for their system was provided and the students were left to brainstorm possible solutions, select their best option and sketch their design. To increase reusability of these parts over many offerings of the activity, the largest structural elements (a 4-sided laser cut acrylic box with a grid of holes for attachments, see Fig. 1) were prefabricated and every team was given an identical set.

Emphasis was placed on ensuring the students worked through the engineering design process. A "customer" was brought in to talk to the class about why they needed an STM and provide customer requirements. Each group was then provided with a large paper format worksheet (used throughout the event) that guided them from problem definition, engineering requirements, brainstorming solutions, design concept sketches, writing out a plan with details on implementation, to results of the testing and finishing with possible areas of improvement to the design.

Teamwork was an intended focus of the project. By assigning students into teams, they were forced to work with other classmates they might not normally select. The students had to work together as a group for certain activities such as the piezoelectric disc, as well as the brainstorming and design of the vibration isolation system. However, in order to complete all the steps during the two days, the students also had to divide up the work as new activities were introduced throughout the day.

While the activity was largely coordinated and offered by teaching staff from NE and from the Ideas Clinic, it was important to have broad faculty involvement during both planning, and the event itself. The activity was designed to have the professors teaching in that term provide related content in a mini tutorial during the Design Day activity. Information was also included in course lectures that related to the project content, allowing the students to see how the course content connected to a real world project. The professors and teaching assistants were also invited to spend whatever time they could over the two days speaking to the student teams and asking questions about their project. As additional motivators to take the activity seriously, students could earn small bonus marks for classes by attending and completing the event; and inexpensive prizes were offered at the end of Day 2 to select teams.

2.3 Incremental Changes

The first delivery of the STM project overall was a success with positive feedback in all areas (see section 5 for full analysis of student feedback). There were some identified areas of improvement, however, in the areas of logistics and the specific deliverables required from the teams. Feedback showed that there was frustration in how supplies and parts were distributed to each team for building the vibration isolation system. Observations from the winter 2019 (W19) offering led to changes that were introduced for the winter 2020 (W20) class to improve this process. In W19, it was also difficult on Day 2 to complete all the activities and have time to do the final testing of the STM, so an additional 2 hours were given on Day 2 for W20, allowing for more time for building and final testing.

3. Activity Evaluation

The activity was offered in the winter 2019 and 2020 terms for the first year NE students, and in spring 2019 for the second year NE students. Each class had approximately 120 students that were broken into groups of 5 creating approximately 24 teams each term. The project was run over two full days, with 1–2 weeks in between, in a room dedicated to the activity.

To assess the impact of the activity, a series of surveys were given to the students in each of these terms[1]. Prior to the activity, students were asked to fill in the Engineering Design Self-Efficacy instru-

---

[1] University of Waterloo Office of Research Ethics #43162.

ment developed by Carberry et al. [28]. Immediately following the activity, students submitted anonymous feedback on their experience, including open answers to Brookfield's Critical Incident Questionnaire [29]. This survey was intended to capture the immediate student reaction to the event and was given anonymously (unlike the pre-/post-surveys) to give students the freedom to be critical of the activity if they desired – with no possibility of repercussions, either academically, socially, or otherwise. Lastly, near the end of term, students again answered the Design Self-efficacy Instrument to provide evidence of any changes in student self-efficacy beliefs after participating in the Design Day activity. The pre-activity and post-activity surveys required students to enter their names and student ID numbers so that the responses could be combined and compared. Students were given a small bonus in one course for filling in the pre- and post- surveys, and so names were also required to apply this bonus.

This evaluation was conducted as a nested, mixed-methods study, with both quantitative and qualitative data captured through online surveys. Analysis was conducted on the qualitative and quantitative data simultaneously. Initial data cleaning was performed in Excel before all quantitative data were imported into Stata 15 for statistical analysis. This resulted in 91 valid responses for the winter 2019 term, 80 for the spring 2019 term, and 84 for the winter 2020 term (these numbers will vary slightly question by question as some questions may have been left blank). While demographic data were not explicitly collected during the activity evaluation, the student body in NE is made up of approximately 10% international students and is approximately 40% female. As the activity was mandatory, all students participated in the activity, and response rates for the survey were above 67% in all terms.

