DEVELOPMENT OF AN INSTRUMENT TO ASSESS DESIGN ABILITY OF ENGINEERING STUDENTS

by

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ABSTRACT

Students complete design projects in order to put theoretical and technical knowledge gained from engineering science courses into practice to solve real-world problems, to expose students to industry practices, and improve their design ability (DA). If instructors were able to characterize and assess DA in students, they could optimize the learning environment to ensure learning outcomes are maximized. The existing measures of DA are performed for a limited number of students due to the time-consuming post-processing. An instrument is desired to measure DA quantitatively in order to provide immediate feedback.

This research contains 2 quantitative, 1 qualitative, and 1 mixed-methods study to produce an instrument to measure DA. The first study piloted a design scenario to measure DA. The second study developed the design scenario items and introduced qualitative items. The third study documented 9 qualities of design engineers according to professional engineers: collaborative, confident, creative, driven, engaged, intuitive, inquisitive, systematic and versatile. A classification of the interaction between design and engineering was produced, categorized by balance, level of tasks, and amount of design in a job.

The fourth study validated a quantitative instrument to measure DA by recording steps in a design process for a proposed design scenario. Students and professional engineers documented the steps and assigned a duration to each step. It was found that experts selected significantly fewer steps than students ($p < .05$), but spent significantly more time at each of the 4 major design stages ($p < .001$). Students and experts selected different steps, specifically for the first step. Students spent more time modelling the idea where experts spent more time in implementation. There were significant differences ($p < .05$) between planning and implementation among female and male professional engineers; female engineers spent 5 more hours planning the design whereas male engineers spent 8 more hours in implementation. After 4 studies, an instrument was successfully developed and validated to assess DA.

LIST OF ABBREVIATIONS AND SYMBOLS USED

ABBREVIATIONS

ANOVA	Analyses of variance
ANCOVA	Analyses of co-variance
CAD	Computer aided design
CEAB	Canadian Engineering Accreditation Board
DA	Design ability
Dal	Dalhousie University
DE	Design engineer
SL	Service-learning
UPEI	University of Prince Edward Island

GREEK LETTERS

α	Chronbach's alpha
η	Effect size
σ	Standard deviation

MATHEMATICAL SYMBOLS

p	Statistical significance
F	Statistical power

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CHAPTER 1: INTRODUCTION

1.1. BACKGROUND

Engineers are characterized by their ability to solve problems, often employing a structured design process that varies based on the engineering field, duration of the project, and scope of the problem. This practice of engineering design begins in university design courses (more traditionally cornerstone and capstone courses) where students apply theoretical knowledge to solve real-world problems. Engineering design is not limited to the conception of devices, but rather extends to the ideation and optimization of systems, components, and processes to satisfy a need [1, 2].

Through design courses, students develop many different types of skills in addition to improving their ability to design [3 - 8]. They apply the theory introduced in engineering science courses to solve real problems presented by the design projects [3, 4, 6]. Through these projects, students employ the full range of communication skills, furthering their oral and written ability, learning sketching and computer aided design (CAD) tools, as well as developing interpersonal communication techniques [3, 8]. By working on teams, students practice professional skills such as leadership and teamwork [3, 8]. To necessitate staying on schedule and within budget, students employ project management and engineering economics [9]. They are presented with situations where they organically experience engineering ethics and the necessity of safe practices [3, 7]. Working together to solve a problem allows students to experience many of the skills they will need for professional practice [10].

Whether in the design courses or in professional practice, there are as many variations of the design process as there are applications [11]. With so many possible problems, processes, and products, each university design course offers a unique experience for students. Instructors of design courses must make many decisions to bound the project, considering scope, duration, group size, client availability, assessment techniques, and available funding; a subset of project variables are shown in Table 1-1 with common options listed for each variable [6, 9, 12 - 14].

Table 1-1: Variables within design courses [9, 12, 15]

Variables	***Options***	
Length of project	1 week 2-6 weeks	1 semester Multiple semesters
Documentation	Logbooks Portfolios Design reports Analysis reports Drawing packages	Build plans Test plans Progress reports Presentations Online group collaboration
Students per team	1-12 students	3-6 (most common)
Teams per project	1 – 10 teams	
Team formation	Students select Instructor select	Randomized Combination
Source of project	Hypothetical problem Faculty research External competition Student selected	Client from the community, industry, or represented by the instructor Local or global problem
Desired output	Paper design: sketch, CAD, design report	Prototype of design Final product
Team composition	1 engineering discipline Interdisciplinary teams	>1 engineering disciplines

If there was a method to quantify student learning in design projects, the efficacy of each variable in Table 1-1 could be determined to optimize the experience for students and maximize student learning. Additionally, quantification of student learning could allow the optimization of the entire design course, to alter the material and types of activities. Current assessment techniques utilized in design courses review the quality of the students' design documentation, consisting of reports, logbooks, and online communication to measure engagement and understanding of the clients' needs, as well as the highly subjective review of the 'goodness' of the design. Existing tools found in the literature to quantify learning in design courses fall into 3 categories:

1. Quantitative tools that measure student preference, efficacy, or compare course grades [14 - 19]. While these data are important to assess, they do not necessarily measure *ability* of students.

2. Qualitative tools measure ability, confidence, or efficacy [9, 20 - 28]. While these studies are rich in data, they require too much post processing time to deploy in courses with many students.
3. Mixed-methods tools, combine options 1 and 2 [29 - 31].

There is a gap in existing tools to quantitatively measure ability.

1.2. OBJECTIVE

My objective is to develop an instrument to measure an engineering student's design ability (DA) that can be delivered online and will provide immediate, objective results.

This objective evolved after performing the 2 studies presented in chapters 2 and 3 that required the measurement of DA in an attempt to answer a different question. Before that question could be accurately addressed, it was determined that a tool was required to responsively assess DA. Chapters 4 and 5 contain 2 studies that address the objective first to understand what is DA and next to deploy an instrument to assess DA. This collection of 4 studies produced an instrument to measure DA so that questions such as those posed in chapters 2 and 3 can be explored.

1.3. SCOPE

The first of what would become four original studies for this research project began with the intent of determining whether the source of the project impacted student learning. Through observation during design courses, students appeared to be more engaged in projects that derived from the community rather than projects with an industrial client or projects without a client (hypothetical problem, student developed, or instructor acts as client). Described as service-learning (SL), this pedagogy claims to improve student engagement and civic responsibility [15, 32, 33], but whether it improves engineering-specific learning objectives as well required further study.

Chapter 2 explores the development of an instrument to determine whether the source of the project (SL, industry, or other) impacts DA. It was delivered online to second-year design students at Dalhousie University (Dal) after they completed a design project. A literature review was performed to compile a list of 15 variables that could impact DA. Recognizing that many factors can affect DA, to only consider the source of the client would present inaccurate findings. Existing tools and studies were consulted to develop the instrument. The items in the instrument consisted of Likert statements using assessment and self-assessment of DA and ethical awareness. One multiple choice item presented a design scenario and was the first measurement of DA. This item was the inspiration and foundation for the revised DA instrument.

Chapter 3 contains the second study that was performed; a mixed-methods instrument was delivered in multiple parts in order to see if there was a change in students' DA due to the source of the project. This study was distributed to a larger population that included Dal and the University of Prince Edward Island (UPEI) first- and second-year students, as well as 19 female high school students participating in an engineering summer design course. The paper-based study allowed students to provide richer data using qualitative items that required sketches and short-answer essays to ethical dilemmas.

Quantitative multiple choice design scenarios were developed to assess how well students understood user need. It was assumed that novice designers will only grasp information that is explicitly provided while more mature designers will incorporate the implied information. While analyzing the results, it was determined that the quantitative items were too subjective as written but were a novel approach to collect data and the qualitative items required too much time to responsively analyze for a large class. It was clear that before the efficacy of SL projects could be accurately studied, more work was required to understand the components of DA and to develop an *online* instrument to measure DA that can provide *immediate, objective* results. This produced the need for the 2 studies presented in chapters 4 and 5.

Chapter 4 documents the qualities that are required of design engineers according to experts. While the literature lists traits of engineering designers such as: optimism, collaboration, communication, ethical consideration, and willingness to fail [34 - 36], these could be said of professions outside of engineering. What is more pertinent to DA is what distinguishes a great design engineer compared to a mediocre design engineer. A qualitative study was performed using unstructured interviews with 12 engineering experts from diverse disciplines and industries to determine if there were similarities among great design engineers.

Chapter 5 contains a quantitative study utilizing an online instrument to objectively measure DA that compares how experts and students employ the design process. This is a straightforward instrument with only 1 question and 7 project variables, asking first-, second-, and fourth-year engineering students at Dal and UPEI as well as professional engineers to select the steps to take for a hypothetical design scenario. The DA question was validated using the qualitative research of Atman et al. [20] on how novice and expert designers employ the design process. The results from this instrument can be used to meet the objective for this research.

The final chapter synthesizes the data from the 4 studies and proposes potential future studies to further the understanding and measurement of DA.

CHAPTER 2: PILOT STUDY

2.1. INTRODUCTION

The first study was piloted to better understand the timeline and necessary steps required to perform research with engineering students and to determine whether projects that derived from the community, industry, or other sources have a greater impact on the design ability (DA) of students. *It is hypothesized that service-learning (SL) projects, where clients are from a community organization, develop students' DA more than industry projects.*

A literature review produced a list of 15 independent variables to compare to DA, and the first DA items were developed. This chapter details the development of the instrument, key results, and lessons learned that were incorporated in following studies. Each step in the data analysis process is explained in detail in this chapter to establish the process that will be used in future chapters.

2.2. LITERATURE REVIEW

A review of SL and existing measurement tools for design courses were performed. Next, a definition of DA was developed, which produced the construct for the instrument. Finally, a review of independent variables was performed from existing surveys, to determine what to compare to the measurement of DA. Development of the first instrument followed.

2.2.1. Service-Learning Pedagogy

SL, also called community engagement, is an active learning pedagogy that emphasizes developing civic engagement and social responsibility in students [37, 38]. This is achieved by focusing on projects that meet a need for an underserviced area or people, while providing academic credit for learning. By 1990, there were 147 definitions of SL in the literature [39], including the National and Community Act of 1990, legislated by the US Congress [40]. The common components of SL throughout the definitions are: a service is completed for a community partner, there are learning outcomes for the students, and students reflect on the experience [40 - 45]. The balance of these outcomes vary depending on the focus of the project [40].

The source of the project can have many variations, whether the problem is hypothetical or represented by a real client, local or global, and selected by the student or the instructor. In the context of this chapter, the source of the project is classified as: *community, industry*, and *other*. Figure 2-1 presents a classification of source of projects and an elaboration of *other*.

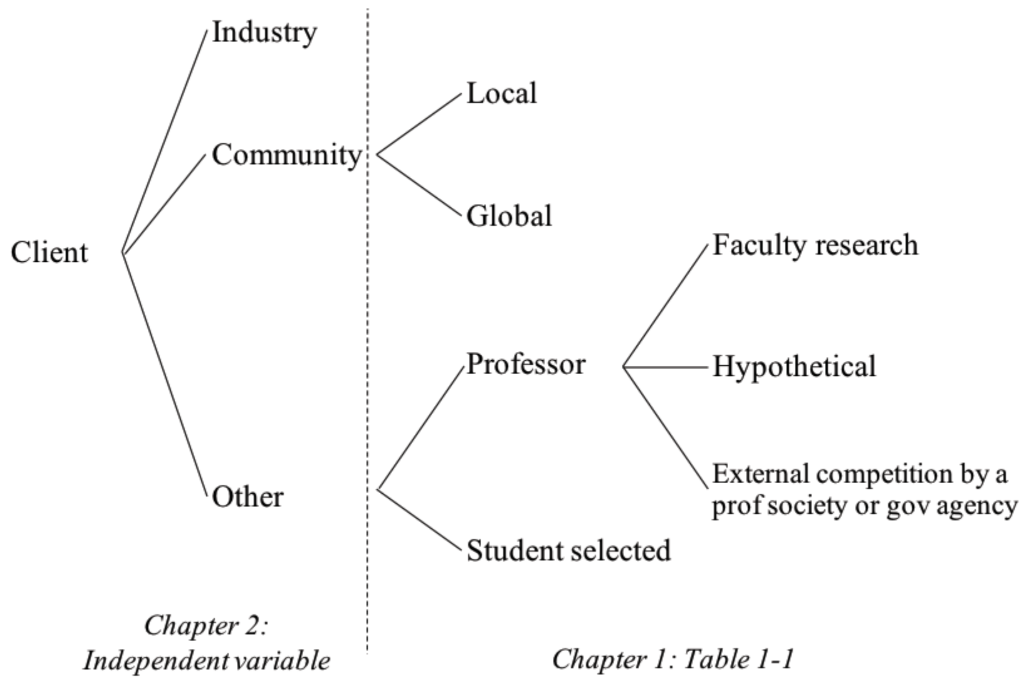


Figure 2-1: Classification of source of project

Though SL is implemented in programs across all university faculties, SL is especially tailored for engineering design projects as real problems increase student engagement [40]. The decision whether or not to involve an external client as opposed to *other*, has been shown to have impacts on student learning. While traditional cornerstone and capstone design courses attempt to teach problem-solving abilities, many fall-short as students perceive the design experience to be contrived when the professor acts as the client. The most authentic design experience is one in which a client poses a real need to the students, and the professor acts as a supervisor or colleague, guiding the students through the design process rather than trying to play both roles [45].

The ideal client for a design project is one who has a need within the scope of the students' abilities and is willing to work with students to achieve necessary educational outcomes [41]. In light of this student-client relationship, an opportunity exists to expand students' social context. Community organizations often have unmet needs that the students can address. "Students then critically reflect, examine, and converse about the service activity from both technical and nontechnical perspectives" [43]. In addition to learning the engineering design process, students are encouraged to become active within their community and have the opportunity to confront potential ethical dilemmas during the process. It is hypothesized that this deeper level of engagement increases DA in students who work on SL projects as opposed to a project from industry or one where there is no client.

2.2.2. Existing Measurement Tools

Instruments and surveys that currently measure DA require extensive post processing time and can have subjective interpretations. The Transferable Integrated Design Engineering Education project includes essay, self-assessment, reflection, and review of design assignments [21]. Reflection entries in logbooks can be analyzed with a rubric to determine how well the student understands and solves the problem for a user [27]. Design essays can be coded and analyzed based on rubrics [46]. The Design Task Test and Experimental Design Ability Test use design scenarios to assess ability through essays and are scored using rubrics [22, 26]. Rubrics apply a quantitative measure to qualitative data, but are time-intensive and subject to interpretation by the reviewer. In a rubric, guidelines are provided for a reviewer to assess which description best categorizes the quantitative data; separate guidelines are developed for each of the defined criteria. Compared to multiple choice or numeric responses, rubrics require more time to review the data multiple times for each of the criteria. The guidelines can also be interpreted multiple ways, necessitating multiple reviewers to analyze the same data. Although multiple reviewers reduce the subjectivity bias, the processing time is increased.

Additional DA measures include focus groups, observing group behavior, and speaking aloud while completing an activity [25, 28, 29]. These qualitative activities produce a large volume of data that is often recorded and analyzed multiple times. Notes are taken during the activities by multiple observers, coded by multiple reviewers, and then analyzed. A single qualitative activity is viewed and analyzed multiple times before a conclusion is made, and a large amount of study data is produced for each participant. The large volume of data and processing time reduce the desirability to use these measures as assessment techniques in large classes. The accuracy and value of the data that is produced is not under question, only the ability for an educator to deploy this type of assessment in a large classroom environment.

Current quantitative tools compare preference and project variables to design documentation grades, such as reports or presentations [30]. This can produce misleading data as grades are often based on communication skills and ability to describe the design, not the ability to design. A student may have poor documentation skills, but a great understanding of the problem or a creative design that perfectly meets the user need. Assessing students' grades can be a less effective measure of DA. Therefore, existing measurement tools are not sufficient to measure DA in a large classroom environment and a more responsive instrument is required.

2.2.3. Design Ability Construct

There are many skills required of engineers in order to produce a good design. Someone who understands and follows the design process has a mature DA, so a literature review was performed the design process. The selected design process became the DA construct, or definition of DA for this study. Then a literature review was performed to determine whether the DA construct matched student and expert perception of DA.

2.2.3.1. Design Process

Dym, Agogino, Ozgur, and Frey [47] described the design process as the generation, evaluation, and description of ideas. A more complex model is utilized by Carberry and Lee [16], of an iterative 8-step process: (a) identify the need or problem, (b) research the need or problem, (c) develop possible solutions, (d) select the best possible solution, (e) construct a prototype, (f) test and evaluate the solutions, (g) communicate the solutions, and (h) redesign [48]. This process was developed by the Massachusetts Department of Education Science and Technology/Engineering Curriculum Framework. Carberry and Lee [16] asked participants to self-assess levels of motivation, confidence, anticipated success/self-efficacy, and anxiety for each of the 8 steps. The instrument was found to be reliable, which could indicate that a reasonable design process was utilized. Significant correlations ($p < .01$) existed between self-efficacy and motivation, success, and anxiety; an extension of this study to correlate ability to self-assessed ability could be noteworthy.

The design process according to Carroll, Goldman, Britos, Koh, Royalty, and Hornstein [49] was: (a) understand, (b) observe, (c) point of view, (d) ideate, (e) prototype, and (f) test. The focus of this design process is on the collection of data rather than the evaluation of ideas.

Kim, Jin, and Lee [22] utilized a 3-part design model (problem understanding, idea generation, and design elaboration) to code participants' explanation of a design solution for a simulated problem. The model was then broken down into an 8-step process with similar elements to Carberry and Lee [16], but Kim et al. [22] put more emphasis on developing ideas: (a) understand design assignment and task, (b) gather data, (c) clarify constraints and objectives, (d) generate ideas, (e) evaluate ideas, (f) find technical solution, (g) evaluate solution, and (h) refine design. This study linked creativity modes (derived from Myers-Briggs assessments) to an emphasis on a portion of the design process. Additionally, it was shown that expert designers stepped through the design process more consistently than the sporadic route that the students employed..

Sevier, Chyung, Callahan, and Schrader [15] described the design process as follows: (a) problem definition, (b) conceptual design, (c) proof of concept, (d) detailed design, and (e) communication/fabrication.

There were 3 common elements derived from the literature that define the design process for this first study:

- *define the problem*,
- *evaluate alternatives*, and

- *communicate the design*.

Each of the design processes from the literature emphasized one aspect of the 3-step design process, so a simplification of the more complex processes is justified. The definition of DA for this study, referred to as the *construct*, is comprised of the steps in design process.

2.2.3.2. Design Ability

The literature was next reviewed to validate whether the DA construct (*define the problem*, *evaluate the alternatives*, and *communicate the design*) was regarded as important by experts and students. Fifty-one senior students were asked to rate the most and least important skills before and after a human-centered design course, and the results were compared to practicing engineers [50]. Participants' results showed a statistically significant alignment ($p < .01$) with practicing engineers after the design course, indicating the course improved their DA, however a reliability assessment was not provided. The highest rated items according to practicing engineers were communication, understanding the problem, identifying constraints, seeking information, and sketching. Four of the 5 items that practicing engineers considered important are contained in the DA construct, supporting the validity of the construct; the skill that was neglected (sketching) is difficult to assess using a questionnaire.

Student perceptions of the role of the user and the design process in design were assessed using a phenomenographic study by Zoltowski, Oakes, and Cardella [28]. Seven themes were developed from the 33 participants, progressing from no mention of the user or design process to full empathetic design. Novice designers were characterized by presenting decent idea generation but poor problem definition and idea evaluation, whereas expert designers spent considerable time defining the problem. This suggests that 2 of the 3 steps in the DA construct (*define the problem* and *evaluate ideas*) have the potential to differentiate novice and expert designers.

Creativity was assessed by coding 94-participants' ideas and sketches of a simulated design problem over 3 semesters [51]. First-year students produced significantly ($p < .05$)

more innovative ideas than fourth-year students. No significance was found between the first- and fourth-year students' quality of work. This implies that in this sample, students' DA do not significantly improve over the 4 years and creativity is diminished. This would appear to be contrary to the hypothesis of this study, however more information is desired regarding the course content at the university in the study; if students in this study were in primarily didactic courses and not exposed to design projects, an argument could be made to the importance of projects to improve DA.

Passow [8] measured the competencies required for engineering practice according to 4,225 engineering alumni of university who graduated during the last 10 years. Teamwork, communication, data analysis, and problem-solving were identified as statistically distinct ($p < .05$) among the competencies required for engineering practice. Three of these items are measured in the DA construct. However, despite the large sample, consistency is questionable as the instrument was reworded and only 1 university participated in the study.

The literature revealed that the 3 components of the DA construct (*define the problem*, *evaluate the alternatives*, and *communicate the design*) were identified among the most important competencies required for an engineer. This necessitates the need to measure the change in these 3 DA for design projects.

2.2.3.3. Ethical Awareness

In this first study, DA was not limited to technical and professional skills of an engineer, but a second construct considered the level of ethical awareness in students, especially when considering SL projects. According to Al-Khafaji and Morse [52], students' awareness, cultural sensitivity, and empathy are among the qualities and skills that are enhanced, specifically in SL projects. Finelli et al. [32] described 3 concepts within ethical development: (a) knowledge of ethics, (b) ethical reasoning, and (c) ethical behavior. The study compared curricular and co-curricular experiences to ethical development for 4,000 engineering students in 18 universities. Knowledge of ethics was lower than expected, when compared to national averages of the Fundamentals of Engineering exam. Ethical reasoning met expectations, when compared to the averages from the Defining Issues Test Version 2. Ethical behavior was compared to the author's previous research and while self-reported positive ethical behavior met expectations, self-reported negative ethical behavior was more rampant than expected. Significance was not included. Though presenting only descriptive statistics, the study elucidates the need to further measure ethical awareness as the results differ for each criteria.

A mixed-methods study was performed to determine whether students' beliefs could be affected by a SL project [29]. Significance ($p < .1$) was reported in 15 of the items over 4 cohorts of 212 participants. It was concluded that beliefs were changed regarding the work performed by engineers and the impact of engineers, though no statistical significance was evident. Additionally, since the reliability of scale was not provided, it is possible that if a specific item was removed, significance could be established, especially for such a permissive level of significance. Literature has shown that students' beliefs can be influenced by SL projects [53], necessitating a study to measure the change in ethical awareness, one aspect within student beliefs.

Based on the literature review, the construct for ethical awareness consists of: (a) equal treatment of all persons, (b) ethical conduct in all situations, (c) cultural diversity for all ethnicities, and (d) keen awareness of responsibility to society.

2.2.4. Independent Variables for Comparison

After the DA construct was defined, the project and participant variables needed to be established. The list of 15 independent variables, shown in Table 2-1, was developed through consultation with the literature.

The columns in Table 2-1 contain descriptive information about the participant and the project. The first 3 rows contain nominal variables that can be described by categories such as male and female. The remaining rows contain ordinal variables representing a numerical response grouped into intervals such as ages: <18, 18-21, 22-25, etc. Both nominal and ordinal variables are discrete variables which determines the type of data analysis that can be performed.

Table 2-1: Independent variables for study 1

	Participant variables	Project variables
Nominal	Engineering discipline	Source of the project: community, industry, other
	Gender	Maturity of the product: paper, prototype, final
	Identifies as a minority	Whether the course was mandatory
Ordinal	Age	Project length
	Year in studies	Amount of time spent with the professor
	Time travelled internationally	Amount of time spent with the client
		Rate project length
		Rate amount of time with professor
		Rate amount of time with the client

The year in studies described how many years the participant was in university, ranging from first- to fifth-year and higher, and participants were asked to provide their age. Students who are further along in their studies or are more mature in age are expected to have a better DA than first-year engineering students.

Gender was assessed as an independent variable, because previous studies show that women have a higher motivation level in SL projects than men [54 - 56]. It is desirable to quantify the difference in women's DA between SL and industry projects and compare this to the men's difference.

The effect of international travel is targeted more specifically to the ethical awareness construct than DA, but more cultural awareness could indicate better empathy and thus students could have a better understanding of the problem. Additional independent variables were recorded to provide a full snapshot of the student and project, as the anonymous nature of the instrument prevented consulting students for further information after data collection. While the intended focus of this study was to compare the source of the project to DA and ethical awareness, the remaining independent variables could provide data for future studies.

2.3. DEVELOPMENT OF INSTRUMENT

Once the DA construct was defined and independent variables were selected, the development of each item on the instrument could begin. The intention was to compose items that measure DA and also eliminate the need for rubrics or time intensive data review techniques seen in the literature. Three types of items were developed: assessment, self-assessment, and design scenarios. Table 2-2 shows the distribution of items across the construct, broken down by type of item.