4. Results

As part of the anonymous, post-event survey, students were asked to state their opinion of seven questions using a five-item Likert scale in addition to Brookfield's Questionnaire. The Likert questions sought students' affective reaction to the event, as well as their perception on how well the activity achieved some of the intended outcomes. These data show that 90% of students enjoyed the activity, 93% felt future students should participate in the activity, 94% learned something new, 87% felt similar events should happen in upper years, 89% felt they were able to use their creativity during the activity, and 94% felt it was a good opportunity to practice teamwork. The full results are summarized in Table 1.

4.1 Evaluation of Student Self-Efficacy

Carberry et al.'s engineering design self-efficacy instrument [28] consists of 36 questions, grouped into four blocks of nine questions (representing four self-concepts). The four blocks of prompts independently measure individuals' engineering design self-efficacy, motivation, outcome expectancy, and anxiety by asking respondents to rate themselves from 0-100 on nine items. These nine items consist of an overall evaluation of a respondent's self-concept as it relates to "conducting engineering design" (referred to as ED moving forwards) followed by eight prompts associated with each step of the design process, in order: identify a need, research a need, develop solutions, select the best possible design, construct a prototype, evaluate/test a design, communicate, and redesign.

4.1.1 Validation of Survey Results

Carberry et al.'s instrument had students respond on a scale from 0–100 for each of the 36 items; the data collected for this paper implemented this scale in increments of 10 (i.e. students could rate themselves a 10, or a 20, but not any number in between). These values were then divided by 10 to get a number between 0 and 10, inclusive. Prior to any other statistical analysis, the validity of the student responses to the survey was verified using an abbreviated set of methods from Carberry et al.'s paper.

Table 1. Post-event student perceptions, combined 3 offerings (n = 308)

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
I enjoyed NE Days	157 (52%)	114 (38%)	16 (5%)	6 (2%)	7 (2%)
Future students should participate in this event	220 (74%)	56 (19%)	9 (3%)	9 (3%)	4 (1%)
I think NE Days should only happen in first year*	21 (10%)	28 (14%)	44 (22%)	55 (27%)	53 (26%)
I learned something new	182 (61%)	98 (33%)	10 (3%)	5 (2%)	3 (1%)
Similar events should happen in upper years	192 (64%)	69 (23%)	25 8%)	9 (3%)	5 (2%)
During NE Days, I was able to use my creativity	153 (51%)	113 (38%)	20 (7%)	9 (3%)	3 (1%)
NE Days was a good place to practice my teamwork skills	186 (62%)	96 (32%)	8 (3%)	6 (2%)	3 (1%)

* Not asked in winter 2019.

As part of this process, eight new variables were created by averaging items 2 through 9 for each of the four self-concepts for both the pre-activity and post-activity surveys (labelled the Engineering Design Process score, or EDP as per the original paper). These tests revealed no validity issues with the collected data, nor with the EDP score, and so the EDP score will be used for the remainder of the analysis presented in this paper.

4.1.2 Student Self-efficacy

This activity was designed as a mastery experience for students, and so an increase in student self-efficacy scores is expected (and desired). To evaluate whether this was the case, a paired t-test was used to investigate whether there were any statistically significant changes in students' EDP scores as measured before the activity (pre-activity), and 1–2 weeks after the activity concluded (post-activity). These results show there were statistically significant increases in students' self-efficacy in design ($p < 0.001$), motivation to conduct design ($p < 0.01$), and in their expectations at success ($p < 0.001$), while there was not a statistically significant decrease in anxiety (see Table 2).