Table 2-2: Distribution of items in study 1 [57]

Type of Item	***Design ability***			***Ethical awareness***
	Define the problem	Evaluate alternatives	Communicate design	
Assessment[a]	2	3	7	7
Self-assessment[a]	3	1	7	3
Design scenario[b]	3	-	1	-

[a]Assessment items employ Likert-scale. [b]Scenario items employ multiple choice

Participants answered 12 items assessing DA and 7 items assessing ethical awareness on a labeled 4-point Likert-scale from 'strongly agree' (1) to 'strongly disagree' (4), with an option for 'don't know'. Likert-scale is a common technique to target different levels of DA in students; when designed correctly, a student with a better DA would select 'strongly agree' for an item that a student with a worse DA would select 'strongly disagree'.

Seven out of the 12 items assessing DA were reverse scored, as were 4 of the 7 items assessing ethical awareness. Negatively worded or reverse scored is employed to ensure participants read each item rather than select all 'strongly agree'. An example DA assessment item is as follows:

Research is not necessary to develop product requirements.

This item was reverse scored, so a student with a better DA was expected to select 'disagree' or 'strongly disagree'. Participants also performed a self-assessment for 12 items for the DA construct and 2 items for the ethical awareness construct. Two of the 12 DA items were reverse scored. An example of a self-assessment item is as follows:

My ability to define client specifications or requirements improved during this project.

Participants with a better DA were expected to select ‘strongly agree’. Participants then answered 4 multiple choice design scenario items that required them to design a chair for a person over 6 feet tall. An example design scenario item is as follows.

You were asked to design a chair for a person over 6 feet tall, for their office. When developing ideas, the chair should be:

		Score
a.	*Treated as one unit.*	*4*
b.	*Broken up by sections: base, armrest, and seat.*	*3*
c.	*Broken up by components: wheels, stem, seat, backrest, armrest, screws, bolts, and springs.*	*2*
d.	*Broken up by function: height adjustment, mobility, back support, and arm support.*	*1*

This item addresses the ability to *define the problem* within the construct. The detail about the height of the person should separate responses of participants with a better DA compared to a worse DA. A score was recorded from 1 to 4, where 1 represented the most correct and 4 represented the least correct answer. Participants with a better DA should select option d because it addresses the height. The full instrument can be found in Appendix A.

2.4. METHOD

The study was administered to a purposive sample of second-year students at Dalhousie University (Dal) in the winter of 2013. The 240 multi-disciplinary students completed a 6-week design project that culminated in a working prototype. The students were divided into 4 sections based on desired engineering discipline, and each section had a different project. Participation was voluntary and anonymous. Students were recruited during class and provided a link through email to the instrument using Opinio software.

After the semester ended, the data were entered into IBM’s Statistical Package for Social Sciences. Data were cleaned by removing entry errors. Negatively worded and multiple choice items were recoded. An exploratory principal component factorial analysis was performed and factors were selected after reviewing the scree plot. A mean value was calculated for the constructs and new factors. The dependent variables are shown in Table 2-3 and comprised of the constructs and factors.

Table 2-3: Dependent variables and items for study 1

	Dependent variables	Variable type	Values
Constructs	Design ability *Define the problem* *Evaluate alternatives* *Communicate the design* Ethical awareness	Ratio	1.00 to 4.00
Factors	Factor 1 Factor 2 Factor 3 Factor 4 Factor 5	Ratio	1.00 to 4.00

The constructs and factors are ratio variables on a continuous scale; when continuous dependent variables are combined with discrete independent variables, the appropriate analysis technique is analysis of variance (ANOVA). The 37 items are ordinal variables due to the 4-point Likert-scale; when discrete dependent variables are combined with discrete independent variables, a chi-squared technique should be utilized. Although debated in the literature, general practice allows for a Likert-scale to be considered continuous and can be analyzed using parametric tests such as ANOVA [58].

Validity checks were then performed. Reliability of scale was determined for the constructs and factors. Assumptions of normality and homogeneity of means and variances were reviewed for all dependent variables. The dependent variables that met validity requirements were processed using ANOVA to determine whether there were significant differences between the independent and dependent variables.

2.5. RESULTS

2.5.1. Participant Data

Of the 240 students in the course, 19 students completed the instrument. There were an additional 11 students that started the instrument, but have not been included in the results because the data were incomplete. Table 2-4 shows the independent variables that are common to all participants.

Table 2-4: Independent variables common to all respondents for study 1

Participant variable	***Response***
Year in studies	2nd year students
Project variables	***Response***
Source of the project	Professor acting as client
Maturity of the product	Proof of concept
Whether the course was mandatory	Yes
Project length	6 weeks
Amount of time spent with the client	No client
Rate amount of time with the client	No client

Figure 2-2 shows the number of participants for each participant and project independent variable that were not constant. There were 6 engineering disciplines represented (Figure 2-2 a), with 58% of participants pursuing Mechanical Engineering. Thus, more than half of the respondents worked on the same project while the remaining 42% of participants worked on the other 3 projects.

There was a representative gender distribution (Figure 2-2 b) where 16% of respondents were female; this is within the admittedly large margin of percentage of female engineers, ranging from 12% of professional engineers according to Engineers Canada in 2012 [59] through 23% of all engineers according to Statistics Canada in 2011 [60]. Whether there was a representative racial distribution (Figure 2-2 d) is more difficult to assess because while 15% of participants identified with a minority, 16% of respondents chose not to submit racial identity information. Seventy-four percent of participants are 18-21 years old (Figure 2-2 c), which represents the most common ages of second-year students in university.

The highest responses for international travel were 37% of respondents have not travelled out of the country and 26% have travelled between 2 and 6 months over their lifetime (Figure 2-2 e). The 3 project variables revealed that 52% of respondents (Figure 2-2 f) would like more time for the project and 42% desired more time with the professor outside of class (Figure 2-2 h).

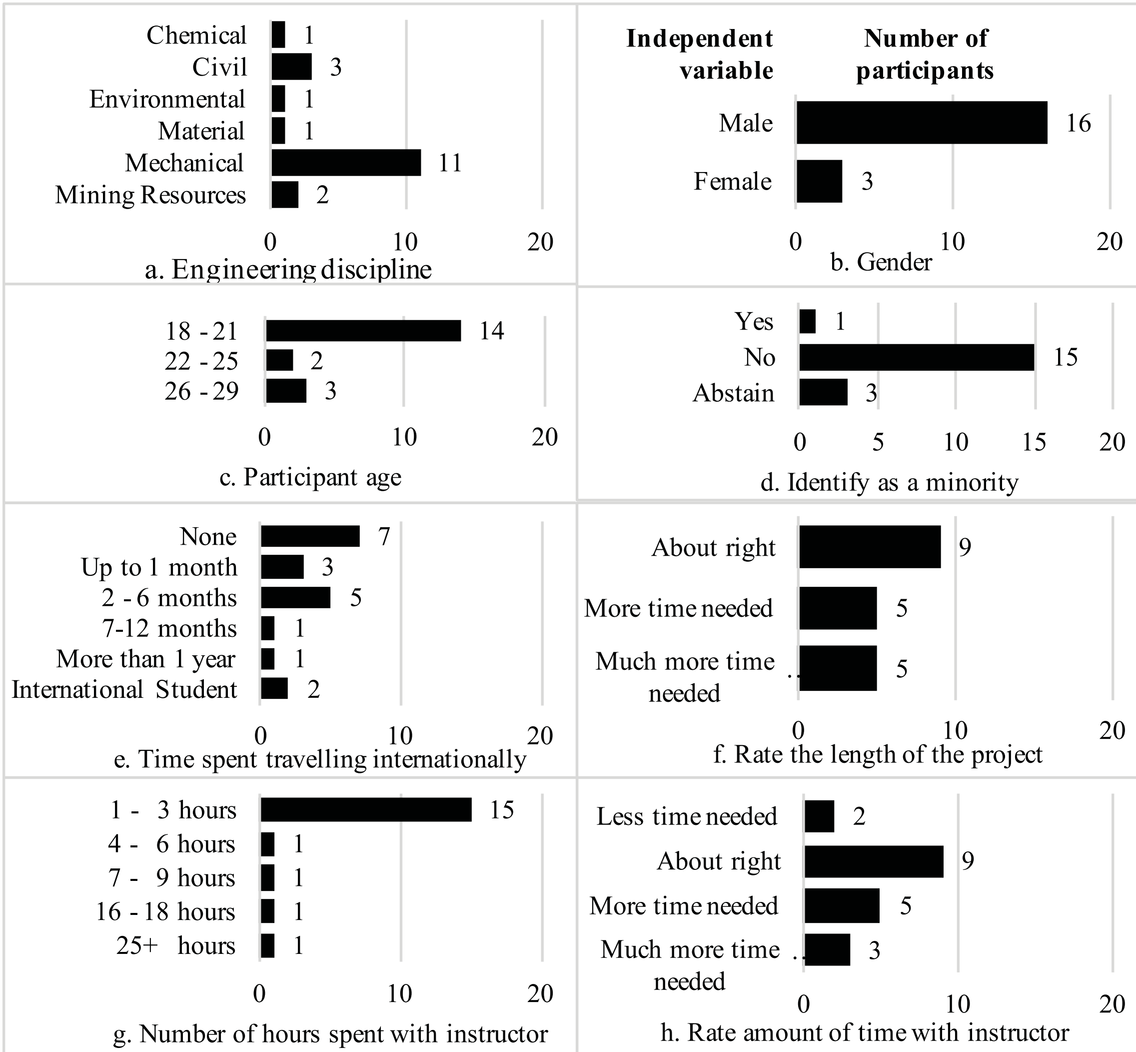
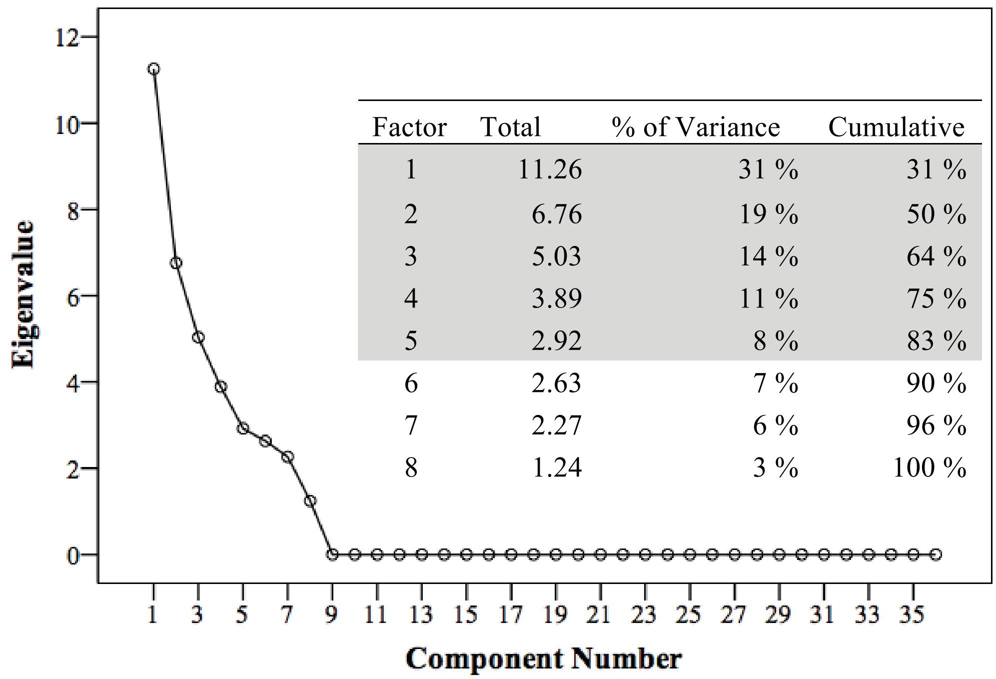


Figure 2-2: Participants and project data for study 1

Of the 79% of students that spent less that 3 hours with their instructor outside of class (Figure 2-2 g), 7 desired more time with the professor, 6 felt the time was right, and 2 desired less time. This supports the belief that design projects shift responsibility for learning from the instructor to the students. However, no conclusion can be drawn because this could also suggest that participants were unsatisfied with the time they spent with the faculty member.

2.5.2. Design Ability Data

An exploratory factor analysis was performed to determine if the items could be grouped due to the similarity of the responses using the scree plot method as shown in Figure 2-3.



Factor	Total	% of Variance	Cumulative
1	11.26	31 %	31 %
2	6.76	19 %	50 %
3	5.03	14 %	64 %
4	3.89	11 %	75 %
5	2.92	8 %	83 %
6	2.63	7 %	90 %
7	2.27	6 %	96 %
8	1.24	3 %	100 %

Figure 2-3: Scree plot identifying 5 factors

A factor load of > .3, and varimax rotation was applied, disregarding the fact that the sample size (n = 19) was substantially smaller than is required for factorial analysis [61]. Bryman and Cramer [62] suggest a minimum of 100 participants, while Tabachnick and Fidell [63] recommend a minimum sample of 300 participants. Though the factors will not be considered valid, it is important to practice the process for this pilot study.

The study met the minimum number of items (5) per dependent variable for 4 of the 5 constructs [61]; *evaluate the alternatives* has only 4 items, but this was deemed acceptable for the pilot study. The sharp turn or 'elbow' in the scree plot occurs after the fifth factor, signifying 5 factors were identified from the 37 items, accounting for 83% of the variance. Typically, a review of the items within each factor is performed and commonalities are sought. However, as shown in Table 2-5, the distribution of items across the constructs does not produce a theme in the factors.

Table 2-5: Distribution of items for factorial analysis for study 1

		Factor 1	2	3	4	5
DA: Define the problem						
DD1	First task	x				
DD2	Component	x				
DD3	Requirements			x		
DD5	Research					x
DD7	Requirements					
DD23	Tasks			x	x	
DD25	Design process	x			x	
DA: Evaluate the alternatives						
DE8	Cheapest			x		
DE13	Decision matrix	x				
DE14	Disadvantages	x				
DE17	Compare		x		x	
Ethical awareness						
E1	Most important	x	x			x
E2	Graduate		x			
E3	Best teams			x		x
E4	Men vs women	x			x	
E5	Isolate			x		
E6	Responsible	x				
E7	Think same		x			
E8	Engaged		x			
E9	Meaningful	x			x	x
E10	Hired					

		Factor 1	2	3	4	5
DA: Communicate the design						
DC4	Presentation			x		
DC6	Oral presentation	x				
DC9	Rehearse	x	x			
DC10	Sections		x			
DC11	Team		x			x
DC12	Tables		x		x	
DC15	Slides			x		
DC16	Design					
DC18	Um		x			
DC19	Doc		x		x	
DC20	Share idea		x			x
DC21	Report errors					x
DC22	Client specification				x	
DC24	Ideas incorporated			x		
DC26	Oral presentation		x		x	x
DC27	Explain		x			

Ten dependent variables were assessed for each participant using the average of the items for: (a) DA, (b) each of the 3 subconstructs for DA, (c) ethical awareness, and (d) the 5 factors. Table 2-6 displays a list of the descriptive statistics for the dependent variables.

Table 2-6: Descriptive statistics of selected dependent variables for study 1

Dependent variable	***Mean***	***Standard deviation (σ)***	***Reliability (α)***
Design ability +	1.88	.45	*.729 (n=17)*
Define the problem	2.16	.35	*.024 (n=8)*
Evaluate alternatives	1.76	.50	*.608 (n=3)*
Communicate the design +	1.98	.43	*.704 (n=13)*
Ethical awareness	1.99	.33	*.252 (n=10)*
Factor 1 +	1.87	.36	*.862 (n=11)*
Factor 2 +	1.91	.45	*.733 (n=14)*
Factor 3 +	2.02	.45	*.758 (n=8)*
Factor 4 +	2.12	.48	*.743 (n=9)*
Factor 5	2.30	.44	*.609 (n=9)*

Note: 1.00 corresponds to a better DA and 4.00 is a worse DA, + denotes scales that have α ≥ .7

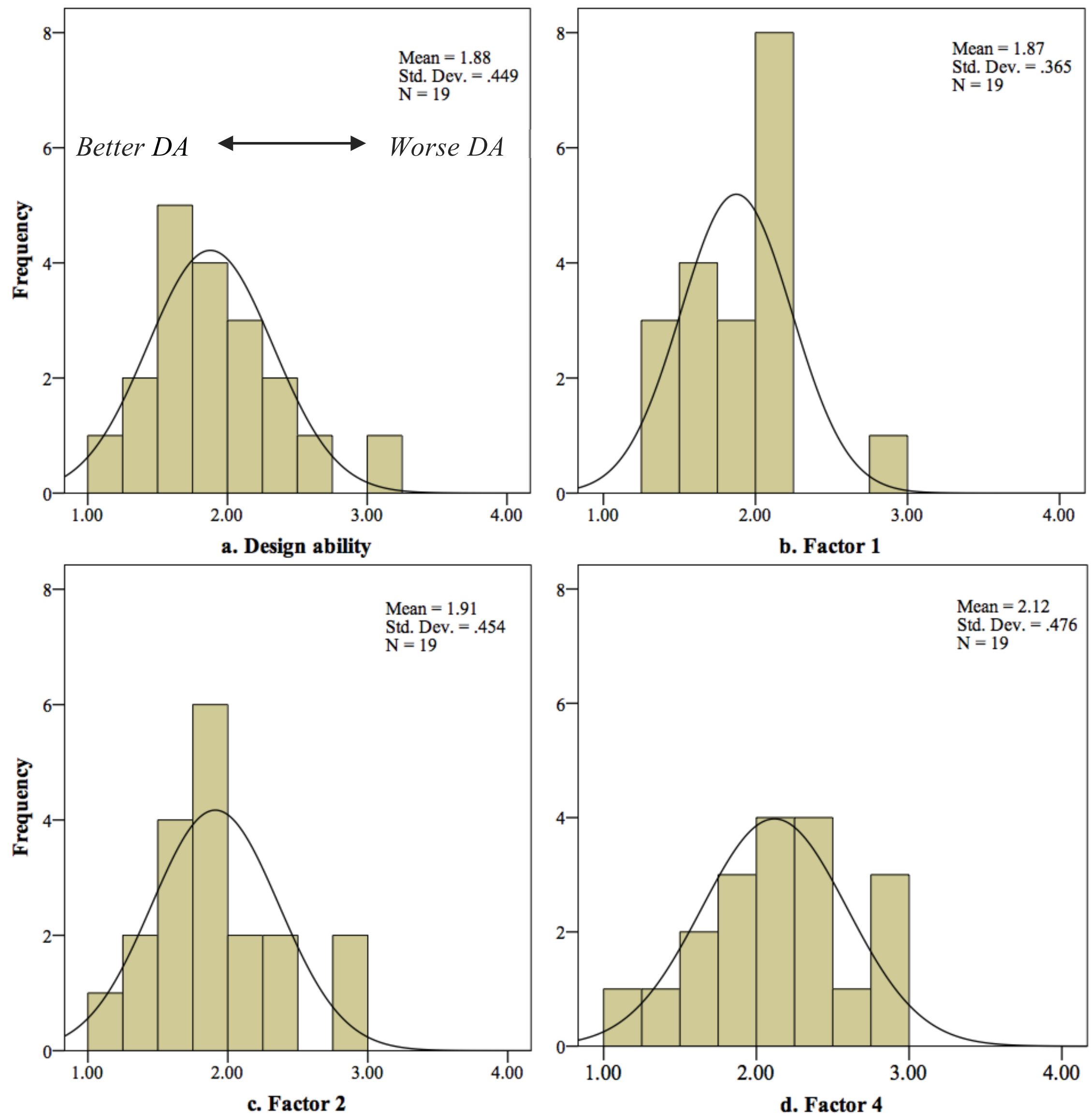
Tables A-1, A-2, and A-3 in Appendix A contain complete descriptive statistics for all of the dependent variables, independent variables, and items, respectively. The reliability analysis for the DA construct initially produced a Cronbach's alpha [64] of α = .18 (n = 27), indicating it is not reliable [65, 66]. However after 10 items were removed, the reliability increased to α = .729 (n = 17) which met the .7 threshold for reliability [66]. Items were removed due to the homogeneity of the response from all participants. For example, the item 'It is necessary to rehearse before a presentation for the client' was removed from both DA and *communicate the design* because 18 out of 19 participants selected 'agree' or 'strongly agree'. Five of the items removed from the DA construct due to homogeneity of responses were:

- It is necessary to rehearse before a presentation for the client.
- Tables are a concise way to display data.
- There are never too many slides in a presentation for the client.
- My ideas were heard and incorporated nicely into this project.
- When evaluating possible designs, it is best to choose the least expensive design.

Items were removed if the participants responded differently to that item than to similar items, which indicated the content or wording of the item was confusing. For example, 'My client was pleased with my design' caused many participants to respond with 'don't know' and was removed from both DA construct and *communicate the design* construct. The following 5 items were removed due to inconsistency of response:

- My client was pleased with my design.
- In my last engineering report, there were at least 3 errors.
- You were asked to design a chair for a person over 6 feet tall, for their office. You just finished the first meeting with the client to discuss the problem, which lasted 15 minutes. Select the first task you should complete.
- My ability to define client specifications or requirements improved in this project.
- Requirements are measureable and specific pieces of information.

These items will be revised or removed from future studies. Reliability data are listed in Table 2-6 for the dependent variables (denoted with +). The *DA* (α = .729) construct, *communicate the design* (α = .704) construct, and factors 1 – 4 (α = .862 .733 .758 .743) were found to have reliability of scale. Constructs for *define the problem*, *evaluate alternatives*, ethical awareness, and factor 5 did not meet the threshold for reliability. Assumptions of normality were checked for the dependent variables and accepted if both the skewness and kurtosis were within 2 times the standard error [67]. It was determined that 7 dependent variables met normality requirements. Figure 2-4 shows the histogram for the 4 dependent variables that met reliability and normality requirements.



Note: 1.00 corresponds to a better DA and 4.00 is a worse DA

Figure 2-4: Dependent variables that meet assumptions of normality and reliability

Most participants responded with a better DA, evidenced by the positive skew of the 12 items that did not meet normality requirements. Similarly, the 12 items that did not meet normality requirements displayed positive kurtosis (a defined peak), which indicated a large number of participants answered the same way.

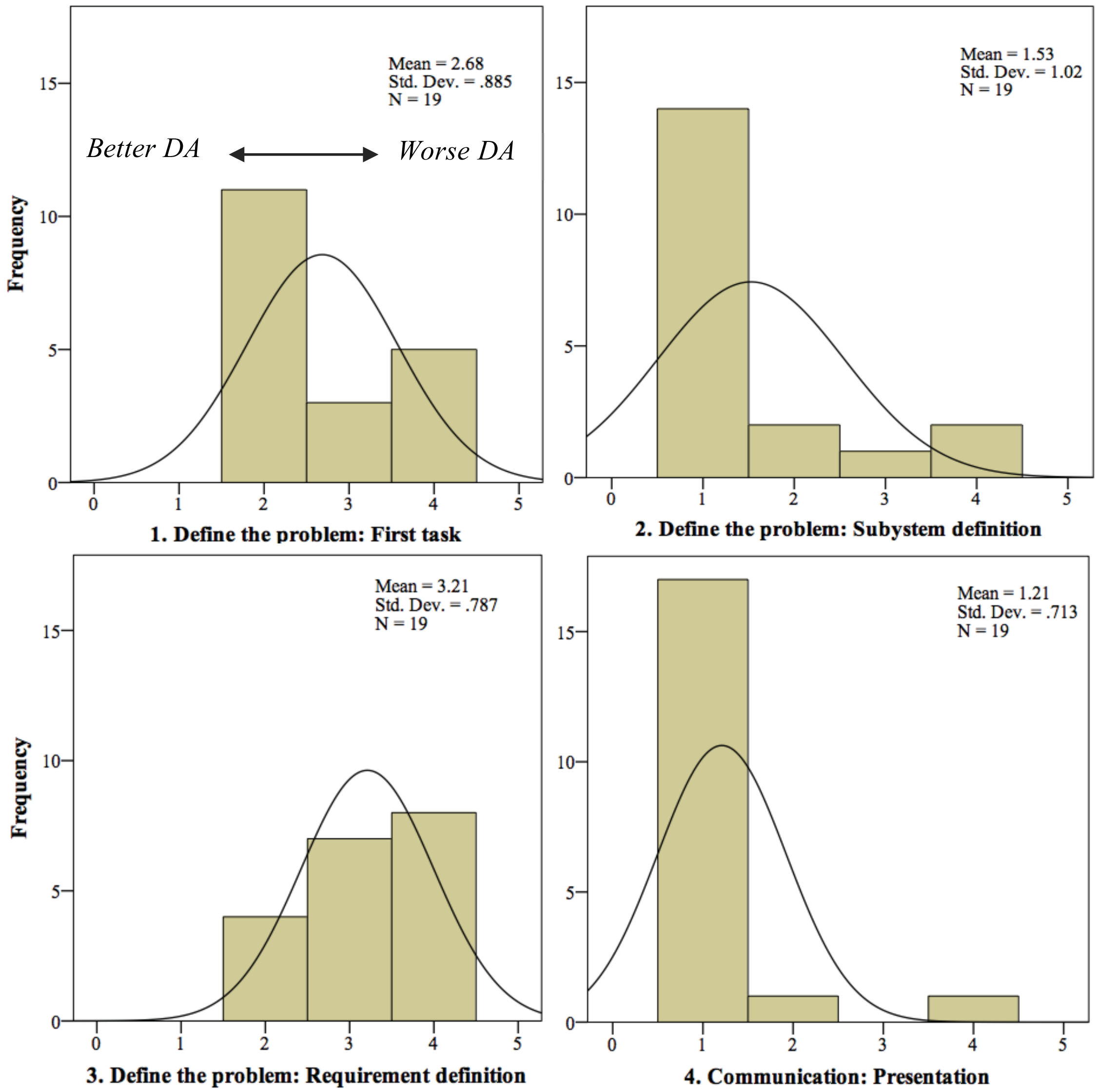
Homoegenity of means and variances were calculated for the dependent variables and items using Levene's statistic (where significance must be $p > .05$) to ensure that the spread in values was similar for each variables. Once all preconditions for ANOVA were performed: independence of observations, assumptions of normality, and homogeneity of variances, the ANOVA determined if the dependent variables and items were reliant upon the independent variables. No difference in means were found for the factors or DA constructs. However, 2 significant effects at the $p < .05$ level were found for 2 ethical awareness items and will now be presented.