These results are very promising as students reported an increase in their engineering design self-efficacy, motivation to conduct design, and in their expectations of success in designing. However, as the activity was offered to both first year and second year students, the authors wanted to verify that both populations of students benefitted from the activity. To assess this, a paired t-test was conducted on the pre-activity and post-activity EDP scores between the 188 first years and the 89 second year student respondents. These results showed a statistically significant difference in pre-activity anxiety scores between the first year students (mean EDP = 3.64) and second year students (mean EDP = 4.51; $p < 0.01$), while there were no statistically significant differences in the remaining pre-activity scores ($p = 0.51$, $p = 0.13$, $p = 0.71$ for self-efficacy, motivation, and outcome expectancy, respectively); nor in the post-activity scores between these groups ($p = 0.17$, $p = 0.77$, $p = 0.82$, $p = 0.20$ for self-efficacy, motivation, outcome expectancy, and anxiety, respectively). As a follow-up test, the paired t-test comparing pre-activity and post-activity anxiety ratings was re-calculated for only the second year students. These results showed a noticeable reduction in anxiety (pre-activity mean EDP = 4.63 vs. post-activity mean EDP = 4.10) that bordered on statistical significance ($p = 0.06$). It is difficult to draw strong conclusions from these data, though the data suggest that the second year students were more anxious going in to the activity than the first year students, and that there was a larger reduction in anxiety after the activity for the second year students than for the population as a whole, even though the reduction in anxiety was not statistically significant for either population. The second years participated in the activity in a later week in the term than either first year cohort, so it is possible their anxiety was amplified by the looming final exams.

The final statistical analysis sought to determine whether there were any changes in outcomes in the winter 2020 offering as compared to the winter 2019 offering. As described earlier in this paper, changes were made to the offering of the activity between the first offering in winter 2019 and the most recent offering in 2020; and so the authors wanted to determine whether these changes improved student outcomes, or not. To assess this, paired t-tests were conducted on the pre-activity and post-activity EDP scores between the approximately 90 student respondents in each cohort (see Table 3).

These results show that students rated themselves similarly on the pre-activity, self-efficacy questions, while the winter 2020 students rated themselves

Table 2. Paired t-test comparison of means, pre-survey responses vs. post-survey (n = 225)

	Self-efficacy		**Motivation**		**Outcome**		**Anxiety**	
	Pre-	**Post-**	**Pre-**	**Post-**	**Pre-**	**Post-**	**Pre-**	**Post-**
Mean EDP score (std. dev.)	7.08 (1.47)	7.72*** (1.38)	7.76 (1.65)	8.02** (1.56)	7.02 (1.53)	7.62*** (1.56)	3.93 (2.48)	3.74 (2.68)

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 3. Paired t-test comparison of means, winter 2019 vs winter 2020 (n = 170 combined)

	Self-efficacy		**Motivation**		**Outcome**		**Anxiety**	
	Pre-	**Post-**	**Pre-**	**Post-**	**Pre-**	**Post-**	**Pre-**	**Post-**
Mean EDP score (std. dev.) – W19	6.83 (1.66)	7.59* (1.68)	7.61* (1.97)	7.65** (1.95)	6.78* (1.73)	7.25** (1.97)	3.65 (2.28)	4.3*** (2.82)
Mean EDP score (std. dev.) – W20	7.19 (1.49)	8.05* (0.99)	8.18* (1.37)	8.39** (1.20)	7.29* (1.37)	7.94** (1.38)	3.63 (2.38)	2.77*** (2.41)

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

higher on the post-activity, self-efficacy question ($p < 0.05$). While the delta between the pre- and post-activity self-efficacy scores are similar, the winter 2020 students had greater confidence in their ability to conduct engineering design than their winter 2019 peers. For motivation and outcome expectancy, the winter 2020 students generally rated themselves higher on both the pre- and post-activity surveys; with a slightly larger improvement for the winter 2020 students after taking part in the activity. These results are statistically significant, but it is unclear how meaningful they are in practice; generally, the winter 2020 students were a little more confident in their abilities than the winter 2019 students. Where there is a significant change between these groups, is in their anxiety scores: the two classes of students rated their anxiety to conduct design approximately the same in the pre-activity survey; however, where the 2019 students showed greater anxiety after the activity, the 2020 students showed noticeably lower anxiety ($p<0.001$). Anecdotally, the winter 2019 offering was much more chaotic than the winter 2020 offering, and it’s possible that the logistical difficulties during the activity may have had some negative consequences to the first group taking part in the activity.

4.2 Qualitative Data

The data presented in this section were collected through the anonymous, online survey offered immediately following the conclusion of the Design Day activity. In total there were 306 valid responses to this survey across the three activity offerings. In addition to the questions presented in Table 1, students were given an opportunity to answer Brookfield’s Critical Incident Questionnaire [29] in open text boxes in the survey. Analysis of this data focussed on the first two prompts from Brookfield’s questionnaire: “At what moment during the Design Days event did you feel most engaged with what was happening”; and “At what moment during the Design Days event did you feel most distanced from what was happening”. These questions were selected for analysis as the authors felt they lent themselves the best to identifying both the strengths of the activity, and areas for improvement. The answers to these two prompts were analysed two ways: the responses were coded using the steps of the design process used for the self-efficacy instrument; and a thematic analysis was conducted to identify any other patterns in student responses. The former coding was used to investigate which steps of the design process resonated with students, and which parts students struggled with (or disengaged from); while the latter was to ensure nothing was missed in their comments. For clarity, this paper will only present categories of responses with 10 or more total responses.

Table 4 summarizes the responses (with example student quotes) to the two prompts from the Critical Incident Questionnaire, broken down by the step in the design process mentioned in the comment. From these data, it appears that students were most engaged during the prototype construction phase of the project (which was also where the most time was spent), followed by “developing

Table 4. Critical Incident Questionnaire coding using design process steps

Design Process	**Response Categorization**	**Number of responses**	
		Most Engaged	**Most Distanced**
2. Research a design need/ problem	Responses mention presentations, lectures, information session, or theory about the systems	4	12
	Most engaged examples: *“listening to professors explain the design and concepts”* **Most distanced examples:** *“I probably felt most distanced at the beginning because I hadn’t read the STM papers and info and so I felt behind.”*		
3. Develop design solution	Responses mention Solidworks, brainstorming ideas, designing the vibration isolation system, planning	59	35
	Most engaged examples: *“Creating the Solidworks prototype”* *“During the design aspect where I was able to use my creativity to solve the problem.”* **Most distanced examples:** *“The solidworks segment as I am not really familiar with CAD drawings at all”*		
5. Construct a prototype	Responses circuitry, building/assembling the VIS or piezoelectric, electrochemistry process, tip making	178	84
	Most engaged examples: *“Designing the circuit component, as well as actually starting the building process for the STM”* **Most distanced examples:** *“The circuit board design process seemed convoluted and highly technical. It was more about connected [sic] the circuitry rather than understanding what really happened.”*		
6. Test and evaluate solutions	Responses mention testing STM and/or circuitry	26	43
	Most engaged examples: *“During testing of the Op Amp”* *“During the testing process at the end.”* **Most distanced examples:** *“the tunneling testing station for the tip. We went there not even knowing what we would find on the oscilloscope, we didn’t understand how the device was hooked up to show what we were seeing etc.”*		

design solution", and to a lesser extent, "testing and evaluating solutions". As this activity follows the design-build-test activity structure common in design studio experiences, it is a promising result that students felt highly engaged during these parts of the activity.

Examining student responses to where they felt most distanced during the activity, students felt most distanced during the prototype construction phase, followed by the testing/evaluating solutions phase, and the developing design solutions phase. In digging deeper into the responses, the electronics component of the project was the most prevalent activity mentioned by students (mentioned by 50 students in their response to this prompt). This could have a couple of causes: in at least one offering (winter 2020), students hadn't yet learned the course content required to fully understand this aspect of the project; it is difficult for more than one person to work on the electronics at the same time as it was completed on a single prototyping breadboard; and students construct their amplifier circuit on the first day, but it is not integrated into the design until the very end of the second day. More than anything, this speaks to the complicated logistics of offering an event of this scale and complexity.

As mentioned previously, these data were analysed a second time using an open, inductive approach to check for any other emergent patterns in the data. Table 5 summarizes the themes identified from student responses to where they felt most engaged during the activity. The largest number of responses related to the teamwork aspects of the activity. As one outcome of Design Days is to build community and provide a place to practice teamwork, this is an encouraging result. Some students also mentioned the ability to brainstorm and be creative during the event. For the students who mentioned a particular day, the second day was more prevalent in comments than the first day; but some students seemed to prefer the more structured first day (which was predominantly the designing) over the more challenging second day (predominantly building/integrating the different components together, and testing).