Female and male participants responded significantly differently to the statement 'My design for this project is more meaningful to society than other design projects I worked on' [$F(17,1) = 5.448$, $p = 0.032$]. Most male participants responded with 'disagree' whereas female participants replied more commonly with 'don't know'. The independent variable for gender only has 2 options, so a simple t-test could have been used instead of ANOVA.

There was a second statistically significant result that utilizes post-hoc tests, which require 3 groups. There were significant effects between participants requesting more time with the instructor and how they answered 'Acting ethically is the most important part of being an engineer' [$F(15,3) = 5.996$, $p = 0.007$]. Using Tukey's post-hoc test, a statistically significant difference was found between participants that wanted 'less time with the instructor' and those that said the time was 'about right'. All participants who replied that they spent an appropriate amount of time with the instructor 'strongly agree' that 'ethics is the most important part of being an engineer', while participants who wanted less time with the instructor 'agree' to the statement. Participants who requested more time answered either 'strongly agree' or 'agree'. However, this item was not used in future studies, because all participants either 'agreed' or 'strongly agree' to the item, indicating a bad item. Albeit statistically significant, the implications of this statistic are not meaningful.

2.5.3. Design Scenario

The design scenario items warrant further review of the results. There were no responses for what was considered the best answer to items 1 and 3, as shown in Figure 2-5. This indicates that either the participants have not developed their DA, the answers are too subjective, or the items should be reworded.



Note: 1.00 corresponds to a better DA and 4.00 is a worse DA

Figure 2-5: Design scenario histogram

The answers for items 2 and 4 were too obvious, as the majority of participants responded correctly. The large spike in plots 2 and 4, regardless of accuracy, indicated a positive kurtosis, which negated the assumptions of normality, and indicated a poorly worded item. The items should be revised so the correct answer was less obvious or new items should be developed. The design scenario items were a novel method developed to measure DA, however the item wording required revision.

2.6. DISCUSSION

There was not enough information to support or disprove the hypothesis that source of client impacts DA, because all participants surveyed had the same source where the professor acted as the client. Rather than continue the study with a larger population, it was decided to correct identified issues, and administer the revised instrument to a larger population with a more diverse source of projects.

This study provided a better understanding of the data analysis process, but little was learned about DA as there were no statistically significant inferences from the ANOVA between the DA dependent variable and the 8 independent variables. The DA construct was found to be reliable ($\alpha = .729$) once non-conforming items were removed. The assumptions of normality and reliability analyses necessitated a review to either remove or reword each item, to prevent too many 'don't know' entries, homogeneous responses, highly skewed results, or items with a high kurtosis.

Due to the small sample size, the factorial analysis was not valid and any significance that was determined for ethical awareness could be attributed to a type I error. Similarly, the absence of significance could be attributed to a type II error. However it was important to pilot the analysis technique to increase the sample size to provide valid results in future studies.

Having 15 independent variables resulted in an exaggerated statistical significance and a type I error. The statistical significance value $p < .05$ did not take into account the multiple factors being assessed during the one-way ANOVA tests. The Bonferroni adjustment should be considered to correct this, reducing the significance value from .05 to .05/c, where c is the number of factors or hypotheses [65]. However, the list of 15 independent variables was not exhaustive, nor were all variables interrelated, so an estimation will be required to determine the appropriate value for c.

After completing the data review, it was discovered that the ‘don’t know’ items were listed as 5.0 on the 4-point scale. This oversight misrepresented the responses so that answers appeared more incorrect than if the participant picked the least desirable response. The data were re-coded to change ‘don’t know’ entries to blank, as if no data were entered, and the analyses were rerun. Based on the way the analyses handle missing data, there were no statistically significant results to report. The reliability and factor analyses employed list-wise deletion, removing all of a participant’s responses if there were any missing data. This reduced the sample size to 9 participants; no construct was reliable, no factors were available, and there were no significant inferences. To prevent this, a larger sample is required, items must be reworded so there are less ‘don’t know’ entries, and data will be recoded as a blank entry before data analysis.

2.7. CONCLUSION

In this first study, items were developed to quantitatively assess DA, defined as: *define the problem, evaluate alternatives*, and *communicate the design.* Items were also developed to measure ethical awareness. Assessment and self-assessment Likert-scale items were derived from the literature and a new method to quantitatively assess DA was developed through a sample design scenario employing multiple choice. There were 15 independent variables selected from the literature to compare against DA, subdivided into 6 participant and 9 project variables. The methodology to collect and compile the results was piloted, utilizing Chronbach’s reliability of scale, factorial analysis, ANOVA, and post-hoc tests. DA was found to have a reliable scale (n=17), 5 factors were produced, 2 items displayed statistically significant results, and post-hoc tests were performed.

The hypothesis was neither supported nor negated, as the source of the project did not change in the 19 participants, making it impossible to determine whether there was a change in DA between participants with clients from the community or industry. Though no meaningful conclusions were drawn due to the small sample size and necessary rewording of items, the value of this study resides in the framework that was constructed. The development of the design scenario, independent variables, and items, as well as piloting the process, increase the probability of success for later studies.

CHAPTER 3: EXPLORATORY DESIGN SCENARIO STUDY: PRE-POST DELIVERY

3.1. INTRODUCTION

Design ability (DA) is not as straightforward and easily measured as was initially expected. In order to determine the efficacy of service-learning (SL) projects on DA, the instrument was revised. Recognizing that the design scenario items offered a better measure of DA than the self-assessment items that measured confidence, the definition of DA was reviewed and the construct was refined, influenced by the Canadian Engineering Accreditation Board (CEAB). The previous assessment lacked the ability to acquire rich data and instead took a dartboard approach, assuming students' DA would be revealed if enough items were asked. The number of dependent variables increased to 26 and independent variables to 18. The methodology was also revised in order to increase the response rate and reach a more diverse population of students. In order to determine if there was a change in DA, the instrument was delivered before and after design projects. Where most studies contain only 1 independent variable, 18 may be considered a high number. However, little research has been performed to assess DA, necessitating an exploratory approach to determine potential effects. The study has 3 ambitious goals:

1. *Measure DA.*
2. *Determine if there was a change in DA before and after the design project.*
3. *Identify the cause for the change, specifically the effect of SL projects.*

To measure DA, there were revisions to the instrument and its delivery. To determine the change in DA and cause for the change, 2 statistical techniques were utilized. Finally, results and recommendations were summarized.

3.2. DEVELOPMENT OF INSTRUMENT

3.2.1. Revised Design Ability Construct

In chapter 2, the construct was: define the problem, evaluate alternatives, and communicate the design. This neglected the realization step of building and testing.

Surely, a student cannot have a fully formed DA unless they have an awareness of the build and test step. CEAB defines the graduate attribute for design as:

> *An ability to design solutions for complex, open-ended engineering problems and to design systems, components or processes that meet specified needs with appropriate attention to health and safety risks, applicable standards, and economic, environmental, cultural and societal considerations* [2].

This definition lists a number of tasks students need to do, but does not specify abilities they need to complete the tasks. Faculty at Dalhousie University (Dal) deconstructed this definition into 5 different levels of performance indicators in April 2012 [68]. Design was defined as the ability to:

A. Define functional specifications using engineering methods; check against user needs
B. Conceptualize alternative approaches and evaluate advantages and disadvantages
C. Quantify tasks required for timely implementation of the chosen solution
D. Synthesize components of a design into an integrated whole
E. Optimize functionality, safety and sustainability; identify constraints, risks, and tradeoffs.

While neither of these definitions includes build and test, each of the design process presented in the literature review in 2.2.2.1 included a step to actually build the device and verify it met user need. Upon further review of the design processes, a revised process will be used for study 2: *understand the problem, ideate, build & test*. Table 3-1 shows how DA was deconstructed to develop items for the instrument.

Rather than simply defining the problem, students must first understand the problem and user need to provide a good definition of the problem. This step takes the focus off of the problem and onto the user, which allows for a more holistic, complete design. Additionally, understanding is a higher order process than defining, so more is expected of the students [69]. The second step changed from evaluate alternatives to *ideate*. The evaluation of ideas is a very specific step within ideation, so this change is a recognition that more occurs during ideation than simply choosing 1 idea. The third step changed from communicate the design to *build & test*. While a student's ability to communicate the design does reflect how well they understand the problem, solution, and ability to transfer this to paper, it can be misinterpreted as simply the ability to follow standards in written and verbal forms of communication. Focusing instead on building and testing completes the design process and is more design-centric.

Table 3-1: Study 2 construct development

Understand the problem	***Ideate***	***Build & test***
Define functional specifications (A)	Conceptualize alternative approaches (B)	Validate and verify user need is met through analysis and testing (A)
Perform background research	Evaluate advantages and disadvantages (B)	Produce a proof of concept
Recognize importance of understanding the problem before ideation	Quantify tasks required for timely implementation of the chosen solution (C)	State standards for build documents such as drawings
Differentiate important versus extraneous aspects of the user need	Synthesize components of a design into an integrated whole (D)	Understand purpose and limitations of prototyping
	Optimize functionality, safety and sustainability; identify constraints, risks, and tradeoffs. (E)	
	Convey ideas through sketches	
	Identify constraints, risks, tradeoffs	

Note: Letters refer to the Dal performance indicators stated above.

There are many aspects of DA that could have been included in the construct, but that could have obscured the ability to measure DA. This redirection of the construct to the design process should allow better items to be developed that focus more on DA and have the potential to measure DA using the design scenarios.

3.2.2. Revised Instrument Item Development

The instrument changed in 3 ways: an increase in the number of parts of the instrument with a pre/post delivery, the way items were delivered utilizing design scenarios, and an increase in the number of items. The full instrument can be found in Appendix B.

3.2.2.1. Number of Parts of the Instrument

In order to determine whether DA changed before and after a design activity, the number of times the instrument was delivered increased. Rather than use the same instrument twice, with the potential for a testing effect bias [70], multiple parts to the instrument were developed to be delivered at different times.

In order to increase the sample size, the instrument had to accommodate the existing structure of different design courses. Some courses had 2 design projects while other courses had only 1 project. The instrument was delivered in 3 parts for courses with 2 projects (pre, mid, and post), and 2 parts for courses that have 1 project (pre and post), but covered the same items overall. Although this complicated the data analysis, the 3-part delivery allowed for a comparison of the source of project and length of project for the same data set of students. The 2-part delivery required a large sample to determine if an independent variable changed students' DA, but the 3-part delivery compared the development of the same students. The instrument was then responsive, fit within the constraints of the existing courses, and took advantage of the differences.

3.2.2.2. Item Delivery

The delivery of the items diversified, with the addition of qualitative items. With multiple choice or Likert-style quantitative items, participants have a 25% chance of getting the right answer. However, an open-ended item does not prompt participants with information so a more accurate DA is revealed. Due to the low response rate of the previous instrument, this instrument was delivered on paper during class, allowing for more creative forms of questions. A sample open ended item is:

> *For the purposes of this survey, assume you are a Professional Engineer with your own business. A client asks you to build a bridge for a stream crossing on their property. What questions do you ask?*

Because there is not an exact answer to these open-ended items, a rubric is utilized to assess DA. The rubric for this item is as follows:

- *Poor: Focus on project – cost, material, schedule, dimensions*
- *Good: Focus on items – type of vehicle, regulations, purpose of bridge*

- *Great: Focus on user – months of operation, other stakeholders*

All of the quantitative items on the instrument measured DA, but the qualitative items addressed both DA and ethical awareness. Some of the qualitative items also addressed SL by asking the same item as above for an underserved or underrepresented person:

> *A client who uses an electric wheelchair for mobility asks you to design a desk for them. What are the questions you would ask?*

The assessment used a similar rubric that classified whether the focus was on the project, items, or user, corresponding to a poor, good, or great DA, respectively. This item could show that SL can increase DA if the response was focused on the user, compared to a focus on the project for the previous non-SL item. Of the 9 qualitative items, 4 items provided this additional insight on SL, as well as addressing DA or ethical awareness.

The quantitative items in the 3 parts of the instrument solely assessed DA using design scenarios and knowledge of design tools, such as the necessary parts of an engineering drawing. Items that employed self-assessment or focused on ethical awareness were removed. The design scenarios provided a client, problem, and 3 potential designs, as shown in Figure 3-1. Participants answered Likert-style items (4-point, left aligned) as in the following example. This design scenario had 7 items relating to different aspects of the potential designs as well as general engineering knowledge, though only 2 are listed.

Figure 3-1: Potential designs for design scenario

> *Consider you have a client who lives on a remote island where wood is scarce and supplies arrive by plane. Her daughter loves dogs and princesses. She wants a doghouse for her german shepherd for the backyard. There are 3 prospective designs, A, B, and C. State how strongly you agree or disagree*

- *Design C provides the most strength so it should be selected.* (Disagree)
- *Design A should be selected because the daughter's taste is important to the client.* (Agree)

The first bullet describes a poor DA because it assumes the client wants a strong dog cage as opposed to a dog house. The second bullet describes a great DA because it recognized client need. It was anticipated that by moving to this type of assessment and away from self-assessment, the items are more targeted towards DA.

3.2.2.3. Number of Items

The number of items increased to ensure a balance across the multiple parts of the instrument; the construct (*understand the problem*, *ideate*, and *build & test*), SL and non-SL, and qualitative and quantitative items were distributed across the different parts. The 83 quantitative items were organized in 14 groupings. The distribution of items across the construct was 40 *understand the problem*, 22 *ideate,* and 24 *build & test* items, organized into 5, 4, and 5 groupings respectively, as shown in Figure 3-2. Of the groupings, 9 were design scenarios that involved a client and 5 assessed general engineering knowledge. Note the numbering for the 3-part instrument is 0, 1, 2 because parts 0 and 1 are equivalent to part 1 of the 2-part instrument. Part 0 contained no quantitative items.

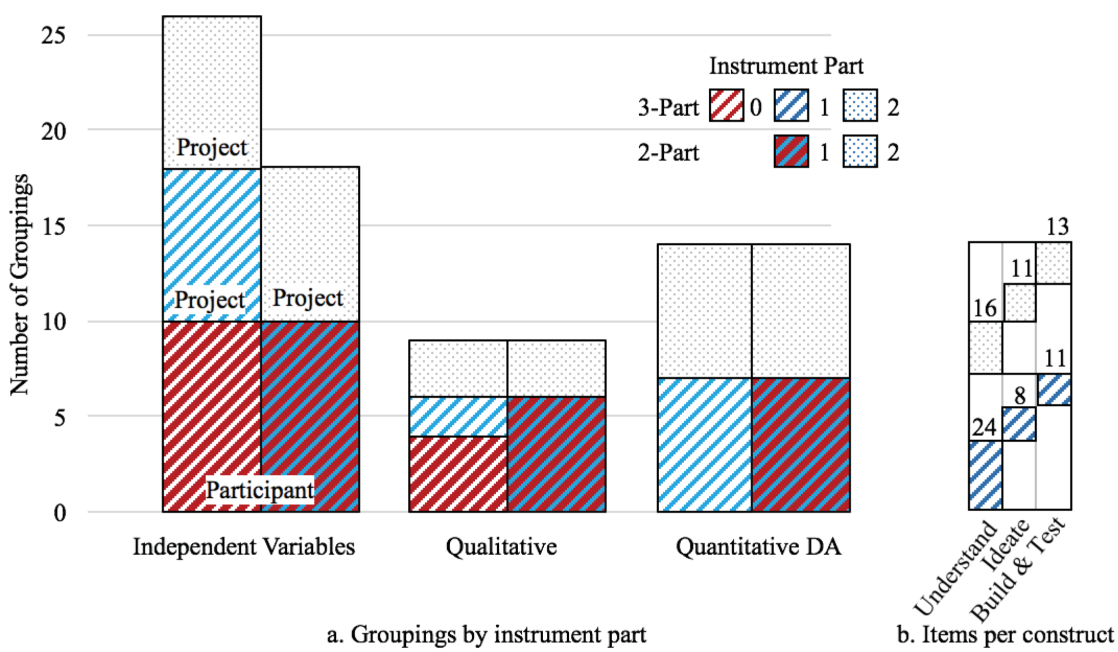


Figure 3-2: Distribution by part of instrument by grouping (a) and item (b)

3.2.2.4. Independent Variables

Identified in goal 3 of the study, the 18 independent variables are shown in Table 3-2, classified as either project or participant variables. There were 14 variables that were retained from study 1 that could have potential impacts on DA. Due to the anticipated homogeneity of response, the independent variable from study 1 that recorded whether the course was mandatory was replaced with the course number in which the participant was enrolled. Additionally, there were 3 new independent variables regarding student scores in the course: logbook, design report, and overall design score. Some studies use grades as the measure of DA, and are included in this study to explore whether there is a correlation between grade and DA.

Table 3-2: Independent variables for study 2

	Participant variables	***Project variables***
Nominal	Engineering discipline	Source of the project: community, industry, other
	Gender	Maturity of the product: paper, prototype, final
	Identifies as a minority	
	Course enrolled	
Ordinal	Age	Project length
	Year in studies	Amount of time spent with the professor
	Time travelled internationally	Amount of time spent with the client
	Logbook score	Rate project length
	Design report score	Rate amount of time with professor
	Overall design score	Rate amount of time with the client

For the 3-part instrument, the project variables were documented for both projects, which increased the number of independent variables from 18 to 26. This will facilitate the comparison of DA after each project.

3.3. METHOD

The instrument was administered in a second-year engineering design course at Dal and first- and second-year engineering design courses at the University of Prince Edward Island (UPEI) in the winter of 2014. This purposive sample of 321 engineering students was complemented by 19 female high school students who attended an engineering design camp in the summers of 2014 and 2015.

The Dal students took part 0 of the instrument, completed a short 3-week design project with no client followed by part 1 of the instrument, and then completed a major 6-week design project, some with a SL client and some with no client, followed by part 2 of the instrument. The UPEI first-year students took part 1 of the instrument, completed a 6-week project with a SL client, and then completed part 2 of the instrument. The UPEI second-year students took part 1 of the instrument, completed an 18-week project with SL clients and clients from industry, and then completed part 2 of the instrument. The high school students took part 1 of the instrument, completed a 6-day SL project, and then took part 2 of the instrument.

The instrument was delivered on paper, in-class. Participation was voluntary but not anonymous as participant responses were linked to their grades. The instructors of each course did not know which students participated until after the semester ended and course grades were input. Using IBM's Statistical Package for Social Sciences, data were entered, cleaned, and recoded. An exploratory factor analysis was performed. Reliability of scale and validity checks were assessed for 16 dependent variables, comprised of DA construct and the 3 subconstructs (*understand the problem, ideate, build & test*) for part 1, part 2, combined, and the difference between part 2 and 1. There were an additional 9 dependent variables from the factorial analysis (5 for part 1 and 4 for part 2), totaling 25 dependent variables of type ratio, with values from 1.00 (better DA) to 4.00 (worse DA). Poor items were removed from each dependent variable to ensure the minimum reliability of scale of $\alpha = .7$ was met, where possible.

All of the 25 dependent variables were continuous, so an analysis of variance (ANOVA) was performed between the dependent and independent variables that met assumptions of normality, homogeneity of means and variances, and independence of observations. An ANOVA of the differences between dependent variables for part 1 and part 2 checked if there were significant differences in the amount each student changed during the semester for each independent variable, however that technique did not account for how differences in the initial condition (part 1 scores) may have influenced the results. For example, if a fourth-year student has a better part 1 DA, there may be less potential for growth than a first-year student who has a worse part 1 DA.

The statistical technique called an analysis of covariance (ANCOVA) uses regression in addition to ANOVA to account for the influence that extraneous variables, or covariates, play in the analysis of the dependent variable [65] . In this study, an ANCOVA was performed for each of the 18 independent variables on the part 2 dependent variables with the corresponding part 1 dependent variables as the covariate. There were 6 assumptions that had to be met in order for the ANCOVA results to be considered valid [65, 71]. The design of the study addressed 2 of the assumptions. First, independence of scores for dependent variables required participants to be in only 1 group within each dependent variable and scores to be independent between those groups; this assumption was met as participants had only 1 post-test score for each dependent variable. The next assumption required the dependent and covariate variables to be continuous and the independent variables to be discrete; these were met for all runs by study design.

The next 2 assumptions were available from the ANOVA results and checked for each run. For each group in the independent variables, the part 1 and 2 values were required to be linear [71]. The ANOVA for part 1 and the independent variable was consulted for each combination. If the interaction was not statistically significant, the assumption was met. Next the normality was assessed to ensure the skewness and kurtosis were within 2 times the error values [67] and the data were also reviewed for outliers.

The final 2 assumptions were performed for each run. Homogeneity of the regression of slopes assumption required the independent variable and covariate to be independent. This was checked by running a regression analysis of the interaction between the independent variable and covariate. Finally, the homogeneity of variances was assessed using the Levene statistic; the assumption was met if significance was greater than .05. ANCOVA data were reviewed and recommendations were made.

3.4. RESULTS

3.4.1. Participant and Project Data

Of the 340 potential participants, 240 completed at least one part of the instrument and 140 completed all parts. Table 3-3 shows the number of participants in each course.

Table 3-3: Participants distributed by course and instrument part

	Part 0	*Part 1*	*Part 2*	*All parts*	*Any part*	*Class size*
Dal 2nd year	160	126	111	**94**	165	240
UPEI 1st year	-	31	29	**25**	34	45
UPEI 2nd year	-	20	16	**13**	23	36
High school	-	13	15	**8**	18	19
Total number of participants				***140***	240	340

Figure 3-3 shows the participant variables. Twenty-eight percent of participants were female (Figure 3-3 a) and 12% identified as a minority (Figure 3-3 b). Of the 240 participants, 19% were studying Mechanical Engineering, 20% were studying Electrical Engineering, and 7 other disciplines were represented (Figure 3-3 c). Seventy percent of participants were between the ages of 18 and 21 (Figure 3-3 d), the expected age for first- and second-year students. While 18% of participants were older than 21, only 8% of participants were in their third-year or higher (Figure 3-3 f).

The participant variable for international travel (Figure 3-3 e) was included for the ethical awareness construct; the extremes are of interest: 17% of participants have not travelled internationally and 66% have spent 2 months or more outside of the US and Canada. The 3 new participant variables for grades are shown in Figure 3-3 g, h, and i.

There was an even distribution of logbook score (Figure 3-3 g) with a visible low kurtosis. The report score (Figure 3-3 h) had a normal distribution with 38% of participants receiving a score of ‘B’ or 75%-87% and 22% of participants receiving a score of ‘A’ or 88%-100%. The overall score (Figure 3-3 i) for participants displayed a high kurtosis and skewness with 52% of participants receiving a score of ‘B’ or 75%-87% and 8% of participants receiving a score of ‘A’ or 88%-100%.