Table 6 summarizes the themes identified from students' responses to where they felt most distanced during the activity. The largest number of responses relate to issues within their teams (either direct conflicts with groupmates, or issues with task division). In some cases, the issues with task division related to logistical challenges of the event, where students were not able to participate in some aspects of the activity (it would have been unsafe to allow the entire group of 5 to participate in the tip etching activity, for example). In other cases, however, it seems there was some unhealthy conflict between members of the group. As teamwork is one outcome of this activity, future offerings might benefit from additional teamwork instruction prior to the event to better prepare students for the activity [30, 31]. Another significant population of students commented on some of the logistical issues during the event. These students explicitly mentioned having to wait for access to part of the activity, or of downtime during the activity. Students also mentioned issues with how materials were distributed during the activity. As mentioned in section 3.1, the most recent offering of the activity attempted to address some of these issues.

Overall, these responses generally reinforce the earlier findings: students tended to enjoy the activity, students were able to practice working in a team on an authentic engineering challenge, and students engaged with the design process throughout the activity. There are clearly still some logistical challenges to overcome in future offerings of the activity, and there are opportunities to improve the learning outcomes of the activity (e.g., as they relate to the electronics component), but the activity has value for students.

Table 5. Thematic analysis of student responses to where they felt most engaged during the activity

Theme	**Response Categorization**	**Number of responses**
Team	Responses mention teamwork in some form	48
	"Building the stm together as a team." *"When designing and building the STM with the team by dividing and conquering different tasks. Watching the project come together was extremely rewarding."*	
Creativity	Responses mention brainstorming – thinking of ideas	15
	"When we were given the opportunity to share ideas to build stabilizing mechanics for the microscope."	
First day	Responses explicitly mention day 1	8
	"I felt most engaged during the first design day, when there seemed to be more tasks to accomplish and the tasks seemed to be more clear."	
Second day	Responses explicitly mention day 2	23
	"Day 2 actually building, lot of sitting around in day 1"	

Table 6. Thematic analysis of student responses to where they felt most distanced during the activity

Theme	Response Categorization	Number of responses
Team	Responses mention issues with team	9
	"There were a few control freaks in my group and completely disregarded any advice or suggestions I had in the creation and construction of the system. I felt myself becoming increasingly uninterested in the project because of this."	
Waiting	Responses explicitly mention waiting	29
	"Waiting to be able to test our STM (which we never did)"	
Task division	Responses mention issues with tasks being split within group, often unable to participate in other activities	34
	"Tip making and circuit design -only 2 people per group could participate" *"I wanted to see how the tip was being made, however only two people from my group got to go so I did not know much about that portion."*	
Materials	Responses mention issues with materials, materials distribution	8
	"When we were designing the case on the first day and were deciding what materials we should order. It wasn't interesting to me."	
First day	Responses explicitly mention day 1	13
	"Initial steps on Day 1 since I had zero to no knowledge in this area."	
Second day	Responses explicitly mention day 1	11
	"The second half of the second day"	
None	Responses mention no moments of the event	12
	"never during any time"	

5. Discussion

From the results it appears that the incremental changes that were made between the offerings did positively affect the scores in terms of greater confidence in the student ability to conduct engineering design. Generally speaking, the first offering of the activity was chaotic, and a lot of lessons were learned about the logistics of running the event which were improved upon through subsequent offerings, though the final testing of the STM has remained a big hurdle for the Nano Design Days and is still being investigated and improved.

An important outcome from this event was the creation of an immersive design experience for first year students who had not had previous experience with engineering practices or engineering design. While we cannot conclude that Design Days caused an increase in self-efficacy, based on the results in this paper, students reported increases in their self-efficacy in design, motivation to conduct design, and in their expectations at success. It is interesting to note that from the qualitative data there were clearly areas that the students engaged with the most; however, there was spread between what activities the students responded with. The authors believe this is in-line with the multi-disciplinary nature of nanotechnology – that some students enjoyed the tip preparation (chemistry) versus the amplifier circuit build (electronics) versus the Solidworks (mechanical) activities – all core courses in the first year NE curriculum.

Overall, it appears that the activity outcomes of engagement and teamwork were being met through this activity. From observation on the event days, and speaking with students both during and after the activity, it was mentioned numerous times that they enjoyed having the class professors and teaching assistants interacting with them during the activity. This further emphasized that the activity strengthened engagement within the NE program.

As mentioned in the introduction of this paper, there are few studies investigating the impact of short-duration design activities on students' engineering design self-efficacy in the literature, which this paper sought to address. It is also important to note that while the authors have structured the mixed-methods study presented in this paper to cross-validate the quantitative results with the qualitative results, this paper does not show causation between the gains in self-efficacy reported by students and the design activity that takes place during the Nano Design Days event. It is conceivable that these gains were at least partially the result of other experiences that students may have had during the term, however this event is the single largest design activity that students take part in during this particular academic term and the pre- and post-activity assessments were offered to students close to when they took part in the activity. From the data presented in this paper, curricular design activities of duration shorter than a week may represent a useful pedagogy for improving student design self-efficacy beliefs. Future longitudinal research will seek to investigate the long-term impact of Design Days on student design learning and self-efficacy.

Finally, after running the event for three classes, two first year and one second year, it was determined that the STM project was better suited for the second year class mainly due to the course content knowledge that allowed a deeper understanding of all the project components. In second year, the students have taken courses in quantum mechanics and learned more about springs, harmonic oscillators, and damping which are helpful in the design of the vibration isolation system. Moving forwards, this activity will permanently shift into the second year curriculum, and development is already well underway on a new Nano Design Days project for the first year students. The new first year activity is expected to be completed in early 2021.

6. Conclusions

This paper describes the implementation and evaluation of a short-duration, design-build-test project for students in the Nanotechnology Engineering program. This "Engineering Design Day" activity sought to provide a formative, mastery experience in engineering design early in students' academic careers as a means to improve their design self-efficacy, show them the context of their classroom learning, and provide an authentic opportunity to work in teams. During the activity, students worked in teams of five to design, build, and test a working scanning tunneling microscope over the course of two, 8-hour days.

Students were given the opportunity to fill in an anonymous survey immediately following the activity to capture their immediate impressions of the event. The data collected from this survey showed that students enjoyed the activity, felt the activity was a good place to practice teamwork, should continue happening for future students, and provided an opportunity to exercise their creativity. Open-text responses to the Critical Incident Questionnaire were also analysed to investigate the strengths and weaknesses of the activity. These results show there are some areas of improvement for future offerings of the activity, but overall, students were engaged in the design task.

The Engineering Design Self-Efficacy Instrument was given to students before taking part in the activity, and again at the end of the semester (approximately 2-3 weeks after the conclusion of the activity), to assess whether there was any growth in student self-efficacy in conducting engineering design. These results show a statistically significant increase in their confidence and motivation in conducting design, and in their expectations of success at design, while there was no change in their anxiety regarding design. While further research into the impacts of short duration design activities is required, these results contribute to the design self-efficacy literature by showing design activities of shorter duration than a typical course project may lead to positive change in students' engineering design self-efficacy beliefs.

In conclusion, the "Design Days" format of holding a design-build-test activity within 2 dedicated days where students did not have to attend classes was highly successful and the outlined goals were met. The Design Days structure, and selection of the STM project, was successful in bringing together the intended activity outcomes for the first year students of the Nanotechnology Engineering program with little to no disruption to the core courses.

Acknowledgements –The authors would like to acknowledge the financial assistance of the NSERC Chair in IDEAs, the Faculty of Engineering, and the Waterloo Engineering Endowment Foundation.

Many students were involved in the creation and running of these events with special mention and thanks going to Erica Fu, Cecilia Cancellara, Pavitra Kurseja, and Saleem Najib all from the Nanotechnology Engineering program as well as the numerous Ideas Clinic coop students, and those who volunteered their time during events. Thank you to Kelvin Liew for creating the electronic boxes and helping at the event, and thank you to Aaron Dai for analysing the qualitative data for this paper.

A special thank you also goes to Dr. Elizabeth Hassan and Dr. Robert Fleisig both from McMaster University for providing the idea of using a large size paper format worksheet for guiding the students through a design cycle activity.