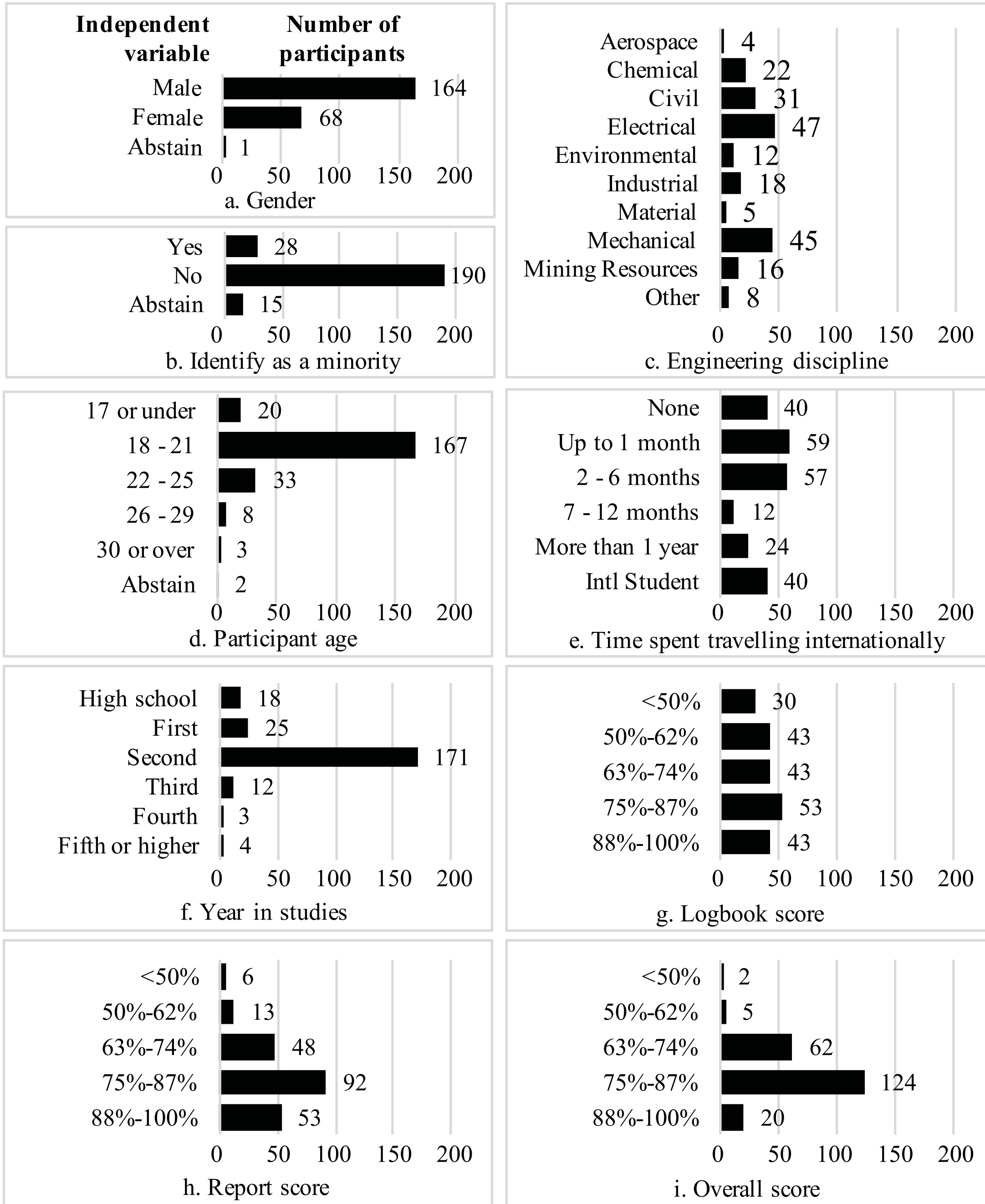


Figure 3-3: Participant data for study 2

The project variables for the main design project that were collected in part 2 of the instrument are shown in Figure 3-4. Of the 171 participants that completed part 2 of the instrument, 46% had a client from the community and 6% had a client from industry (Figure 3-4 a). Of the participants with clients, 74% spent only 1-3 hours with their client

(Figure 3-4 g), so it is not surprising that 57% of participants with clients requested more time with the client and only 7% requested less time with the client (Figure 3-4 h).

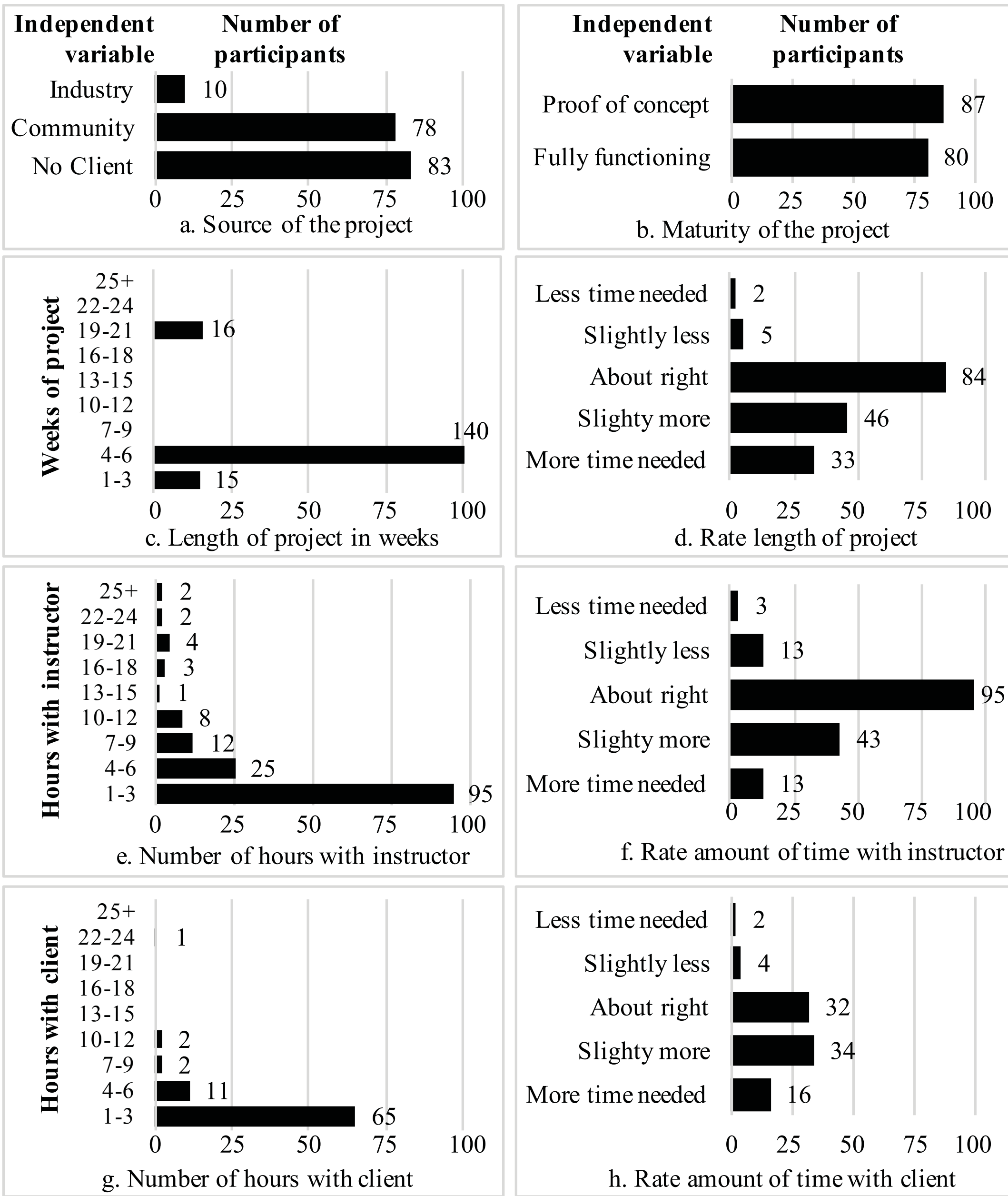


Figure 3-4: Project data for study 2 for main project

The length of the project (Figure 3-4 c) was directly correlated to which course the participants were in (Table 3-3). While 49% of participants felt the length of the project was appropriate, 46% requested more time (Figure 3-4 d). Although 56% percent of participants spent only 1-3 hours with the instructor outside of class (Figure 3-4 e) and an additional 25% spent between 4 and 12 hours with the instructor outside of class, only

33% requested more time with the instructor (Figure 3-4 f). Fifty-six percent of participants felt the amount of time with the instructor outside of class was appropriate.

The project variables for the 3-week design project the Dal students completed in between parts 0 and 1 of the instrument are listed in Figure B-1 in Appendix B. Of the 126 participants, 75% did *not* have a client. Although 98% of participants reported building a fully functioning device or proof of concept for their main project in part 2 (Figure 3-3 b), 73% of participants build a product for part 1. The remaining 27% of participants documented their design on paper and through computer aided design. The source of client, maturity of the design, and the differing lengths of the projects in part 1 compared to part 2 elucidate the different depth of design expectations for the 2 projects.

3.4.2. Design Ability Data

After cleaning and recoding negative items, a factorial analysis was performed on the data. The 43 items in part 1 produced 5 factors (1a, 1b, 1c, 1d, 1e) using the scree plot method with a factor load of > .3 that account for 29% of the variance and n = 40 items. The 40 items in part 2 produced 4 factors (2a, 2b, 2c, and 2d) accounting for 34% of the variance and n = 35 items. Table B-1 in Appendix B contains the mapping of the items in each factor; there is no clear collection of items in order to label the factors. The large number of participants met minimum standards for factorial analysis, however typically more of the variance than 29% or 34% is accounted for. The scree plots, variance tables, and items in each factor can be found in Figures B-2 and B-3 in Appendix B.

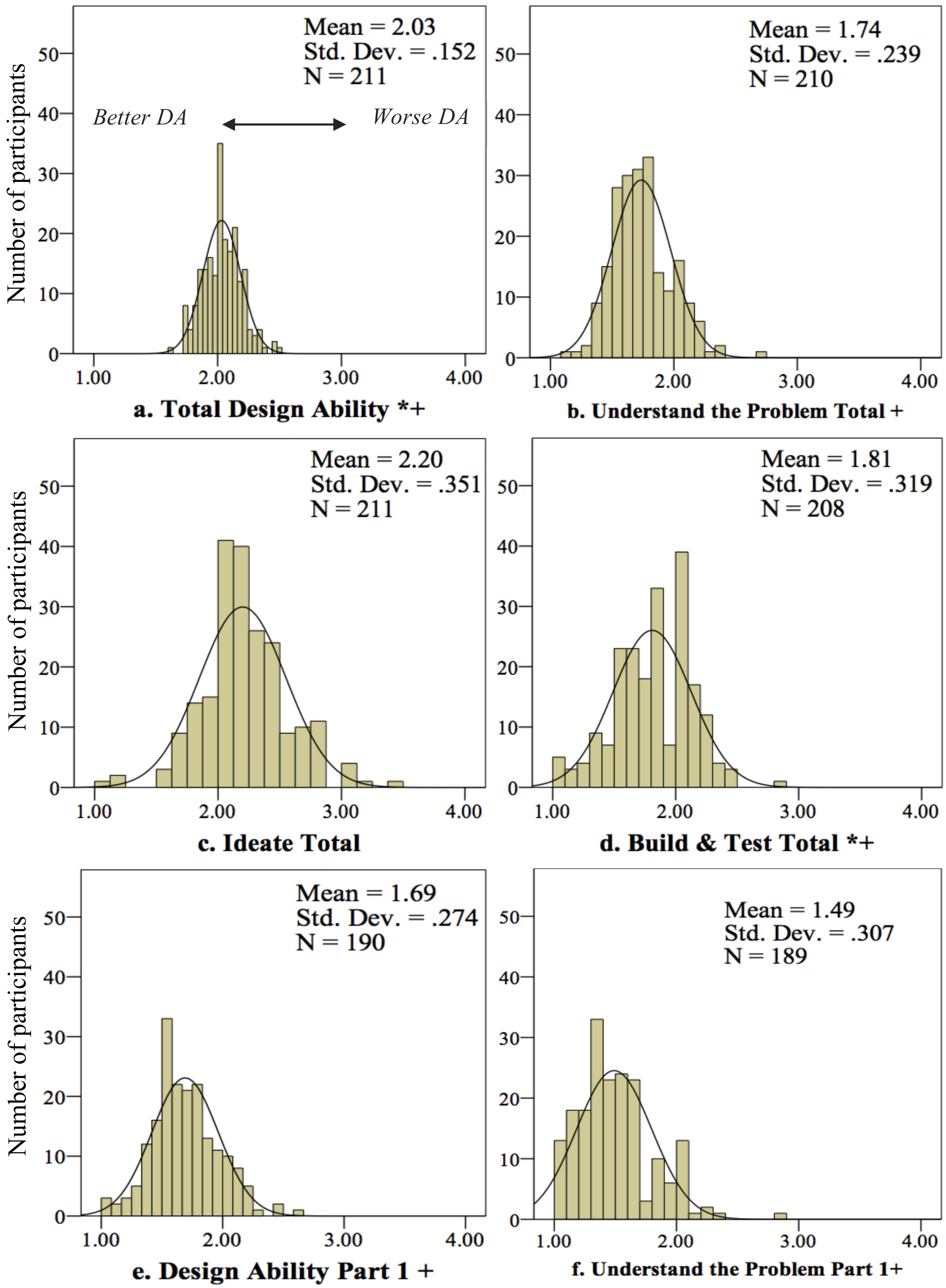
The reliability of scale was assessed for 21 of the 25 dependent variables to determine if participants responded to a subset of items in a similar way ($\alpha \geq .7$) [66]; the differences between the part 2 and 1 items contained only 1 data point, so reliability could not be assessed for these 4 dependent variables. As shown in Table 3-4, initially none of the dependent variables displayed reliability of scale. Due to the large number of items however, items where participants answered inconsistently were removed, and the reliability for each dependent variable was reassessed. All revised dependent variables were reliable (denoted with a + in the table), except for the 3 *ideate* variables (part 1, part 2, and total) and *build & test* part 1. The revised total DA, a combination of all items for parts 1 and 2, was reliable (α = .712, n = 75), which confirmed that participants replied in a consistent manner, an important step towards validation of the instrument. Next the assumptions of normality were checked for the dependent variables, independent variables, and individual items. Assumptions of normality were met if both the skewness and kurtosis were within a band of 2 times the error, denoted in Table 3-4 with a '*'.

Table 3-4: Reliability of dependent variables for study 2

	Initial reliability α	***Number items removed***	***Revised reliability α***
Total design ability*	**.538 (n=83)**	**8**	**.712 (n=75)** +
Understand the problem total	.442 (*n*=40)	8	.707 (*n*=32) +
Ideate total	.075 (*n*=19)	6	.523 (*n*=13)
*Build & test total**	.333 (*n*=24)	8	.704 (*n*=16) +
Design ability part 1	.286 (n=43)	20	**.705** (n= 2) +
Understand the problem 1	.339 (*n*=24)	8	.705 (*n*=16) +
Ideate 1	-.107 (*n*= 8)	4	.204 (*n*= 4)
Build & test 1	.230 (*n*=11)	6	.521 (*n*= 5)
Design ability part 2*	.361 (n=40)	10	**.703** (n=30) +
*Understand the problem 2**	.345 (*n*=16)	4	.707 (*n*=12) +
*Ideate 2**	.019 (*n*=11)	3	.450 (*n*= 8)
Build & test 2	.180 (*n*=13)	4	.739 (*n*= 9) +
Factor 1a	.595 (*n*=13)	1	.701 (*n*=12) +
Factor 1b	-.179 (*n*=8)	3	.615 (*n*= 5)
Factor 1c	.343 (*n*=12)	2	.613 (*n*=10)
Factor 1d*	-.016 (*n*= 9)	3	.460 (*n*= 6)
Factor 1e*	-.214 (*n*= 7)	2	.232 (*n*= 5)
Factor 2a	.382 (*n*=13)	4	.781 (*n*= 9) +
Factor 2b	-.599 (*n*= 7)	3	.715 (*n*= 4) +
Factor 2c*	.331 (*n*=12)	2	.642 (*n*=10)
Factor 2d*	.233 (*n*= 9)	2	.470 (*n*= 7)

*+ Denotes scales that have α ≥ .7 and * denotes scales that meets assumptions of normality.*

The histogram for the 16 dependent variables are shown in Figure 3-5 as well as the mean and standard deviation. A score of 1.00 indicated a better DA and 4.00 indicated a worse DA. While not all dependent variables were both reliable ('+') and normal ('*'), the ideal, the total DA (Figure 3-5 a), *build & test* total (Figure 3-5 d), DA part 2 (Figure 3-5 i), and *understand the problem* part 2 (Figure 3-5 j) satisfied both requirements.



*Note: 1.00 corresponds to a better DA, + denotes reliability α ≥ .7, * denotes assumptions of normality*

Figure 3-5: Histogram of dependent variables

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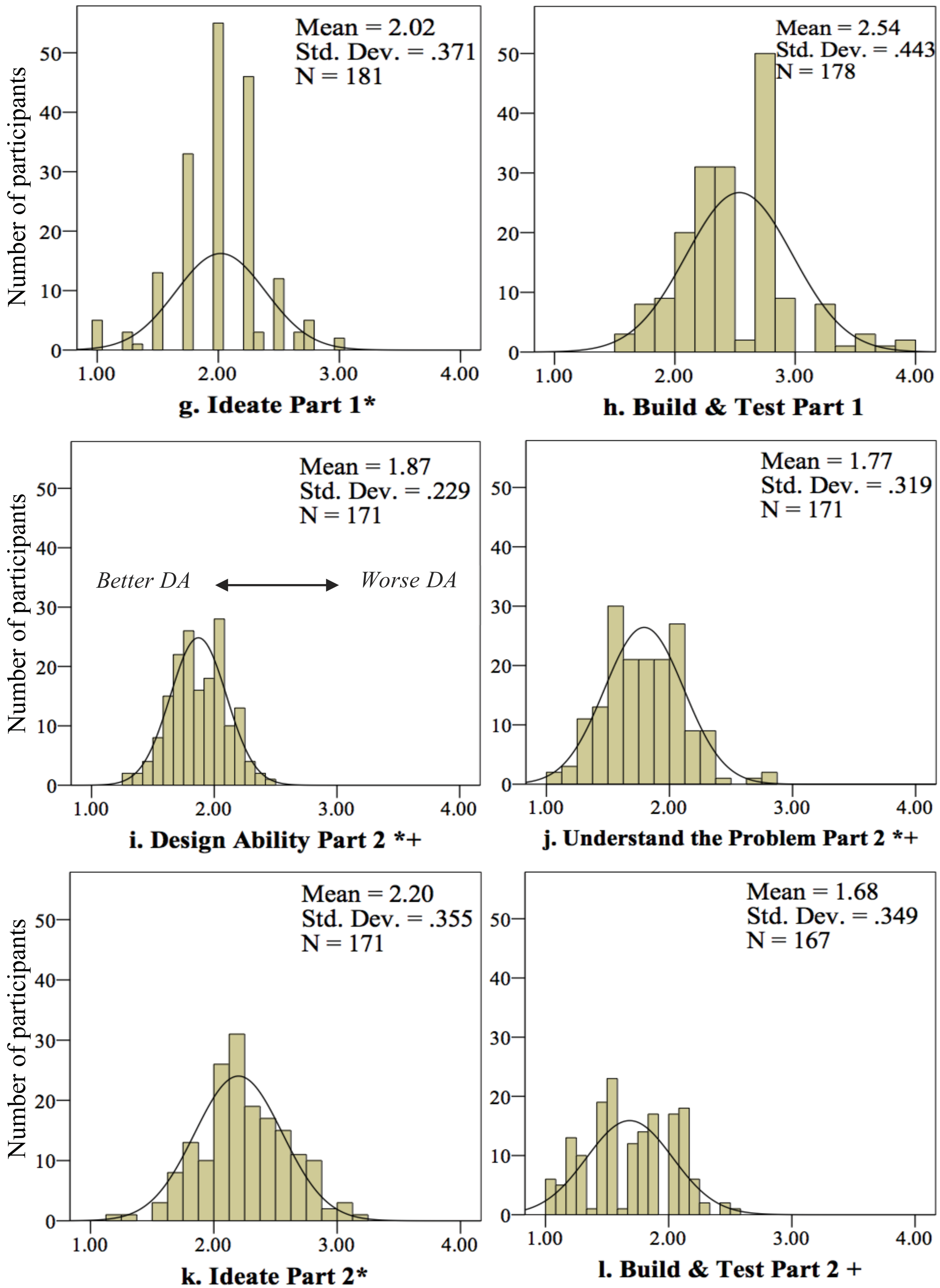


*Note: 1.00 corresponds to a better DA, + denotes reliability $\alpha \geq .7$, * denotes assumptions of normality*

Figure 3-5: Histogram of dependent variables
(continued from previous page)

Descriptive statistics for all variables and items are listed in Tables B-2 through B-5 in Appendix B. Five of the dependent variables displayed both skewness and kurtosis (Figure 3-5 b, f, and h). *Understand the problem* part 1 (Figure 3-5 f) was positively skewed, which indicated that participants did especially well on these items with too few incorrect responses for a normal distribution. There was also positive kurtosis, which indicated that there was not enough distribution of responses, as participants scored between 1.30 to 1.40. No variables were negatively skewed, because the more controversial items were removed during reliability analysis. Negative kurtosis was evident in *ideate* total (Figure 3-5 c) where there was a wider range of responses.

Before documenting ANOVA results, the pertinent assumptions were reviewed. The assumption of independence of observations was met by the study design (each person responded to only one category within each independent variable). Using Levene's statistic, the dependent items were assessed for homogeneity of means and variances to ensure $p > .05$.

An ANOVA was then performed for each of the 26 independent variables compared to the 25 dependent variables. An ANOVA indicated whether there were significant differences in the means of a dependent variable based on an independent variable. Of the possible 650 combinations, Table 3-5 lists the 17 combinations of independent and dependent variables that were reliable, met all assumptions for ANOVA, and produced significant results.

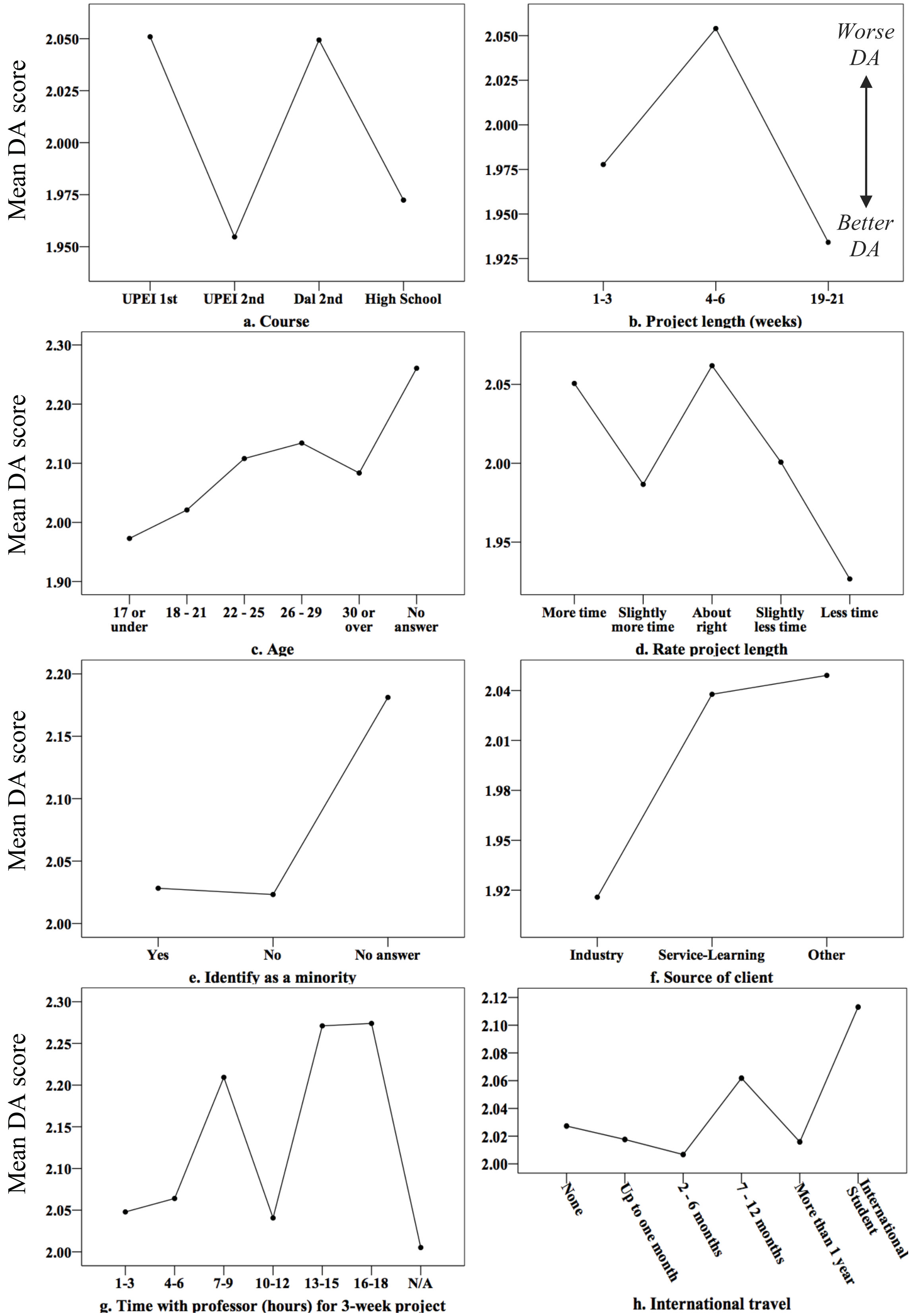
There were an additional 77 combinations that produced significant results but did not meet either normality or reliability requirements. These are listed in Table B-6 in Appendix B. There were no significant differences for gender, report score, maturity of the main product, the amount of time spent with the professor or client for the main project, whether the participants thought they spent enough time with the professor or client for the main project, or for the initial 3-week project: the type of client, maturity of the project, project length, time spent with the client, and what the participants thought about the amount of time spent with the client.

Table 3-5: Significant ANOVA results for study 2

Dependent variable	*Independent variable*	*df*	*F*	η^2	*p*
DA total	Course	3	6.11	.08	.001
	Project length	2	6.76	.07	.001
	Age	5	3.67	.08	.003
	Rate project length	4	2.56	.06	.041
	Identify as a minority	2	6.42	.06	.002
	Source of client	2	3.97	.05	.021
	Time with professor 0	5	3.12	.09	.010
	International travel	5	2.28	.05	.048
Build & test total	Course	3	4.90	.07	.003
	Project length	2	5.43	.06	.005
	Discipline	10	2.39	.11	.011
	Rate project length	4	4.51	.10	.002
Difference in total DA	Logbook grade	4	2.52	.07	.045
	Overall grade	4	2.94	.08	.023
	Rate amount of time with professor 0	6	3.33	.15	.005
Difference in *ideate*	Rate project length 0	5	2.99	.14	.015
Understand the problem part 2	Year in studies	5	2.56	.12	.032

After significance was identified, Bonferroni post-hoc analyses were performed and the means plots were consulted to determine the differences between categories within the independent variables. Shown in Figure 3-6, the total DA produced the most significant results with 8 of the independent variables. A score of 1.00 indicated a better DA while 4.00 indicated a worse DA.

Figure 3-6 a shows the mean of the total DA scores for each course ($F(3, 204) = 6.11$, $p = .001$). Figure 3-6 b shows the project length compared to mean of total DA ($F(2, 168) = 6.76$, $p = .001$). The results in Figure 3-6 b corresponded directly to the course in Figure 3-6 a as UPEI second-year students spent 4-6 weeks on their project, high school students spent 1-3 weeks, and UPEI first-year and Dal second-year students spent 4-6 weeks. UPEI first-year and Dal second-year students had a significantly worse DA (a mean score of 2.050) than UPEI second-year students (a mean score of 1.950). The UPEI second-year students and high school students had the best DA.



Note: 1.00 corresponds to a better DA

Figure 3-6: ANOVA results for total DA

Shown in Figure 3-6 c, DA worsened as participant age increased (F(5, 198) = 3.67, p = .003), as opposed to improving with age. There was a significant difference between ages 17 and under and 22-25. Participants who replied that the project length was about right had a significantly worse total DA than participants who wanted slightly less time (F(4, 165) = 2.56, p = .041) as shown in Figure 3-6 d.

The 8 participants that did not answer whether or not they considered themselves a minority had a significantly worse total DA than participants who did answer (F(2, 201) = 6.42, p = .002), as shown in Figure 3-6 e. There was little difference between participants who identified as a minority and those who do not. The total DA was influenced by the type of clients the participants had (F(2, 168) = 3.97, p = .021) as shown in Figure 3-6 f. Participants who had a client from industry had a significantly better total DA than clients from SL or other.

The total DA had statistically significant differences based on the amount of time spent with the professor (F(5, 158) = 3.12, p = .010), as shown in Figure 3-6 g. Participants who spent 13-21 hours had a worse DA than participants who spent less time with the professor. There was a significant difference in the amount of international travel (F(5, 197) = 2.28, p = .048), where participants with 2 - 6 months of international experience had a significantly better DA than international students, as shown in Figure 3-6 h.

The *build & test* subconstruct had 4 significant results, shown in Figure 3-7. Differences in the course (F(3, 207) = 4.9, p = .003) showed similar performance to the total DA (Figure 3-7 a). Figure 3-7 b shows the project length compared to total DA (F(2, 167) = 5.43, p = .005), which correspond to the course: high school was 1-3 weeks, UPEI first-year and Dal second-year were 4-6 weeks, and UPEI second-year was 19-21 weeks.

The discipline (F(10, 187) = 2.39, p = .011) shown in Figure 3-7 c suggested the 8 students who were in a discipline 'other' had the best DA while students in aerospace and materials had the worst DA. Participants who rated the length of the project as about right had a significantly worse DA than participants who required slightly more or slightly less time (F(4, 164) = 4.51, p = .002), as shown in Figure 3-7 d.

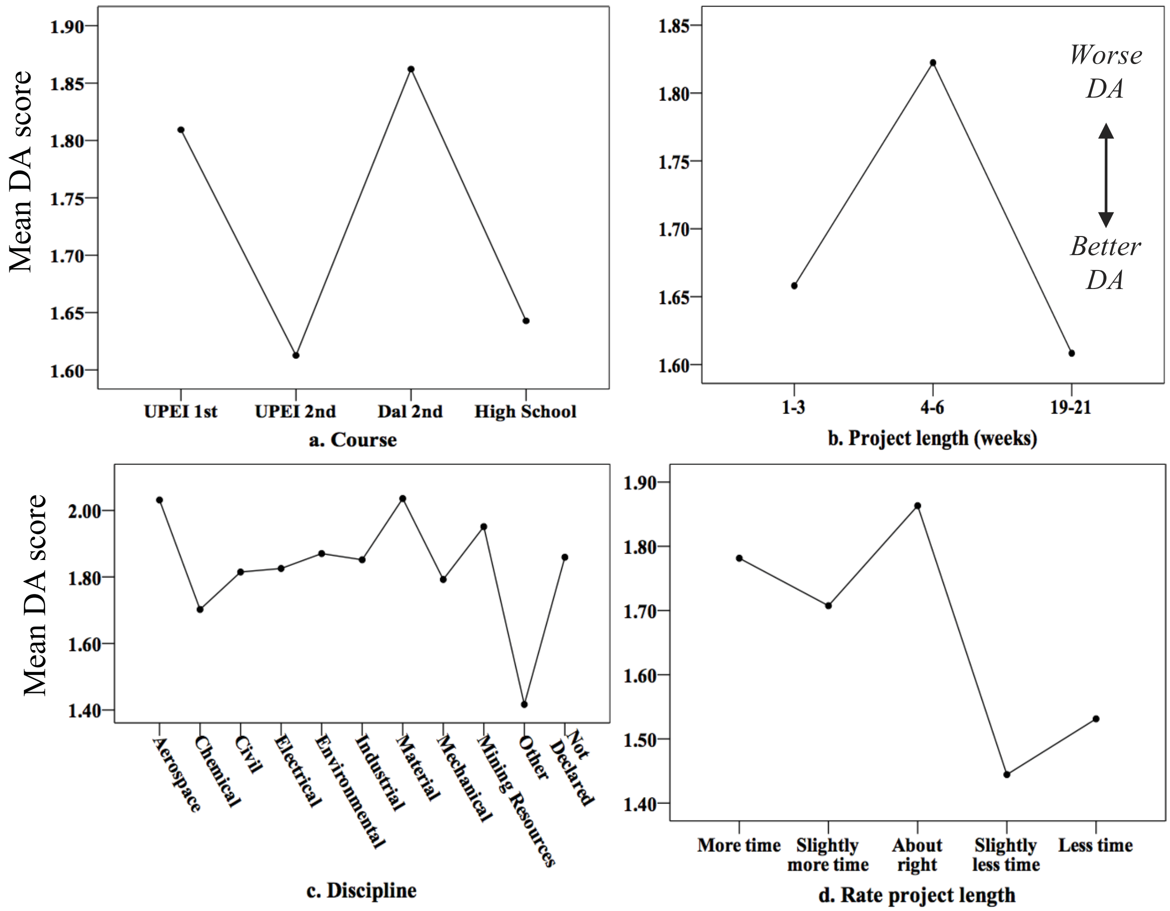


Figure 3-7: ANOVA results for total *build & test*

Figure 3-8 shows the mean of the participants for part 2 *understand the problem* compared to year in studies ($F(5, 95) = 2.56$, $p = .032$). There were significant differences between fourth-year students who exhibited a lower DA score than first-year, second-year, third-year, and high school students.

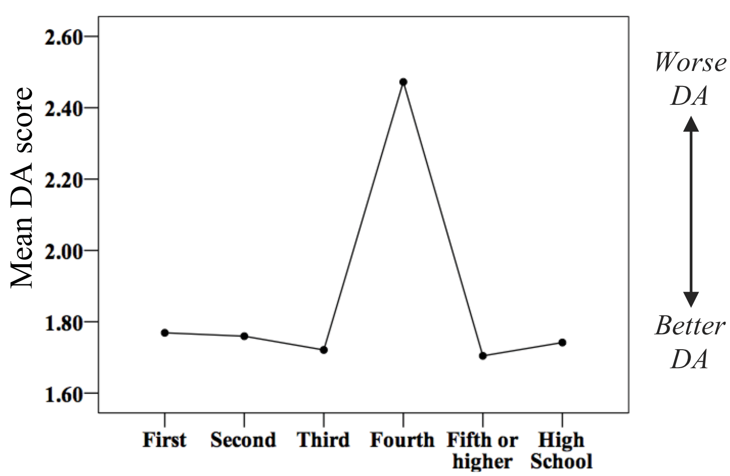


Figure 3-8: ANOVA results for *understand the problem* part 2 and year in studies

Figure 3-9 shows ANOVA results for the dependent variables that calculated difference in the 4 DA construct and subconstructs and *understand the problem*. A negative difference score is desired as it corresponded to an improvement in DA.

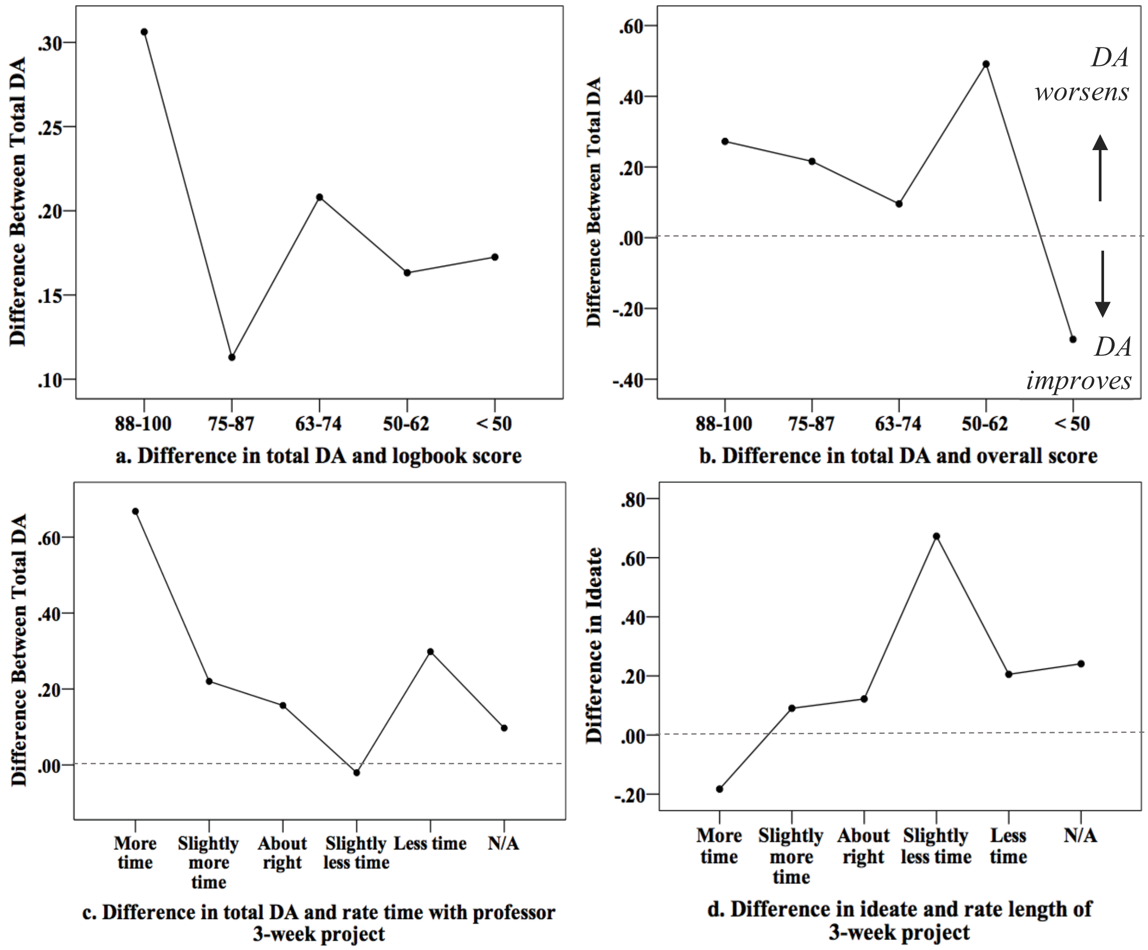


Figure 3-9: ANOVA results for other independent variables

The difference in total DA and logbook scores was significant between participants who received A and B in their logbook ($F(4, 130) = 2.52$, $p = .045$), as shown in Figure 3-9 a. While both scores worsened, the participants who received an A on their logbook had a significantly larger decrease in DA than those who received a B. The overall grade compared to difference in total DA ($F(4, 131) = 2.94$, $p = .023$) was significant in participants who received an F on the project ($n = 2$) and those that received a D ($n = 5$), as shown in Figure 3-9 b. The participants who received an F improved their DA while participants who received an A, B, C, or D worsened their DA. Participants who requested more time with the professor worsened the total DA score in part 2 more than those who requested slightly less time with the professor (F(6, 117) = 3.33, p = .005) as shown in Figure 3-9 c. Participants that requested slightly less time for the 3-week initial project (F(5, 91) = 2.99, p = .015) compared to those that said the length was about right or requested more time decreased more in their ability to *ideate* as shown in Figure 3-9 d.

Finally, an ANCOVA was performed between the part 2 dependent variables (*understand the problem, ideate, build & test,* and total DA) and the 18 independent variables with the part 1 variables as the covariates. Assumptions were checked for normality of the 4 dependent variables within each independent variable category, homogeneity of means and variance, independence of scores, linearity between the covariate and dependent variable, and homogeneity of regression. This produced 72 results, 8 of which shown in Table 3-6 and Figure 3-10 met all assumptions and had statistical significance ($p < .05$).

Table 3-6: Significant ANCOVA results for study 2

Dependent variables	*Independent variables*	*df*	*F*	η^2	*p*
Understand the problem	Source of client	2	3.28	.05	.040
	Rate with time with client	5	2.70	.09	.023
Ideate	Identify as a minority	2	4.01	.06	.020
	Overall grade	4	4.12	.13	.004
Build & test	Discipline	1	2.11	.17	.028
	Project length	2	3.13	.05	.047
	Rate project length	4	2.81	.09	.028
	Rate with time with client	5	2.40	.09	.041

An additional 6 results had statistical significance but did not meet one of the assumptions for ANCOVA; these are listed in Appendix B in Table B-7 with scatter plots of the data in Figure B-4. Note that of the results listed in Table 3-6, only the *understand the problem* dependent variables (for both parts 1 and 2) were reliable; the *ideate* and *build & test* scales were not reliable.

Covariate plots, such as those in Figure 3-10 are used to graphically present ANCOVA results; in the plots, the quadrant in which the points are located and the direction of the linear fit lines are of interest. To demonstrate an improved DA, the collection of data points should be in the lower right quadrant such as in the *build & test* subconstruct (Figure 3-10 e f g h) as opposed to the upper left quadrant such as in the *ideate* subconstruct (Figure 3-10 c d). The lower right quadrant contains participants with a poor

DA score in part 1 (right) to a better DA score in part 2 (bottom), thus improving their DA. The upper left quadrant contains participants with a good DA score for part 1 (left) and to a worse DA score for part 2 (top). The bottom left and top right quadrants show no change in DA, such as *understand the problem* (Figure 3-10 c d).

A linear fit line was applied to each independent variable category to illustrate how each group performs. A negative slope indicates participants for that group had mixed responses; participants who started with a better DA in part 1 changed to a worse DA in part 2 and participants who started with a worse DA in part 1 changed to a better DA in part 2. This indicates DA did not change consistently or the instrument does not accurately measure DA. A positive slope indicates participants maintained DA: participants who started with a better DA in part 1exhibited a good DA in part 2 and participants who started with a worse DA in part 1 exhibited a poor DA in part 2. A positive slope indicates the instrument accurately measured DA. Parallel linear fit lines, such as in Figure 3-10 f, indicated the groups show a consistent difference in means. Participants who spent 1-3 weeks on a project had a better DA score than those who spent 4-6 weeks on a project. If the lines intersect, such as in Figure 3-10 e, then the means for one category improved while the means for the second worsened. Participants interested in Industrial performed consistently better than those interested in Material, but showed no similarity to how participants interested in Aerospace performed.

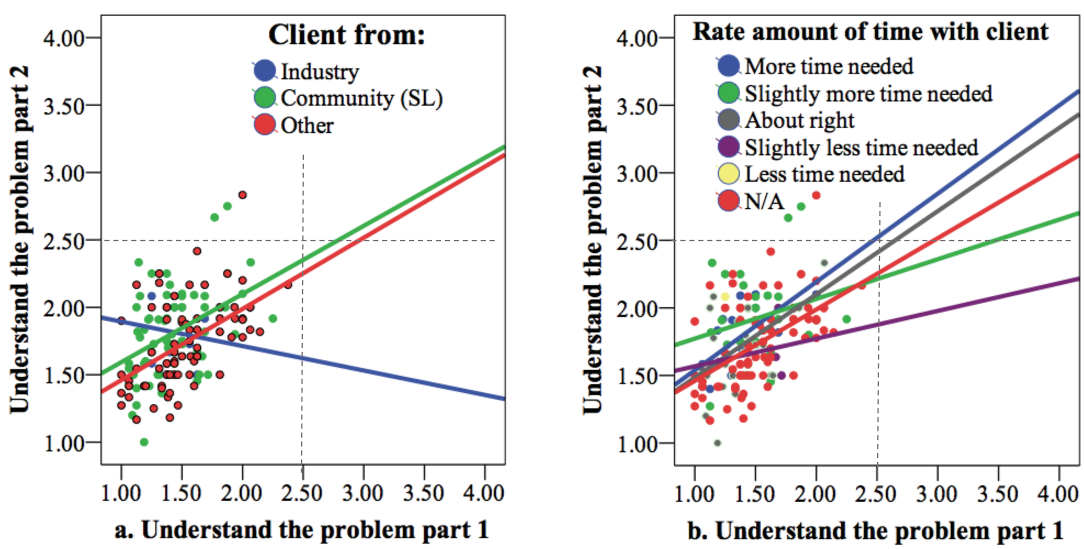


Figure 3-10: ANCOVA results for independent variables with statistical significance (continued on next page)

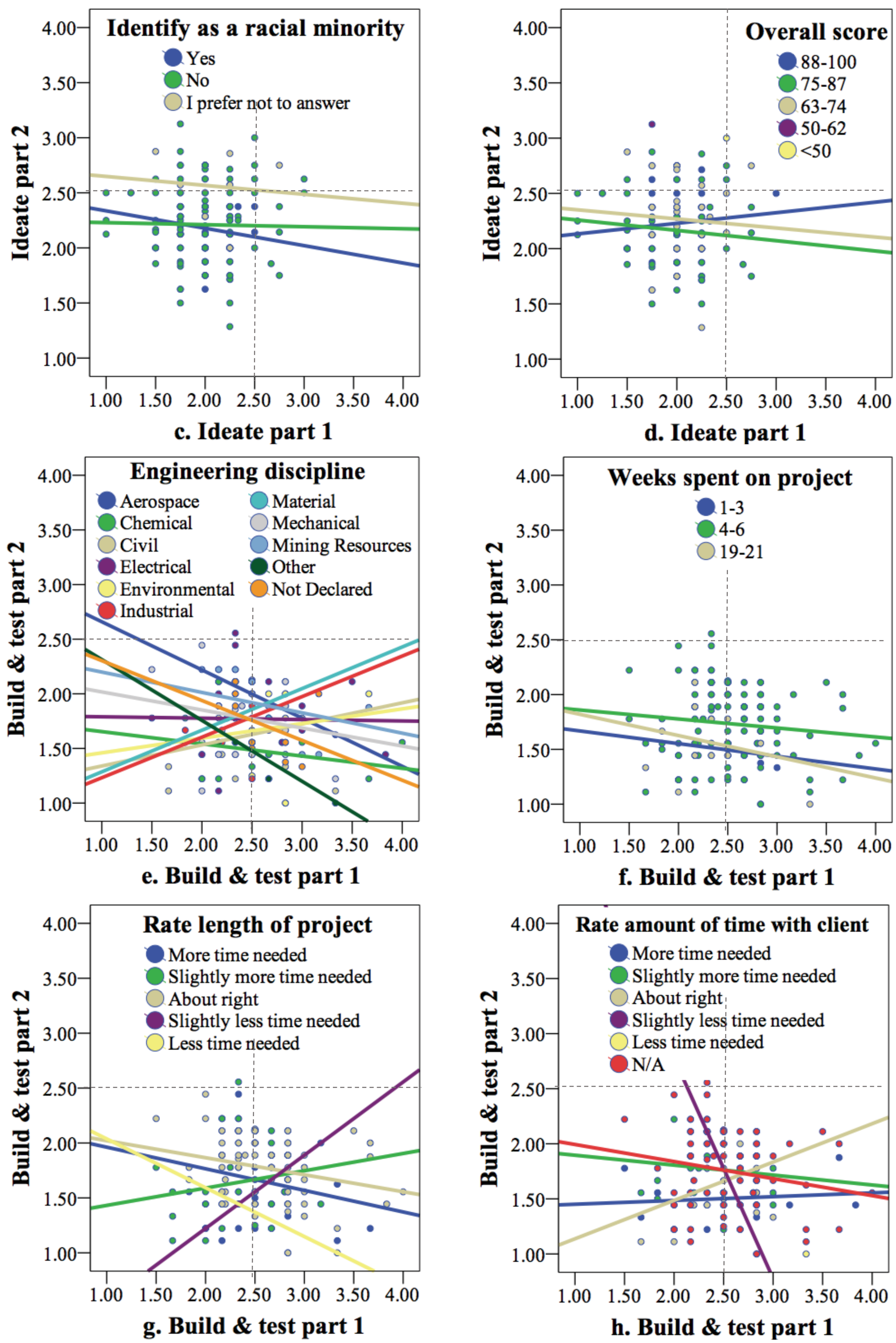


Figure 3-10: ANCOVA results for independent variables with statistical significance (continued from previous page)

The 2 statistically significant ANCOVA results for *understand the problem* part 2 controlling for part 1 were both client centric: source of the client ($F(2, 146) = 3.28$, $p = .04$) as shown in Figure 3-10 a and rate the amount of time with the client ($F(5, 143) = 2.70$, $p = .023$) as shown in Figure 3-10 b. The covariate for both had an F-score of 40 and significance of 0. While significant differences exist, no implications can be made about the differences between groups. The source of the client (Figure 3-10 a) had significant differences between a client from industry and 'other' with a difference in means of .121. Participants with clients from industry exhibited a negative slope while participants with 'other' clients exhibited a positive slope.

There was a significant difference in means for rating the amount of time with the client (Figure 3-10 b) between participants who did not have a client (red fit line) and participants who wanted slightly more time with the client (green fit line). Both are in the lower left quadrant implying little change in DA occurs.

There were 2 ANCOVA results with statistical significance for *ideate* part 2 controlling for part 1. Shown in Figure 3-10 c, there was a significant effect whether participants identified as a minority ($F(2, 137) = 4.01$, $p = .02$) controlling for part 1 scores that were not statistically significant ($F(1, 137) = 0.15$, $p = .704$). Participants who elected not to disclose showed statistical significance with both yes and no with a mean difference in score of .394 and .351 respectively.

Shown in Figure 3-10 d, there was a significant difference in means in *ideate* part 2 from the overall course grade ($F(4, 125) = 4.12$, $p = .004$) controlled by part 1 scores that were not statistically significant ($F(1, 125) = 0.79$, $p = .376$). There was a statistically significant difference in means between participants that scored D and F and participants that scored A, B, and C. The participants who received D and F had the poorest DA scores with a mean of 3.00 for part 2. However, there was a low number of respondents that received D or F, so the information is not meaningful.

The 4 statistically significant results for *build & test* part 2 are: engineering discipline ($F(10, 122) = 2.11$, $p = .028$), number of weeks spent on the project ($F(2, 133) = 3.13$, $p = .047$), a rating of the length of the project ($F(4, 130) = 2.81$, $p = .028$), and a rating of the amount of time with the client ($F(5, 130) = 2.40$, $p = .041$), as shown in Figures 3-10 e, f, g, and h respectively. The covariates showed no statistical significance. There were many differences in means in each of the categories for these independent variables; most notably there was a statistically significant difference in means for rating the length of the project between about right and slightly more (.146 difference) and about right and slightly less (.488 difference). Note the improvement in mean score for the *build & test* of 2.50 in part 1 to 1.75 in part 2. However, the *build & test* dependent variables for part 1 and 2 were not reliable.