References

1. K. A. Ericsson and N. Charness, Expert Performance. Its Structure and Acquisition, *American Psychologist*, **49**(8), pp. 725–747, 1994.
2. A. Hurst, C. Rennick and S. Bedi, A "Lattice" Approach to Design Education: Bringing Real and Integrated Design Experience to the Classroom through Engineering Design Days, in *Proceedings of the Design Society: International Conference on Engineering Design*, Delft, 2019.
3. S. A. Ambrose, M. W. Bridges, M. DiPietro, M. C. Lovett and M. K. Norman, *How Learning Works*, San Francisco: John Wiley & Sons, Inc, 2010.
4. A. Bandura, On the Functional Properties of Perceived Self-Efficacy Revisited, *Journal of Management,* **38**(1), pp. 9–44, 2012.
5. R. W. Lent, S. D. Brown and K. C. Larkin, Comparison of Three Theoretically Derived Variables in Predicting Career and Academic Behavior: Self-Efficacy, Interest Congruence, and Consequence Thinking, *Journal of Counseling Psychology*, **35**(3), pp. 293–298, 1987.
6. B. D. Jones, M. C. Paretti, S. F. Hein and T. W. Knott, An Analysis of Motivation Constructs with First-Year Engineering Students: Relationships Among Expectancies, Values, Achievement, and Career Plans, *Journal of Engineering Education*, **99**(4), pp. 319–336, 2010.