While there were 8 statistically significant results, no meaningful conclusions were gained from the ANCOVA data due to a low response rate in the particular group or the lack of implications on DA. However, the ANCOVA results provide an informative classification about the results. If points are in the bottom right quadrant, participants performed as expected, improving their DA, such as in *build & test.* The *understand the problem* items show little change in DA and should be reviewed. The *ideate* items show that DA worsened and should also be reviewed. Next, the slope of the linear fit of the results elucidate the need to review the instrument where there are groups with a negative slope. It is clear that controlling for part 1 scores provides additional information and ANCOVA is an important measure for development of the instrument.

3.5. DISCUSSION

3.5.1. Validity, Verification, and Potential Bias

The intent of the study was to measure DA, determine if there were changes before and after the project, and then identify a cause for the change, specifically SL. In order to ensure the instrument measured DA and not a different aspect of engineering or design, a revised literature review defined the construct scale. Positively- and negatively-worded items were interspersed in the instrument increasing construct validity. Items were developed and answers selected. Two engineers in industry reviewed the instruments and provided feedback; however, the ‘answer sheet’ was not reviewed. Design questions are not as objective as engineering science questions that have exact answers; because of this potential threat to validity, more expert reviews are required. As a result, this portion of the study cannot conclusively claim that DA was measured.

The data were analyzed 3 times using 3 different answer keys. In the first answer key, items were recoded and ranked from 1 to 4, allowing ‘agree’ or ‘disagree’ to be more correct than ‘strongly agree’ in some items. In the second answer key, responses were combined to 2 points, either correct or incorrect. Neither of these codings produced significant results. The instrument was reviewed once more and the answer key revised so only negative items were recoded and inverted. This is different than the first coding because the data were run either as 1 – 4 or 4 – 1 as most correct, rather than 3,4,2,1 or 2,1,3,4. The data are too subjective to insist the correct answer is ‘agree’ compared to ‘strongly agree’. To better validate the instrument, the parts should be given to experts and the answers they provide be considered the ‘answer key’. An additional solution is to create items that are less subjective.

A representative sample was attained so that the results of the study can be extended to all engineering students. All of the engineering disciplines, age categories, year in studies, and project preferences were represented, however the distribution was not even among the categories, shown in Figures 3-3 and 3-5. While the percentage of female participants (28%) exceeded the national engineering average of female engineers in industry, 5% is deemed a reasonable margin [59, 60]. The response rate was approximately 40% in each of the classes, ranging from 36% to 55%. Additional threats to validity include self-selection and volunteer effects, though this is unavoidable when it is optional to participate in the study.

Threats to statistical conclusions were avoided by dismissing variables that did not meet normality and reliability of scale. In order to ensure reliability of scale, shown in Table 3-4, items were removed that indicated the majority of participants responded inconsistently compared to their other responses. These poor items should not be used in future iterations of the instrument or should be reworded for clarification. The dependent variables for *build & test* had the most items removed, which increased the reliability of scale but reduced the number and range of responses. Reliability of scale is an important measure to ensure consistency of responses, but since items are excluded, it can skew the data if performed incorrectly.

The factors produced in the factorial analysis did not converge or have similar groupings as seen in Table B-1. The items that participants responded to in the most similar way were not similar enough to be labelled. This questions the reliability of the factors. Additionally, the low accumulated variance reduced the meaningfulness of the factors. For this reason, the results of ANOVA were not highlighted for the factors.

While reviewing normality, it was discovered that participants responded only 40% of the time with extreme answers: ‘strongly agree’ or ‘strongly disagree’, when an even distribution of 25% per category would be more reasonable (see Tables B-4 and B-5 mean and standard deviation). For example, when considering whether or not to research duck migration patterns for a logging bridge, as shown in Figure 3-11, the answer should be ‘strongly disagree’, or 1.00. Only 12 participants were willing to give the extreme response. A polarizing result was expected, but 77% of participants selected ‘agree’ or ‘disagree’ while only 23% selected one of the extremes. While this item meets normality requirements, this presents an acquiescence bias. The avoidance of extremes could indicate a lack of confidence in the response or support the subjectivity of the item. For this reason, an even Likert-scale was employed forcing participants to select an option as opposed to an odd scale that would have allowed participants to have no opinion.

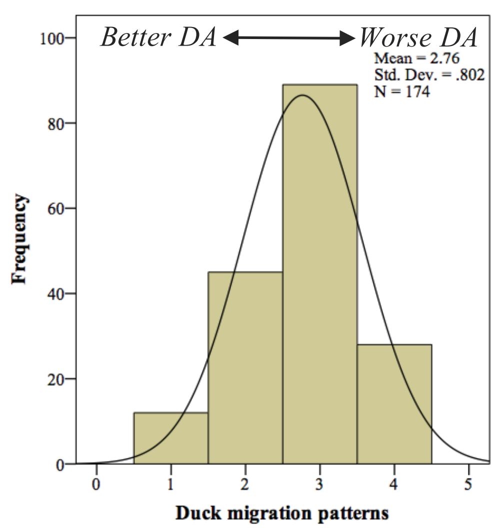


Figure 3-11: Histogram of item with few extreme responses

This effect explains why the third recoding of data produced more normal results than allowing 'agree' or 'disagree' to be the best response. An analysis of the histograms in Figure 3-5 show a tendency to be left of the expected mean of 2.5. This could indicate that participants selected the more accurate answer more often, or it could indicate the items were poorly worded and encouraged the correct answer.

Items that did not meet normality could have been processed to remove outliers or reduce the effect before running ANOVA or ANCOVA, but because of the subjectivity of response and questionable validity, this was not performed. Additionally, the multitude of independent variables allowed for significant and normal results, whereas a study that considered only 1 independent variable might justify a higher level of data processing.

Because so little is known about quantifying DA, many independent variables were explored to answer objective 3. As the number of independent variables increased, the significance level should be reduced from .05 to .002 per the Bonferroni adjustment to avoid overestimating the effect. This is an extremely stringent significance level to meet and was not employed because the Bonferroni adjustment assumes that each variable effected the results in combination with other variables. The exploratory nature of the study attempts to determine which variables could possibly influence the DA, to be explored further in future studies, so the more stringent significance value was not necessary. The sources of bias that could be anticipated were minimized, however due to the subjectivity of DA, the instrument is not considered validated.

3.5.2. Implications of the Results

The second objective, to determine if there was a difference in the means between part 1 and part 2, was assessed using ANOVA and ANCOVA. If parts 1 and 2 of the instrument were valid and accurately measured DA, it follows that the mean of the dependent variables decreased from part 1 to part 2 to get closer to 1.00. However, the mean scores for each of the dependent variable increased, as shown in Table 3-7.

Only the *build & test* subconstruct score improved. There are 4 possible explanations. First, part 1 and part 2 of the instrument were not of equal levels of difficulty. If the items in part 2 of *understand the problem* were much more difficult than part 1, participants would not score as well. Second, part 1 and part 2 of the instrument do not contain an equal number of items. This is indicated in *ideate* as the part 2 and total values are the same. There may not be enough items in part 1 to accurately measure the *ideate* subconstruct of DA. Third, the instrument does not accurately measure DA, as the instrument has not completed validation and verification procedures. Finally, it is possible that students do not improve their DA through design projects.

Table 3-7: Comparison of means

	Part 1	***Part 2***	***Difference***	***Total***
Understand the problem	1.49	1.77	+ 0.28	1.74
Ideate	2.18	2.20	+ 0.02	2.20
Build & test	2.54	1.68	- 0.86	1.81
Design ability total	1.69	1.87	+ 0.18	2.03

Note: 1.00 corresponds to a better DA and 4.00 is a worse DA

The implications of the ANOVA results are summarized in Table 3-8. The magnitude of the differences provides meaningful information, which can be derived from the effect η^2. There are medium effects ($.06 < \eta^2 < .14$ [65]) of how much variance in each dependent variable that can be accounted by each independent variable. Two items showed large effects ($\eta^2 > .14$ [65]):

- Rate the time with the professor and difference in total DA ($\eta^2 = .15$)
- Rate the project length and difference in *ideate* ($\eta^2 = .14$)

The categories that had low number of responses produced a surprising amount of significant results. For example, when comparing mean DA score and whether participants identified as a minority (Figure 3-6 c), the significant results were between ‘no response’ and ‘no’, as well as ‘no response’ and ‘yes’. Only 8 participants replied with ‘no response’, while 190 participants responded ‘no’ and 28 participants responded ‘yes’. The same effect is shown when comparing the discipline of participants to their *build & test* total (in Figure 3-7 c) where only 8 participants responded with ‘other’, and that was the category to produce significant results.

Table 3-8: Implications of ANOVA results

Dependent	***Independent***	***Correlation***	η^2
Design ability total	Course	UPEI 2nd-year students best DA	.08
	Project length	Students with 19-21 weeks had best DA	.07
	Age	17 & under has best DA	.08
	Rate project length	About right worse DA than slightly less time	.06
	Identify as a minority	No answer has worse DA	.06
	Source of client	Industry has best DA	.05
	Time with professor	13-21 hours worst DA	.09
	International travel	2-6 months travel best DA, international students worst DA	.05
Build & test total	Course	UPEI 2nd-year students best DA	.07
	Project length	Longest and shortest projects have best DA	.06
	Discipline	'Other' has best DA and aerospace and materials has worst	.11
	Rate project length	Slightly less time has best DA and about right has worst DA	.10
Difference in total DA	Logbook grade	A in logbook changed the most (worsened) and B changed the least	.07
	Overall grade	F overall improved DA and D worsened	.08
	Rate amount of time with professor	Requesting slightly less time with professor improved DA and more time worsened DA	.15
Difference in *ideate*	Rate project length	Slightly less time for project worsened the most while more time improved the most	.14
Understand the problem part 2	Year in studies	Fourth-year students had the worst DA (but also the lowest frequency)	.12

Compared to an ANOVA, an ANCOVA compares the resulting means for each group, keeping in mind where each group started (covariate). This is especially useful for a study that calculates the difference in the scores before and after a design activity. Therefore, compared to the previous 2 analyses, the ANCOVA results in Figure 3-10 and Table 3-6 should be considered most valid. Once the part 2 scores were adjusted based on part 1 scores, the DA improved for *build & test* variables, however it decreased for the other subconstructs. Most effect sizes were medium for the ANCOVA results as shown in Table 3-6, however there was 1 large effect between engineering discipline and *build & test* ($\eta^2 = .17$) [65].

It is interesting that the 2 independent variables that showed statistical significance in Table 3-6 and 1 with statistical significance in Table B-7 were client centric, (though not all assumptions were met). The *understand the problem* result was influenced by whether the client was from industry, the amount of time with the client, and rating the time with the client. Clients from industry had a less desirable fit line than those from other or with a SL client, however DA decreased in all categories. This is in contrast to the ANOVA results where participants with a client from industry had a better total DA. This warrants further review into the relationship between source of project and DA.

It is also interesting that the independent variables that showed significance in difference in means for *build & test* were primarily project related rather than participant. The understanding of the *build & test* phase may be influenced by project length, attitude towards project length, and attitude towards time with the client. Because the *build & test* part 1 and 2 variables were not reliable, not much can be concluded regarding this analysis, but it is something to investigate further.

3.5.3. Recommendations

The most pertinent realization from this study was that DA is highly subjective. There is not enough literature and existing studies to definitively state what is a 'good' DA compared to a 'poor' DA. Before an instrument can be developed, a comprehensive understanding of DA must be determined from experts in diverse engineering fields. While the items in this study were validated, the answers were not. A study must be performed to develop the answers. Specific considerations could include:

- how to define DA,
- what makes a good or bad designer, and
- whether engineers agree on the design process.

After gaining a better definition of DA, version 3 of the instrument would need to be revised based on the experience from study 2. First, the instrument should be electronic, not paper-based. While this delivery method increased the sample size, the time to enter the data was cumbersome and allowed for inaccuracies and entry bias. Additionally, the qualitative aspects of the instrument were not reviewed due to time requirements. This could be a future study to analyze the qualitative data in light of what the experts produce, however qualitative items should be removed from the next iteration of the instrument to allow for electronic delivery. It would also be interesting to repeat the analyses for the subset of participants that completed all 3 parts to see if there are differences in their DA.

While ethical awareness is an important measure, only DA should be considered in the future instrument as there are existing tools that consider ethics. Individual items should be reviewed and quantitative items should be reconsidered using Bloom's taxonomy to rank DA. The question should change from looking at how DA is affected by an independent variable to defining DA. Study 2 assumed validation of the instrument occurred by the design of the instrument. The next iteration could perform the validation while analyzing the data, if the question were changed. Rather than measuring DA, the next version of the instrument could document an aspect of DA and compare this to the experts' understanding of the same question.

3.6. CONCLUSION

Study 2 had 3 objectives. First, to measure DA. An instrument was developed, subconstructs were deemed appropriate, and the necessary components of the next iteration of the instrument were revealed. Second, to determine if there was a change in DA before and after the design project. There was a decrease in total DA, *understand the problem* and *ideate*, and an increase for *build & test*. However, this assumes that the items were of equal difficulty and accurately assessed DA. The third objective was to identify causes of the change in DA. There were many variables that through ANOVA and ANCOVA showed a difference in means for each category. The most interesting discoveries were between *understand the problem* and client-centric independent variables and *build & test* and project-centric independent variables. It is recommended that the definition of DA be further explored and the next quantitative instrument ask a broader question to aid in the definition of DA rather than focus on causes of the change. This study provided a clear direction and need for further understanding and development in DA.

CHAPTER 4: QUALITATIVE STUDY: CAPTURING QUALITIES OF DESIGNERS ACCORDING TO PROFESSIONAL ENGINEERS

4.1. INTRODUCTION

In order to develop an assessment of design ability (DA), a holistic understanding of what constitutes an expert design engineer (DE) is required. Showing that students can replicate the design process illustrates one aspect of a DE, but that one ability does not wholly summarize a good DE [21].

Suppose there were commonality among experts as to what qualities constitute an expert DE. If those qualities can be identified, engineering design courses can be tailored to encourage students to develop those traits and increase DA. The information could refine DA assessment tools and students with identified potential could use this information to intentionally develop their DA.

From October 2015 to May 2016, one-hour interviews were conducted with 12 engineers with extensive professional experience from diverse disciplines and industries to address the study objective: *Define the qualities of an expert design engineer.* This chapter documents the qualities of expert DE according to the literature, presents the study design and resulting themes, and proposes implications and future research.

4.2. LITERATURE REVIEW

In 2004, the National Academy of Engineering listed attributes of the engineer of 2020. These included: strong analytical skills, practical ingenuity, creativity, communication, project management, leadership, professionalism, agility, resilience, flexibility, and lifelong learning [72]. If these attributes are required for all engineers, and DEs are one type of engineer, then it follows that these attributes are required for DEs. Before concluding that the study objective has been met with this one source, we must examine the language. Attributes, like abilities and skills are not equivalent to qualities. This section will present descriptions of designers in the literature while examining the terminology and methodology of the studies.

4.2.1. Abilities, Skills, and Qualities Terminology

According to Koen [73], engineering design is a complicated combination of behaviors; it includes many different actions such as: researching, brainstorming, and decision making. The person doing the design possesses a set of abilities, skills, competencies, and qualities to allow these actions to be performed. Examples of each of the 3 descriptions (abilities, skills, and qualities) of DEs can be found in the literature [21, 34 - 36, 74 - 78].

Design abilities are found in the context of learning objectives [74] and accreditation [75]; although specific, design abilities are hard to measure. The Accreditation Board for Engineering and Technology developed criteria in 2000 using a list of abilities of designers [6]. Over 400 engineers were asked to rank a list of 172 abilities, which was condensed to 11 categories. The category for design contains 18 abilities; 5 of top rated categories are:

a. a demonstrated ability to design a component,
b. a demonstrated ability in an upper-division, team-based design project,
c. an understanding of the concept and meaning of “form follows function”,
d. knowledge and understanding of the “concept of robustness”, and
e. experience in designing systems considering performance requirements. [6]

Abilities c. and d. can be assessed, however a. b. and e are too vague to measure DA in students or expert designers. One of the assessment methods presented in chapter 2 that uses rubrics to measure DA describes professional DEs as possessing 3 abilities: ‘all elements [of the design process] used skillfully, repeatedly, revised’, ‘team structured for responsibility and performance’, and ‘professional quality recording, transfer, presentation of information’ [21].

Where abilities are specific but not measureable, skills are described using generic categories and are not measureable or specific. A report from the Natural Sciences and Engineering Research Council design chairs includes a literature review summarizing the skills DEs possess: a hands-on knowledge of tools, technical, business, communication, and teamwork skills, a professional attitude, and experience with the design process, brainstorming, safety, iteration, and computer aided design [75]. These skills present the image of a very appealing employee, but are too broad to measure design. According to the literature, engineering habits of mind include optimism, collaboration, communication, ethical consideration, and willingness to fail [34 - 36].

Qualities of DE are descriptive pieces of information such as personality traits or identification of behavior. It is a fundamentally different question than what skills or abilities a DE possesses because the focus is on affect rather than actions. Although a qualitative study could not be found on qualities of expert DE according to professional engineers, similar characteristics were described by professionals: design thinking [76], dimensions of informed design [77], and creativity [78].

An engineer who possesses design thinking seeks input from others, pursues challenging problems head on, is open to experimentation, works well with many other disciplines, and thoroughly considers problems [76]. Dimensions of informed design include continual learning, a logical decision-making process, a knowledge of heuristics, an awareness of time and budget constraints, and an instinctual recognition of relevant and extraneous data [77]. Creativity requires a knowledge of objects, principles, processes, and similar scenarios, being open to opinions and feedback, an awareness of time constraints, and being internally motivated [78]. Additionally, a DE demonstrates flexibility, cycling through the design process in quick succession [79]. There is conflicting data that suggests that this process of optimization can be cut short, as an increased knowledge can cause DEs to fixate on an initial idea [80, 81]. This theme will need to be further explored. Although employing different terminology than 'qualities', it is anticipated that these descriptions will parallel the qualities of DEs.

4.2.2. Participant Selection and Methodology

The following studies documented qualities or behaviors of a DE, employing professors and university staff as the participants. Mavinkurve [82] produced competencies and abilities from a qualitative study coding the design of 4 electrical engineering professors. The identified competencies were to "gather information, represent information in multiple ways, structure open ended problems, think divergent, think convergent, and implement" [82]. Similar findings were developed into a rubric by a team of faculty and administrators [83] and a set of 9 learning outcomes and assessment techniques by multi-disciplinary focus groups of faculty and staff [84]. While these studies produced meaningful data, rubrics, and outcomes, it is important to recognize that professors and university staff may have limited design experience compared to DEs in industry. According to Cross, "if studies of designer behavior are limited to studies of rather inexpert designers, then our understanding of DA will also be limited" [81]. In order to fully understand the qualities of DEs, expert practitioners should be consulted.

A broad review was performed on studies that have a similar objective but in different fields to find appropriate methodologies to best document the qualities of a DE. Lawson interviewed expert architects, used observational techniques, and reported similarities and key differences in the way expert architects work [85]. Ahn [86] interviewed 23 engineers from industry and academia using a constant comparative method to develop an assessment technique for leadership, adaptability of change, and synthesis ability in students. Using a framework of phenomenography, Daly [87] asked professionals how they experience design, and 6 themes emerged, "(1) evidence based decision-making, (2) organized translation, (3) personal synthesis, (4) intentional progression, (5) directed creative exploration, and (6) freedom". An interview protocol is therefore reasonable to determine qualities of expert designers.

4.3. METHOD

A qualitative study allows for the collection of rich data (depth as opposed to breadth), and an unstructured interview protocol allows for the discussion to organically progress from an initial question [88]. While a quantitative study attempts to find a large representative sample so that the findings can be transferred to a greater population, a qualitative study claims that the findings apply only to the sample of participants [89]. It is not reasonable to apply findings from this qualitative study to the greater population of DEs, but if there is a diverse sample of participants, findings will be more meaningful, wherein they exist across disciplines, industries, and geography. Participants were selected using stratified purposeful sampling to ensure a diversity of engineering disciplines, geography, industry, education, gender, and years of experience [90].

In order for a participant to be considered an expert, a professional engineering designation or at least 10 years of experience was required [91]. Each of the experts who were chosen worked as DEs, but not all of the participants consider themselves to be DEs in their current role. All of the participants have engineering management experience as well; managers must consider the abilities of their employees in order to best utilize their skills, which provides mangers a unique vantage point to better identify qualities of DEs.

Interviews were held over Skype, the phone, and in person and lasted between 30 and 90 minutes. Using an unstructured interview protocol, participants were asked:

> *Describe someone you worked with who was a great designer, perhaps your mentor or someone who has worked for you, who always seemed to know the answer to a difficult problem. When you looked at their solution, you would think, 'that is so simple, why didn't I think of that?' Do you have someone that fits that description?*

Field notes were taken and participants were prompted with follow up questions based on their responses. Prompts encouraged them to continue talking and clarified content, such as the following common prompts:

- What qualities does the person who you are thinking of have? Can you describe that person for me?
- Were there any negative qualities?
- How did the person interact with others socially?
- What did that person do at lunchtime?
- How did the person handle feedback or criticism to their designs?
- Do these qualities differ from qualities required of all engineers?
- What is the relationship between designers and engineers? Can you describe it in Venn-diagram terms?

Consistent with ex post facto protocol, participants were emailed a copy of the notes to edit to ensure accuracy of the content and confirmability [92], as well as to provide triangulation [90]. The notes were collected and reviewed for findings. To maximize participant comfort and increase openness to speak about experiences, interviews were not recorded; direct quotations were not available, but member checking ensured the data correctly captured the views of the participants.

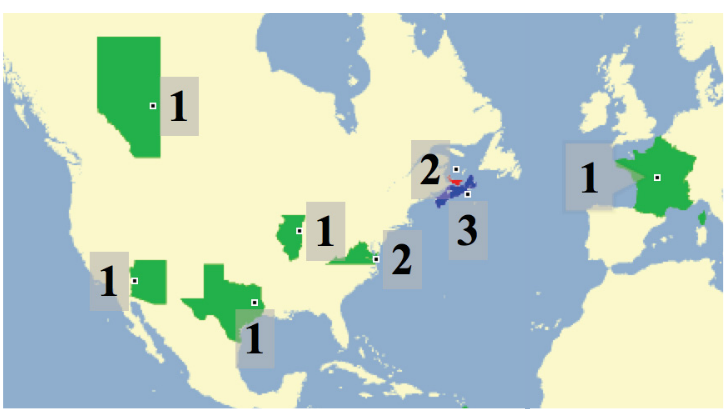
Using inductive analysis, the data were read, coded, and summarized into bullet points for each participant to review the summary as well as the notes. Two weeks later, the original data were coded again without consulting the original summary, to ensure consistency in the coding, providing a form of triangulation and reducing systematic bias [90]. The coded data were condensed into themes and organized into subtopics.

4.4. RESULTS

This section documents 3 sets of results. The participant data will be presented to confirm a diverse study population. The design views for each participant will be presented for context. Finally, the themes describing the qualities of DEs will be presented.

4.4.1. Participant Data

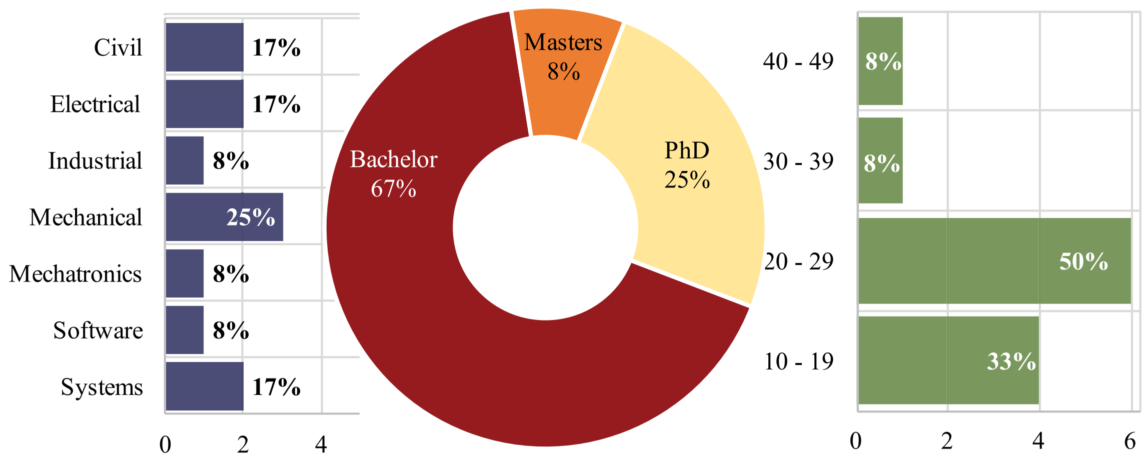
The 12 participants reside in 2 continents, 3 countries, 7 regions, and 8 states or provinces. Figure 4-1 shows a map of the states and provinces with the number of participants from each area, and a table with the number of participants in each region.



Number of participants in each region	
Atlantic Canada	5
NS - 3 & PEI - 2	
Western Canada	1
Eastern US	2
Midwest US	1
Southern US	1
Western US	1
France	1

Figure 4-1: Number of participants in each geographic region

All of the participants have design engineering and management experience, and 42% have teaching experience. Figure 4-2 shows the engineering disciplines (a), educational terminal degrees (b), and years of experience (c) of participants. The most common discipline is mechanical engineering with 3 participants, 33% of participants hold a graduate degree, and 66% of participants have at least 20 years of experience.



a. Engineering disciplines b. Educational terminal degree c. Years of experience

Figure 4-2: Education and experience of participants

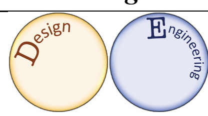
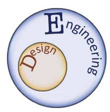
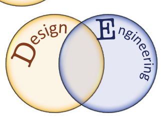
Participants are from the following industries: aerospace, acoustic design, marine robotics, mass production manufacturing, musical tools manufacturing, petro-chemical, utilities, and renewable power. There was a representative distribution of gender, with 3 female (25%) and 9 male (75%) participants [59, 60]. Complete participant information is provided in Table C-1 in Appendix C.

4.4.2. Design and Engineering Context

Just as a diverse participant group is required, it is necessary to document the beliefs of the participants with respect to design. The relationship between engineering and design was explored in every interview and 5 of the participants identified themselves as designers, while 7 did not. Participants used the terms 'design engineer' and 'designer' interchangeably, and will be represented by DE in this document. Three categorical themes emerged from information was extracted from the interview: the *balance* between engineering and design, the *amount* of design within a job, and the *level* of design tasks.

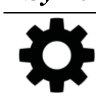
The *balance* between design and engineering produced 4 possibilities shown in Venn diagrams in Table 4-1. Starting at the top row, 3 participants described engineering and design as separate entities. Seven of the participants described design as a subset of engineering. One person stated the opposite, where all engineers are designers but not all designers are engineers. A balance of engineering and design is represented in the bottom row, as a logical 'or', showing a broader definition of design.

Table 4-1: Balance between design and engineering

Venn Diagram	*Description*	*Number of participants*
	Separate	3
	Design subset of engineering	7
	Engineering subset of design	1
	Balance between engineering and design	1

Within the cases where design or engineering entirely encompasses the other (rows 2 and 3), the *amount* of design within a job clarifies whether design is a portion of the job or the entire job, represented in Table 4-2 by a full or partial gear. Responses that are a portion of the job or task-based state 'design is a subset of the responsibilities an engineer has in their job', implying that some of the tasks the engineer performs can be described as design but not all. Whereas, responses that are the entire job or job-based state 'designers are a subset of engineers', implying that the entire job is to do design.

Table 4-2: Amount of design within a job

Symbol	*Description*	*Number of participants*
	Entire job: Designers are a subset of engineers	8
	Portion of job: Design is a subset of the responsibilities an engineer has in their job	3
?	Not discussed	1

The *level* of design tasks, shown in Table 4-3, differentiates whether design tasks are a high or system-level (left column), low or detailed-level (right column), or a combination of all levels (middle column). The system-level tasks are high-level such as system architecture, whereas the detailed-level tasks include development of components.

Table 4-3: Level of design tasks

Description	***Example tasks***	***Number of participants***
System / high-level	Systems architecture	4
Detailed / low-level	Development of components, detailed analyses	5
Both	A combination of all tasks	3

Compiling the data from the 3 themes provides a deeper understanding of the beliefs about design for each participant. Figure 4-3 shows the classification of the *balance* between engineering and design (left column), the *amount* of design within a job (full or partial gear symbol), and the *level* of design tasks (right columns). Each gear represents one participant.

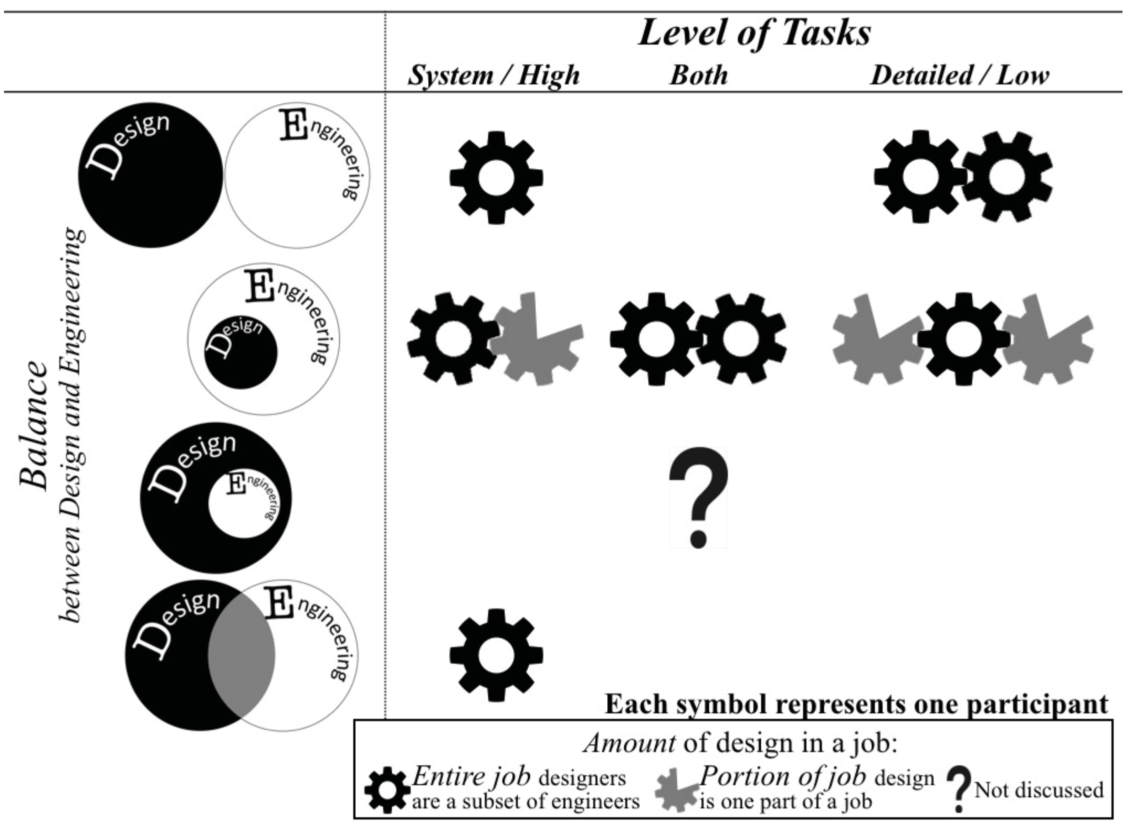


Figure 4-3: Relationship between design and engineering

The synthesis of these 3 themes in each participant produces conflicting definitions about design and is documented in Table C-2 in Appendix C. According to the participant in the top-left cell (A1) in Figure 4-3, designers create the system-level architecture and hand off specifications to the engineers to implement the details. Conversely, the participants in the top-right cell (A3) believe that engineers provide the specifications to the designers to innovate at the detailed-level. It is possible that these participants could be providing descriptions of good engineers, rather than good designers. However, this potential contextual bias was reduced by regular prompts returning to qualities of the individual DE rather than speaking in generalities.

There is consistency between the design definitions (in Table C-1 in Appendix C) and the columns containing level of design tasks. The system-level column on the left focuses on innovation and abandoning constraints. The detailed-level column on the right contains definitions that discuss innovation within constraints, such as during troubleshooting. The middle column contains definitions concerning the reduction of uncertainty and the progression from broad to narrow level.

In a qualitative study, it is necessary to document the beliefs of the investigator, interviewer, and analyst to combat any potential influence [90]. To document the author's beliefs about design, a full gear would be added to cell B4. This corresponds to an equal balance between design and engineering, with tasks at both the system- and detailed-level, signifying design is an entire job, not merely a task. There are no responses in this cell and therefore no evidence of bias.

4.4.3. Qualities of Design Engineers

There were 194 data points produced from the coded data; 186 were categorized into 9 themes and 30 subtopics. There were 8 outliers. If more than 6 participants discussed a quality of a DE, it was recorded as a theme. As shown in Table 4-4, there was an average of 9 participants per theme, ranging from 8 to 12. All participants stated that DEs are systematic and efficient. While there is homogeneity of points in all 9 themes, confirming the reliability of the data, all outliers will be presented.

Table 4-4: Themes and statistical data of each theme

Themes	***Number in each theme of***		
	Participants	*Subtopics*	*Points*
Systematic and efficient	12 (100%)	4	30
Collaborative	10 (83%)	3	17
Creative	9 (75%)	3	14
Engaged	9 (75%)	3	19
Inquisitive	9 (75%)	4	29
Driven	8 (67%)	3	17
Intuitive/perceptive	8 (67%)	4	25
Versatile	8 (67%)	3	17
Confident	8 (67%)	3	18
Average	*9*	*3.3*	*20.7*
Total	*12*	*30*	*186*

Figure 4-4 shows the distribution of themes and points per participant. There was an average of 16 points per participant with a range of 9 through 26 points per participant.

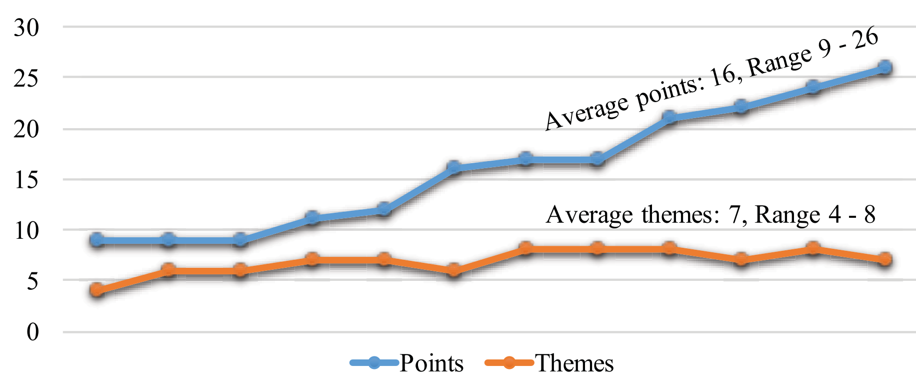


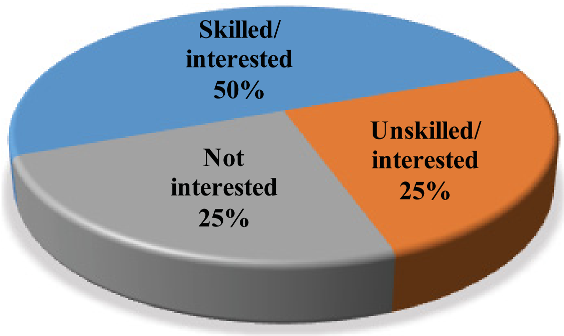
Figure 4-4: Number of points and themes per participant

Each participant discussed 4 through 8 themes with an average of 7 themes; no participant provided information for all 9 themes. Each participant provided an average of 2.4 points per theme, supporting the ability for breadth and depth of qualitative data. The 30 subtopics are listed in Table 4-5, organized by theme. There are 3 or 4 subtopics per theme, some of which contain negative attributes of DEs, presenting a more holistic and realistic picture of DEs.

Table 4-5: Subtopics within each theme

Theme	***Subtopics***
Collaborative	Pleasant, lighthearted, optimistic, and outgoing affect Respected by coworkers because will do 'grunt' work Team player, with almost everyone
Confident	Defensive of solution but receptive and incorporate if sound reason Knows limitations, admits mistakes *Negative:* Can be egotistical
Creative	Innovative Sees possibilities Thinks outside the box
Driven	Constantly learning from a variety of sources, independent learner Likes to be on the forefront of innovation, constantly curious Independent worker who owns the problem and wants less oversight
Engaged	Competent and has a natural ability to design Eager, motivated by interest in the project Motivated by knowing why design is important
Intuitive, perceptive	Empathetic, understands client need Focuses on important details Recognizes patterns, can synthesize information and forecast Understands context
Inquisitive	Talks to anyone in company about technical issues, but can be blunt Seeks input, talks through problem with people with different opinions Would small talk with any individual in a social setting *Negative:* Not the best public speaker, better 1 on 1
Systematic and efficient	Adaptive Good with time management, works to find a solution to be efficient, promotes regular iteration and testing early in process Systematic and breaks a problem down *Negative*: Can have perfectionist tendencies, conservative to a fault
Versatile, broad interests	Develops a deeper understanding from experience, gains 'battle scars' Has multi-disciplinary technical knowledge, including use of heuristics Has a variety of interests outside the office

There were 8 points that remained from the 194 points that did not fit into one of the themes. The 8 points all concerned the ability and desire of a DE to manage people, as shown in Figure 4-5. This was not included as a theme because of insufficient data points (6 participants) and due to the contradictory nature of the information. The data are included here to provide a negative response [72], showing that the data are not purely congruent, which could indicate an analyst bias.



Subtopic	*Points provided by participants*
Skilled/ interested	Good at mentoring
	Understand how to task people according to their abilities (x2)
	Good reviewer and reviewee
Unskilled/ interested	Mentee didn't like mentor’s style
	Sets unrealistic expectations
Not interested	Doesn't want to judge people
	Role is less managerial

Figure 4-5: Management skill and desire

Two participants described DEs as good at management and interested in doing so. Two participants replied that while DEs are interested, they are not good at management. One participant said DEs are not interested in managing as it distracts from solving exciting problems and they do not want to judge people. The final participant said that while DEs can be interested and good at tasking people according to their abilities, they set unrealistic deadlines expecting workers to meet their high standards. The conflicting information from this participant reflects the greater conflicting responses from the 6 participants regarding management. Further study on this topic is required before any conclusions can be drawn.

4.5. DISCUSSION

Each of the 9 themes will be discussed in detail. Because the intent of the study is to develop qualities rather than abilities, the title of each theme had to fit inside the following sentence: ‘An expert DE is’, suggesting all qualities are adjectives. The picture of the ideal DE will be painted through the descriptions of the qualities of notable DEs that the participants describe. Using inductive analysis, individual cases were constructed without categorization. A cross-case analysis was then performed, patterns were detected, hand-coding was employed, and themes were developed. Once patterns began to emerge, categories were judged for internal homogeneity to ensure points were similar and external heterogeneity to ensure categories were clearly differentiated [90]. Deductive analysis was then used to develop subtopics, consulting the literature and interview notes. The process is shown in Figure 4-6. According to Patton, in order to avoid pigeon-holing themes at the beginning which could pervert the data, ‘the initial focus is on full understanding of individual cases before those unique cases are combined or aggregated thematically’ [90, p. 57].

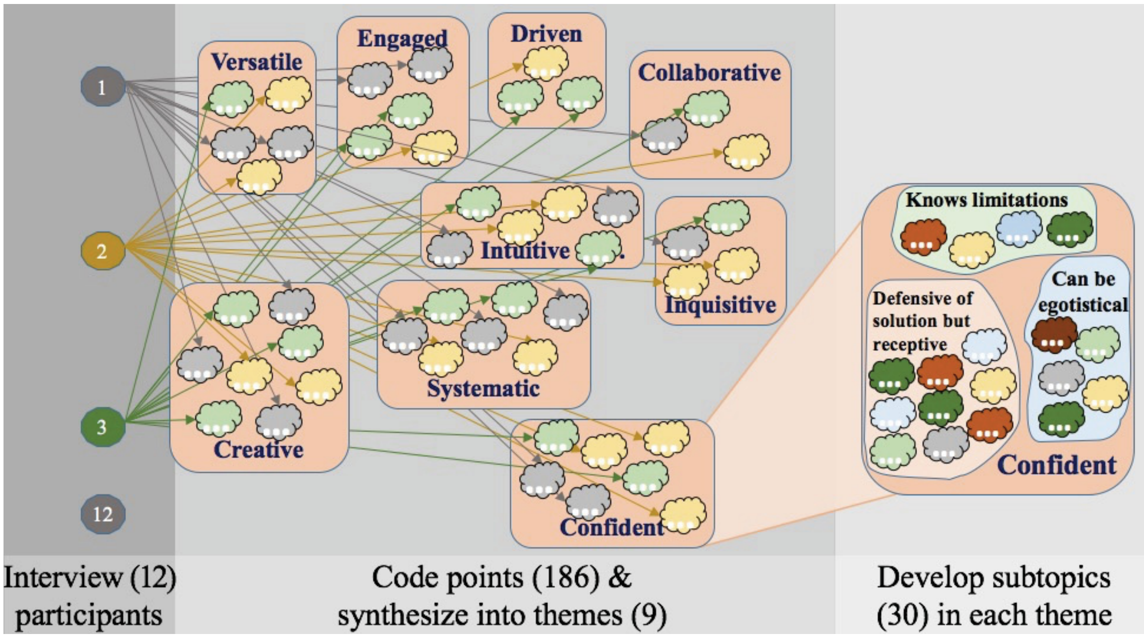


Figure 4-6: Inductive and deductive analysis

Proposed methods of assessment are included following the description of each theme. While it is not the expressed intent of this study to propose assessment techniques, it is the overarching aim of the thesis to develop an assessment of DA.

4.5.1. Collaborative

Ten of the participants commented on the collaborative spirit that DEs possess. Great DEs recognize their role in the bigger picture as a part of the whole and are willing to sacrifice optimum efficiency of their design if it helps the overall system to operate more efficiently. They recognize the importance of teamwork and are willing to do menial tasks that other engineers might not, which earns the respect of their coworkers. One of the participants said the need for the team to succeed is more important than personal glory, but a second participant qualified that the DEs want to be recognized for their contribution. These 2 statements show the bounds of motivation, and rather than being contradictory, recognize the need to give credit within the team, with the larger driving force for the overall team to succeed.

Four of the participants mentioned the pleasant, lighthearted, optimistic, and outgoing affect of DEs, painting them as someone people enjoy being around. It would be interesting to investigate whether they are pleasant by nature or this attribute was developed as a tool to accomplish tasks more efficiently, as most tasks require teamwork.

While DEs recognize the importance of being collaborative, 1 participant qualified that DEs do not necessarily get along with everyone. This is a reasonable statement that implies that while DEs are team oriented, they are not willing to be subdued or suppressed; they are not willing to sacrifice quality and efficiency for team cohesion. This quality could be assessed by asking about motivation and desire to succeed at the expense of the team.

4.5.2. Confident

Eight participants discussed how great DE are confident enough in their ability and skills that they are receptive to feedback. One participant said DEs were not ‘overly sensitive to criticism’, implying that while DEs can be defensive of the solution they developed, they are open to hearing feedback to ensure they have the best possible design. Some participants went on to say that DEs enjoy these opportunities to defend the design because they have put so much thought into the logical and systematic development, that it can be a game to prove the person with feedback wrong. Alternatively, if the reviewer can support the criticism or challenge one of the underlying logical assumptions, great DEs recognize that feedback is part of the process.

An additional example of the confidence of a DE is that they are self-aware and acknowledge their mistakes. They know their limitations, and if something is beyond their scope, they will ask for help. If someone is insecure, they may not be willing to ask for help, however a confident individual recognizes their limitations and is not embarrassed by them. One participant described this as self-doubt, recognizing the need to talk to others when they have reached the limit of their knowledge.

The picture that has been presented of the DE is of a near-ideal worker; however, the most common negative quality mentioned by 5 of the 12 participants is the tendency to have an ego. DEs know they have skills and can be confident to the point of arrogance. This is balanced with their easy-going attitude, perhaps because they are confident they can be relaxed and optimistic. One participant qualified that while DEs have confidence in their skills, they have no ego when it comes to the design, and are willing to abandon an idea and iterate to produce a better design.

Confidence could be assessed using a self-efficacy assessment [16], seeking students' understanding of the limitations of their ability. A design scenario could be proposed that asks them to defend their design and measure the level of defensiveness.

4.5.3. Creative

Nine of the participants discussed the theme of creativity, 6 participants specifically using the word 'creative'. This is not surprising as DE are known for their innovative nature, and they have an ability to think outside the box and see possibilities where other engineers may not. They develop many solutions and do not tie themselves to 1 idea. However, in the quest for innovation, 1 participant shared that DEs may ignore the best design if the solution is too straightforward. Perhaps a measure for creativity in addition to existing tools [22, 46, 80] could be asking students to provide as many solutions as possible to a given design problem; the more ideas, the more creative the student.

4.5.4. Driven

Eight of the participants praised the ability of DEs to work independently, take ownership of the problem, operate with a strong internal drive, and approach problems with curiosity. DEs possess a willingness to take risks and allow themselves to be curious. They challenge themselves to be constantly learning. When coupled with the awareness of their limitations, DEs take it upon themselves to learn what they lack and have the ability to teach themselves through the internet and sometimes unusual resources. One participant described a DE so eager to increase their knowledge, he regularly browsed through a parts catalog to be aware of what was available. This willingness to try new things and explore keeps them at the forefront of innovation.

DEs thrive on working independently, and while they can work in teams and rely on others to enhance the design, they do not perform well with heavy management. In fact, the more direction that is provided, the less interested the DE is in the problem. The participants described this as a positive attribute, not needing to 'babysit' the DE. This quality of ownership allows managers to be comfortable delegating important tasks because the DE has an awareness of their limitations and will ask for help when needed. This independence and ownership of the problem is the most appreciated quality that the participants discussed.

Whether a student is driven or not is a difficult quality to assess, however it is clear in design projects which students 'own' the problem and try to solve it as opposed to participating purely for a grade. Perhaps when coupled with self-awareness, asking students to determine the information they need to gather and where they need to gather it from for a specific design problem can show curiosity. Drive can be assessed by the level of engagement in the design scenario, provided the problem allows for innovation.

4.5.5. Engaged

The theme of motivation was addressed by 9 of the participants, however motivation is not an adjective or quality, so upon further review of the data, it was concluded that DEs are engaged. Six of the participants stated that DEs become engaged because the problem is interesting. They are eager to be involved in something they are interested in, which is often on the forefront of innovation, as discussed by the driven theme. This connects to the desire for efficiency and could describe why DEs are eager to move onto the next project once the functionality of the current project is determined; they want to chase the next new, exciting, unknown possibility. DEs are passionate about their work and eager to accomplish new tasks. Two of the participants presented examples of how DEs can become workaholics because they are so passionate about what they do.

When the task is not innovative and the motivation is not apparent, 2 of the participants discussed needing to provide DEs with motivation of why the project is important. Tied to the collaborative theme, DEs need to know what the bigger picture is to understand the motivation for the project. This helps to clarify the project objectives but also provides an eagerness and motivation for the DE to be engaged.

Perhaps one of the motivations to design is DEs present a natural ability, making gut decisions, and easily ‘cutting through the chaff’, as discussed by 3 of the participants. One participant suggested that practice can improve this ability and 2 of the participants discuss the necessity of DE to be competent rather than excellent. According to these 2 participants, as long as the DE can complete tasks, they may not be the most technically skilled person on the team but the balance of other attributes enhances their importance in the organization. This balance of abilities may provide additional motivation where general engineers may find motivation in completing the details and solving very complex but primarily analytical problems.

The assessment of motivation has been explored in existing studies [15, 16] and successful elements of this can be employed. One assessment of motivation could be as simple as whether the student completes the assessment or not.

4.5.6. Intuitive and Perceptive

This theme is perhaps the least scientific, most intangible, and surprisingly most closely-aligned with what is often connected to DEs. Eight of the participants listed 25 points regarding intuition and perception, first explaining how DEs have an ability to empathize with the client, understand their needs, and as 1 participant described, the ability to ‘climb into [a client’s] mind’. This inherent awareness extends to the greater context of the design challenge, allowing the DE to understand the environment, system as a hole, and consider the long-term and social impacts of the problem.

Seven of the participants identified that DEs can detect nuances, ignore extraneous details, and isolate the problem easily, cutting through to the important aspects of a problem. When troubleshooting a problem, DEs can eliminate causes of problems immediately, ask the right questions, know where to dig deeper, and know when to do nothing. This ties into the natural ability from the the eagerness theme, but includes less tangible aspects of the design process that make design appear easy for great DEs.

Being intuitive and perceptive includes the ability to recognize patterns, predict what will go wrong, visualize the problem, and appear to have insight that others do not have. There are similarities between this ability to synthesize information and the ability to break a problem down in the systematic and efficient theme. However, the systematic theme concentrates on the systematic, logical approach used and the intuitive theme concerns the ability to understand the context without being able to specify a reason.

The assessment techniques developed in study 1 and 2 aim to measure how well students understand the problem. An evolution of these techniques with a new understanding of the thematic relationship between quality and ability may provide better results.