7. C.-L. Ho and D. Raubenheimer, Computing-Related Self-Efficacy: The Roles of Gender, Academic Performance, and Computational Capabilities, in *ASEE Annual Conference and Exposition*, Vancouver, 2011.
8. M. Besterfield-Sacre, M. Moreno, L. J. Shuman and C. J. Atman, Gender and Ethnicity Differences in Freshman Engineering Student Attitudes: A Cross-Institutional Study, *Journal of Engineering Education*, **90**(4), pp. 477–489, 2001.
9. R. M. Marra, K. A. Rodgers, D. Shen and B. Bogue, Women Engineering Students and Self-Efficacy: A Multi-Year, Multi-Institution Study of Women Engineering Student Self-Efficacy, *Journal of Engineering Education,* **98**(1), pp. 27–38, 2009.
10. S. Purzer, The Relationship Between Team Discourse,Self-Efficacy, and Individual Achievement: A Sequential Mixed-Methods Study, *Journal of Engineering Education,* **100**(4), pp. 655–679, 2011.
11. M. A. Hutchison, D. K. Follman, M. Sumpter and G. M. Bodner, Factors Influencing the Self-Efficacy Beliefs of First-Year Engineering Students, *Journal of Engineering Education*, **96**(1), pp. 39–47, 2006.
12. M. A. Hutchison-Green, D. K. Follman and G. M. Bodner, Providing a Voice: Qualitative Investigation of the Impact of a First-Year Engineering Experience on Students' Efficacy Beliefs, *Journal of Engineering Education*, **97**(2), pp. 177–190, 2008.
13. M. Jansen, R. Scherer and U. Schroeders, Students' self-concept and self-efficacy in the sciences: Differential, *Contemporary Educational Psychology*, **41**, pp. 13–24, 2015.
14. S. P. Schaffer, X. Chen, X. Zhu and W. C. Oakes, Self-Efficacy for Cross-Disciplinary Learning in Project-Based Teams, *Journal of Engineering Educationan*, **101**(1), pp. 82–94, 2012.
15. C. Hulls and C. Rennick, Use of a Cornerstone Project to Teach Ill-Structured Software Design in First Year, *IEEE Transactions on Education*, **63**(2), pp. 98–107, 2020.
16. J. L. Hertz, Confidently Uncomfortable: First Year Student Ambiguity, in *ASEE Annual Conference and Exposition*, Salt Lake City, UT, 2018.
17. L. Liebenberg and E. Mathews, Integrating Innovation Skills in an Introductory Engineering Design-Build Course, *International Journal of Technology Design Education,* **22**, pp. 93–113, 2012.
18. B. Robinson, N. Hawkins, J. Lewis and J. Foreman, Creation, Development and Delivery of a New Interactive First-Year Introduction to Engineering Course, in *ASEE Annual Conference and Exposition*, Tampa, FL, 2019.
19. M. Flus and A. Hurst, "Hackathons as a Novel Pedagogy in Engineering Design Education," *IJEE*, In press.
20. C. Telenko, K. Wood, K. Otto, M. Rajesh Elara, S. Foong, K. Leong Pey, U. Tan, B. Camburn, D. Moreno and D. Frey, Designettes: An Approach to Multidisciplinary Engineering Design Education, *ASME J. Mech Des.*, **138**(2), p. 022001 (11 pages), 2016.
21. C. Rennick, C. Hulls, D. Wright, A. J. Milne, E. Li and S. Bedi, Engineering Design Days: Engaging Students with Authentic Problem-Solving in an Academic Hackathon, in *ASEE Annual Conference*, Salt Lake City, UT, 2018.
22. C. Dym, A. Agogino, O. Eris, D. Frey and L. Leifer, Engineering Design Thinking, Teaching, and Learning, *Journal of Engineering Education*, **94**(1), pp. 103–120, 2005.
23. K. McKay, S. Mohamed and L. Stacey, Concepts Only Please! Innovating a First Year Engineering Course, in *CEEA Annual Conference*, Halifax, 2016.
24. I. Ivkovic, T. L. Willett, M. J. Borland and M. Gorbet, Design Days Boot Camp: Enhancing Student Motivation to Start Thinking in Engineering Design Terms in First Year, in *CEEA Annual Conference*, Toronto, 2017.
25. S. Phillips, K. Geisinger, R. Al-Hammoud and S. Walbridge, Enhancing Student Learning by Providing a Failure Risk-Free Environment and Experiential Learning Opportunities, in *ASEE Annual Conference*, Salt Lake CIty, UT, 2018.
26. D. Berard, Home-Built STM, [Online]. Available: https://dberard.com/home-built-stm. [Accessed 04 03 2020].
27. N. Jaksic, A nanotechnology experiment: Design of low cost scanning tunneling microscopes, in *ASEE Annual Conference and Exposition*, Chicago, 2006.
28. A. R. Carberry, H.-S. Lee and M. W. Ohland, Measuring Engineering Design Self-Efficacy, *Journal of Engineering Education*, **99**(1), pp. 71–79, 2010.
29. S. D. Brookfield, Using the Critical Incident Questionnaire (CIQ), [Online]. Available: http://www.stephenbrookfield.com/ciq. [Accessed 3 March 2020].
30. R. Al-Hammoud, M. Barichello, C. Rennick, E. Jobidon and R. Li, Two Student Workshops on Identifying and Resolving Teamwork Conflict, in *ASEE Vrtual Annual Conference*, Virtual, 2020.
31. E. Jobidon, M. Barichello, R. Al-Hammoud, M. Mostafapour, C. Rennick, A. Hurst and J. Grove, Building Engineering Professional and Teamwork Skills: A Workshop on Giving and Receiving Feedback, in *ASEE Annual Conference & Exposition*, Salt Lake City, UT, 2018.

Jennifer A. Coggan received her BSc in Biotechnology from Brock University and an MSc in Chemistry from the University of Waterloo. From here she went on to become a Research Scientist at the Xerox Research Centre of Canada (XRCC) where she worked on projects related to the design and synthesis of organic electronic materials for applications such as OLEDs, TFTs and photoconductors. Jenn is currently an Instructor and Lab Manager for the Nanotechnology Engineering program at the University of Waterloo where she oversees all the lab courses for the program and facilitates engineering design projects, teaches first year nanotechnology fundamentals and technical writing skills. Her current focus is on implementing new experiential activities throughout the program. She holds 50 US patents and has received a Limited Engineering License from Professional Engineers Ontario.

Christopher Rennick received his BASc and MASc in electrical engineering from the University of Windsor, in Windsor, Ontario, Canada. Chris is currently a PhD student in Management Sciences at the University of Waterloo studying students' design and problem-solving skill development. Currently, Chris is the Engineering Educational Developer with the Engineering Ideas Clinic, where he designs and implements real-world, hands-on design activities for undergraduate engineering students.