4.5.7. Inquisitive

Nine of the participants mention the outgoing, inquisitive nature of DEs to seek others out during the problem-solving process. Whether to seek input on a design, hear different opinions to strengthen the design, or just to hear themselves talk through a problem, DEs recognize the need to talk to others. Some DEs seek feedback during the process to engage other engineers to get buy-in on their idea and use time efficiently in case a major change is needed. DEs surround themselves with people with varying opinions, to collect different perspectives. They are willing to talk to anyone in the company and do not possess a fear of asking questions. While some engineers possess political savvy and are pragmatic, some are so charismatic that they can be blunt or even rude, challenging social norms by talking to executives before talking to their boss. From a managerial standpoint, this quality of a DE may be hard to manage, but good or bad, DEs recognize the importance of asking questions and seeking input.

Three of the participants reported that DEs are not great public speakers, but do very well with small groups or individuals. They use lunch as a time to network and share information about a range of topics, both technical and non-technical. DEs treat everyone with the same level of interest and respect, from the president of the company to the custodian; everyone has the potential to provide information. DEs are genuinely curious about why people believe what they do and are eager to understand.

While DEs have the ability to self-learn as discussed in the driven theme, they recognize the importance of people and discussion. An assessment technique to determine whether a student is inquisitive could be to ask how they would gain a certain skill that they currently do not possess. If they answer solely independent sources of learning, they may not have developed an inquisitive nature. As the social paradigm shifts from having conversations and meetings in the workplace to accomplishing tasks through email, it would be interesting to see if this quality persists. Students rely heavily on social media in design courses so a comparison of how regularly students and experts employ this skill would be informative.

4.5.8. Systematic and Efficient

All 12 participants described a DE as systematic and efficient, someone who can break a problem down into manageable tasks and is thorough. They have the ability to think through many possibilities and predict the outcome, performing complex logical scenarios in their head.

Seven of the participants describe the efficient manner DEs complete tasks. Most DEs understand the time constraints, are practical, and want to deliver on schedule, so they have the desire to get to a solution, though not necessarily the perfect, most optimized solution. This prioritization of efficiency over perfection is important to note, as it is a distinguishing characteristic of engineers in general. One participant explained the desire for efficiency is actually a desire to move onto the next problem to continue innovating. Once the solution was solved 80% of the way, the DEs lose interest.

Three of the 7 participants added that while most DEs focus on efficiency in the schedule, some prioritize optimization. In an effort to find the perfect solution, some DEs are happy to optimize the solution indefinitely and spend extra time reviewing assumptions and repeating analyses to ensure perfection. This level of cautiousness, like any extreme, needs to be tempered. The themes should be further explored to determine whether these points are outliers or the desire for efficiency cannot be generalized for great DEs.

In an effort to meet the timeline, DEs are adaptive. They are willing to abandon ideas and iterate many times in quick succession, incorporating prototypes and tests to converge on the best solution as quickly as possible. They promote testing early in the process, and are not afraid of failure of early prototypes as it provides more information to refine designs. One participant described this as fearlessness and another as a disregard for a structured design process, preferring a more adaptive progression.

4.5.9. Versatile and Broad Interests

The final theme considers the broad range of interests that DEs hold. They have multi-disciplinary technical knowledge and likely have experience working in different departments within the company, according to 8 participants. They recognize the importance of experience to see a project from the beginning to the end in order to develop 'battle scars'. In their curiosity and pursuit of knowledge, they employ design heuristics from other fields to be able to quickly assess the plausibility of designs. Having a broad knowledge base allows them to communicate effectively with more people in the company and synthesize information across different departments.

Outside of the office, DEs likely have a wide range of interests such as playing musical instruments, being well-read, and having a variety of experiences. One of the participants describes a great DE who had many jobs while in university and a poor GPA, because the DE was too busy gaining life experience. This DE is a very interesting person, and according to one of the participants, always has a story to tell.

Versatility would be difficult to assess, but students could provide the number of extracurricular activities they are involved in. If they have a high GPA and stick mainly to courses without gaining experiences, they may not have the broad knowledge base that qualifies them as having a strong DA.

4.5.10. Connection to the Literature

It is important to see how these 9 themes connect to the literature. In section 4.2.1, studies were presented that consulted experts regarding design thinking [76], dimensions of informed design [77], creativity [78], and mental representations [79]. Table 4-6 contains a comparison of the 16 qualities derived from the literature and the 9 themes.

Table 4-6: Results comparing literature to themes

	Collaborative	Confident	Creative	Driven	Engaged	Intuitive	Inquisitive	Systematic	Versatile
Pursues challenging problems head on					x				
Seeks input from others							x		
Open to experimentation								x	
Thoroughly considers problems								x	
Works well with many other disciplines [70]	x								
Continual learning				x					
Instinctual recognition of relevant and extraneous data						x			
Knowledge of heuristics									x
Logical decision-making process [71]								x	
Awareness of time and budget constraints [71][72]								x	
Creativity			x						
Internally motivated					x				
Knowledge of objects, principles, processes, and scenarios									x
Open to opinions and feedback [72]		x							
Demonstrates flexibility, cycling through the design process in quick succession [73]								x	

All 9 themes were represented by the themes from the literature review, and vice versa. This triangulation with the literature supports the validity of the findings.

4.6. CONCLUSION

The study sought to determine the qualities of expert DEs, and the findings are promising. Nine themes were derived from the 12 interviews and a classification of the relationship between design and engineering developed from the data. An expert DE is creative, collaborative, confident, driven, engaged, intuitive, inquisitive, systematic, and versatile. This is a person who has a broad range of experiences, seeks individuals to discuss diverse topics, has technical skill, employs a systematic yet adaptive approach to problem-solving, has an innate ability to understand the problem, is self-motived, aware of their limitations, a team-player, efficient, and constantly learning. However, this is also a person who can be egotistical regarding their abilities, unaware of social norms, possibly blunt to rudeness, defensive of ideas, and lack motivation for simplistic designs.

There was less corroboration between negative attributes, so these must be explored further. The relationship between design and engineering can be classified by the *balance*, *level* of tasks, and *amount* of design in a job.

Potential sources of bias were discussed throughout the chapter. Triangulation of the data with the literature and repeated time-delayed coding supported the validity of the results. A stratified, purposive sample was employed and evident in the diverse classification of the relationship between design and engineering. Members were given the opportunity to review study notes to expand upon any points. While the interconnectedness of the themes could threaten the external heterogeneity, this was resolved by the intentional, distinct delineations between themes. The themes are adjacent or connected, but not overlapping. It is possible that the themes would be categorized differently if a different person was interviewed, as is the nature of qualitative studies. However, the validity is intact because the study design required more than half of the participants to comment on a topic in order to consider it a theme.

It is necessary to identify any framing bias of the interviewer or analyst, as no particular framework was applied, only inductive then deductive analysis. The author shares very few of the 9 qualities of a DE. Her view of the relationship between engineering and design was shared by none of the participants. It is unlikely there is a framing bias.

It is recommended that further interviews be performed to document qualities of a DE, with a modification to the method. The interviews should be recorded and transcribed to preserve data more accurately and allow for a deeper comparison of data. The objective of the studies should further develop the relationship between engineering and design, corroborate the positive and negative qualities of a DE, and delve specifically into the desire and ability of DEs to manage a project. The 9 themes could be developed into assessment tools to determine the DA of students using the recommendations in the discussion section. Only 1 of the 9 themes was explored in the previous studies, suggesting the potential novel application of the findings in further studies.

CHAPTER 5: REFINED DESIGN ASSESSMENT STUDY: UNDERSTANDING OF DESIGN PROCESS

5.1. INTRODUCTION

A quantitative technique is required to assess design ability (DA). Building upon the design scenarios from study 2, a questionnaire could be developed based on 1 single scenario rather than many scenarios, to reduce the time required to take the assessment. As seen in studies 1 and 2, the subjective nature of DA assessment necessitates a quantitative delivery method to be validated before a full DA assessment tool can be developed. In order to focus on the delivery method, the most objective and documented aspect of DA should be assessed: students' understanding of the design process. To validate the delivery method, the instrument was taken by engineers in industry to compare to student results, and then validated against existing studies. After the delivery method was refined, the tool was expanded to assess the aspects of DA that experts discussed in the third study. This chapter [20] contains the development, analysis, and validation of a tool to assess students' understanding of the design process, using existing qualitative studies to triangulate the data. The primary question that will be explored is: *Do engineering students select the same steps and duration of each step in the design process as professional engineers?* A secondary objective explores the descriptive factors that can influence DA: year in studies, discipline, age, gender, and whether students identify as a minority.

5.2. LITERATURE REVIEW

Students' understanding of the design process must include the transition from the initial problem, to problem definition, and ultimately implementation [75]. There are many ways to describe the design process ranging from 3- to 14-step processes, abstract divergent-convergent models, or iterative, cyclical models [11, 30, 83, 93 - 102].

Studies that measure students' understanding of the design process primarily employ self-assessment [30, 103], rubrics of written content [104 - 107], or verbal protocol of a design scenario [79, 108, 109]. Schubert [30] uses a combination of design logs and self-assessment. There is a technique that asks participants to critique an existing Gant chart of a design process [110, 111]. An exploratory study asks students and experts to rate the most important steps in the design process and compares the answers [50, 93]. These studies are primarily qualitative and therefore too time intensive for large-scale deployment in the classroom, but aspects of the studies can be captured in a quantitative study. Sims-Knight [106] considers the time spent in each step in addition to the use of rubrics. Atman et al. [20] tracks the number of transitions and time spent on 7 design activities in 3 design stages: problem scoping, developing alternative solutions, and project realization for experts and students in first- and fourth-year.

When comparing experts' and students' understanding of the design process, Fortier [112] found that experts take more time to understand the problem and wait until the problem is well thought out to consider alternative solutions. Also, while experts primarily employ top-down design methods, starting from systems-level and moving to the detailed-level, they often explore 1 component to a detailed level while at the systems-level to determine overall feasibility. Experts practice early and repeated reviews. Atman et al. [20] found a similar result that experts spend more time in problem scoping aspects of the design process, 24% of their time overall whereas students only spent 18%. Additionally, experts gather more data from a diverse field of study and have a greater focus on the user.

5.3. METHOD

An instrument was developed combining aspects of existing qualitative studies to compare professional engineers' and students' understanding of the design process using a predefined list of steps compiled from the literature [11, 30, 83, 93 - 102]. Students in first-, second-, and fourth-year at Dalhousie University (Dal), students in first- and second-year at the University of Prince Edward Island (UPEI), and professional engineers, also referred to as experts, were asked to forecast the activities and duration of the steps that they would take in order to build a prototype within 1 week (40 work hours) for the following design scenario:

> *On Monday morning, your boss at Melodious Consulting Engineers asks you to design a musical device for Jennifer, a new client to the firm. You*

immediately head into the conference room where your client is waiting, and learn that the client requests a new way to play music. You are asked to design a new musical instrument out of materials from a grandfather clock that was in the client's family for generations. There is a family reunion on Saturday that the client would like to bring a prototype to get the family's approval before destroying the clock.

The full instrument can be found in Appendix D. Students were recruited during design classes and provided a link to the survey for voluntary participation. Experts were sent a link by the PI and asked to forward the link to other experts. Of the 33 steps, 30 can be categorized into the 7 design activities and 3 design stages proposed by Atman et al. [20]: *problem scoping, developing alternative solutions, and project realization.* There were 3 steps regarding the *iterative* nature of design that did not fit in the existing design stages so a fourth stage was added. Figure 5-1 shows the design steps, activities, and stages.

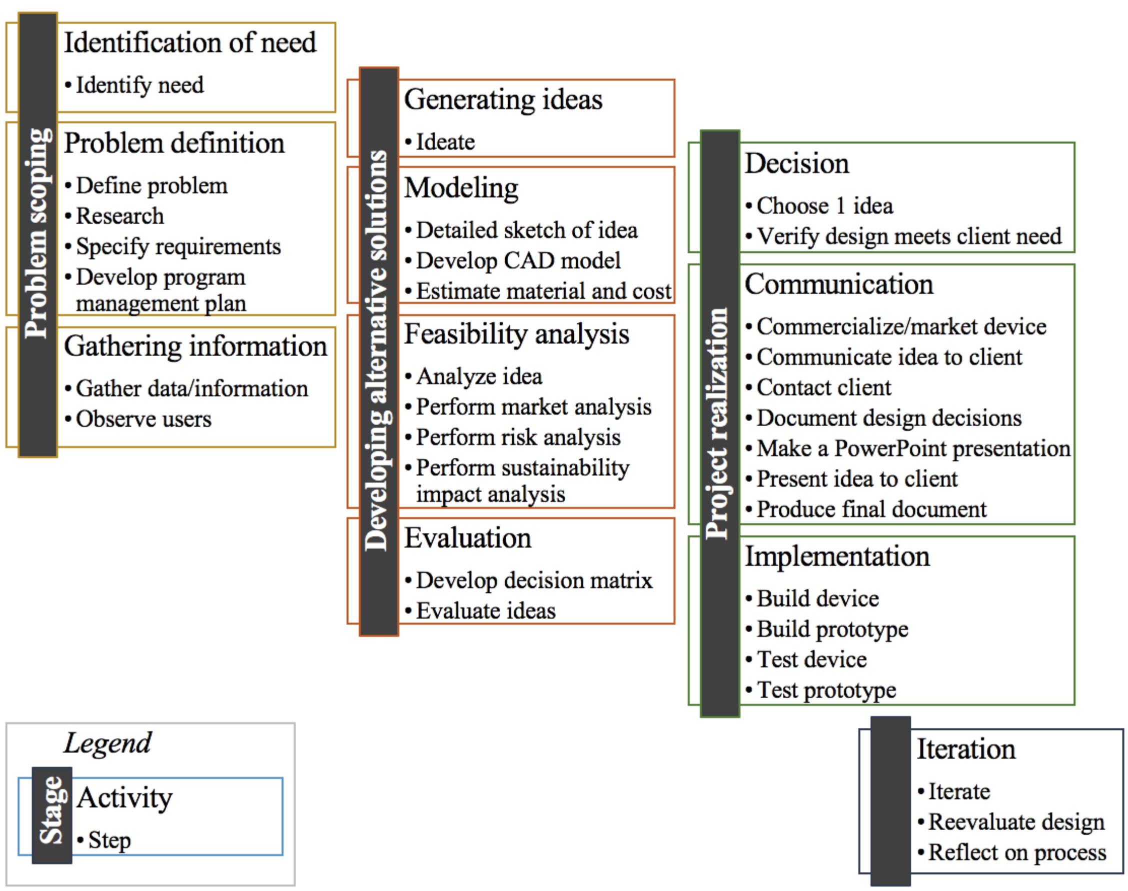


Figure 5-1: Steps in the design scenario

All participants were asked their engineering discipline, age, gender, and whether they identify as a minority. Experts were asked 3 additional questions: whether they hold a professional engineering designation, their industry, and the number of years they worked as an engineer. This additional information was used to ensure the professional engineer had at least 5 years of experience or held a professional engineering designation, the qualification to be an expert. The year of study was recorded for students and participants were classified into participant groups: first-year, second- through fourth-year, or expert.

The data were reviewed and the number of steps, steps per design stage, and steps per design activity were recorded. The list of steps was modified with the classification of 'other' entries. Next, the number of hours spent in each of the design stages and activities were assessed. The first step participants selected was reviewed as well as a comparison of the design stage for the first step.

Descriptive statistics were recorded for the continuous dependent variables and discrete independent variables. The preconditions for analysis of variance (ANOVA) were assessed for each dependent variable: independence of observations, assumptions of normality, and homogeneity of variances. Variables were deemed to have a normal distribution if the z-score (value divided by standard error of value) for both skewness and kurtosis were less than 3.29 [113]. One-way ANOVA was then employed to determine whether there were significant differences between the dependent and independent variables. Finally, a two-way ANOVA was performed for each of the dependent variables to consider the interactions between the participant groups and the independent variables (engineering discipline, age, gender, and identify as a minority). The validity and reliability [114] of the instrument was assessed utilizing the literature.

5.4. RESULTS

5.4.1. Participant Data

Although over 400 people entered data in the online instrument, there were 257 participants who completed assessment: 203 students in their first-year at Dal and UPEI, 33 students in their second-, third-, or fourth-year at Dal and UPEI, and 21 experts. Table

D-1 in Appendix D contains the statistics on sample size. The greatest response was from first-year students, comprising nearly 80% of participants. Of the 21 experts, 11 held a professional engineering designation. Figure 5-2 shows the descriptive information for the sample; the full list of descriptive information for these independent variables is found in Table D-2 in Appendix D. Percentages shown are for each participant group.

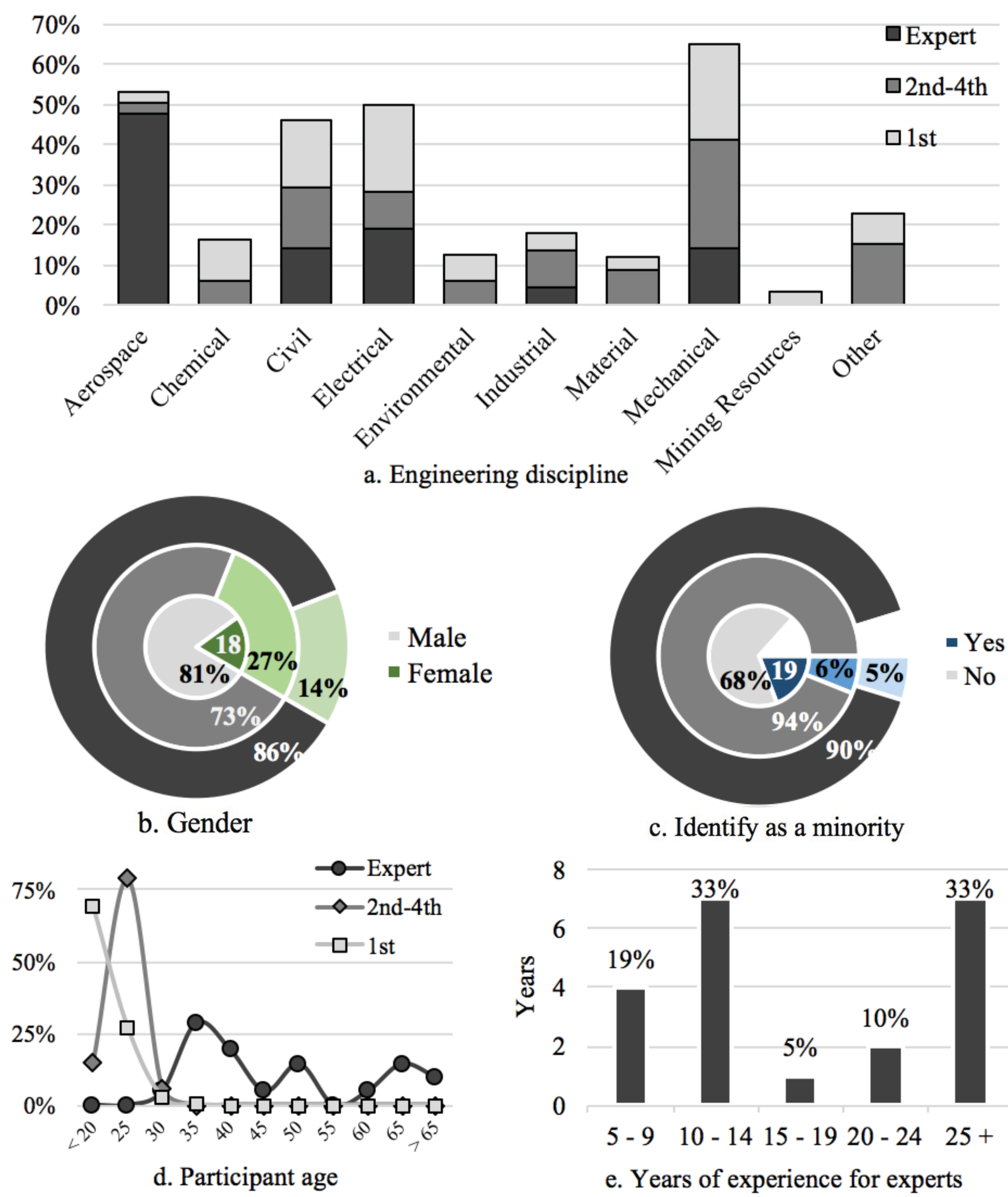


Figure 5-2: Participant data for study 4

There was a wide distribution of engineering disciplines as shown in Figure 5-2 a, with the largest representation of Mechanical students and Aerospace experts. There was a representative distribution of gender, with second- through fourth-year students having the greatest number of female participants (Figure 5-2 b). The number of participants who identify as a minority can be considered low (Figure 5-2 c), but the percentage of participants who abstained from answering the question may have skewed the data. The participant's ages are distributed as expected (Figure 5-2 d), where 73% of first-year students are under 20 years old, 76% of second- through fourth-year students are between 20 and 25 years old, and the ages of the experts correspond to the experience level shown in Figure 5-2 e. One-third of experts have 10 – 14 years of experience and one-third have more than 25 years of experience. This distributed range provides assurance of the expertise.

5.4.2. Number of Steps

After reviewing the data, the 'other' comments were categorized into 'iterate' and 'margin of safety'. 'Choose 1 idea' was listed as an option in the question but was not provided in the drop down list, so some participants wrote this into the 'other' category. This was discovered after the instrument was deployed, so the instrument was not altered for consistency of experience for all participants. The number of design activities increased to 12, adding 'margin of safety'. The number of steps increased to 35, and the number of design stages remained at 4.

The number of steps were calculated for each participant and normalized by the number of steps in each design stage to account for the variance in number of steps per design stage. The normalized average number of steps is shown in Figure 5-3 for each design stage. There is an even distribution of steps between design stages for each group. While experts employed the smallest number of steps, second- through fourth- year students employed the most. A one-way ANOVA confirmed a significant differences in the means between the number of steps and group of participants [$F(2,113) = 3.982$, $p = .021$]. Notice the *iteration* design stage is utilized less than other design stages for first-year students and on par with other stages by experts.

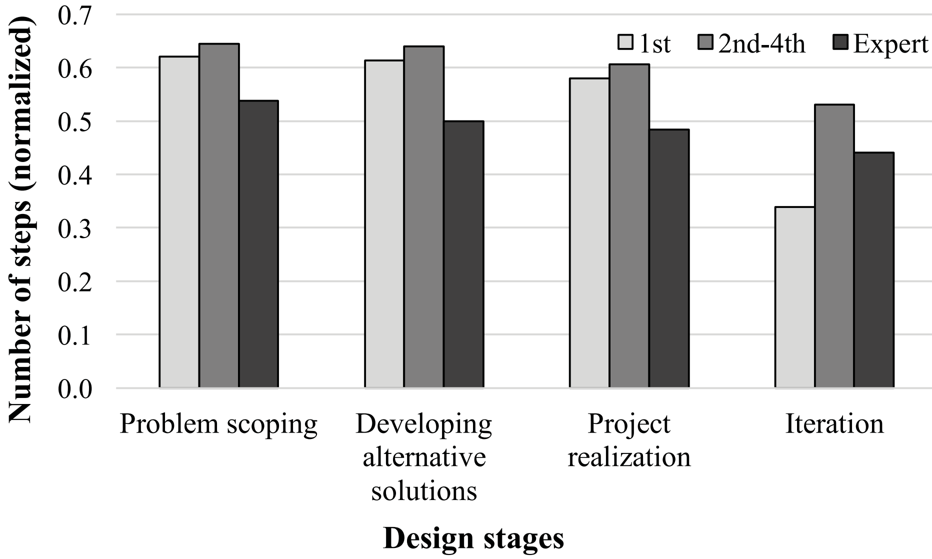


Figure 5-3: Normalized number of steps per design stage

The first step was considered for each participant group as shown in Table 5-1. The most commonly selected step was to define the problem; nearly twice as many second- through fourth-year students selected this option compared to first-year students, indicating this is a step whose value is learned through design courses. More than half of experts selected define problem or identify need as the first step.

Table 5-1: First step selected by participants by design stage for all data

Stages	*1st*	*2nd - 4th*	*Expert*	*Activties*	*1st*	*2nd - 4th*	*Expert*
Problem scoping	56%	85%	71%	Define problem	31%	61%	38%
				Identify need	8%	6%	19%
				Develop program management plan	1%	3%	5%
				Research	9%	3%	
				Specify requirements		6%	5%
				Gather data/information	6%		5%
				Observe users		6%	
Developing alternative solutions	29%		19%	Analyze idea	23%		14%
				Evaluate ideas			5%
				Ideate	4%		
				Detailed sketch of idea(s)	1%		
Project realization	15%	15%	10%	Contact client	15%	15%	10%

It was anticipated that all participants would choose a step from *problem scoping,* however 29% of first-year students and 19% of experts selected a step from *developing* *alternative solutions.* As expected, only first-year students opted to ideate or sketch the idea before problem scoping, and no first-year students selected specify requirements or observe users. Because experts have familiarity with many of the problems they encounter, 5% selected evaluate ideas and 14% selected analyze ideas. Although a surprising result as these steps fall under *developing alternative solutions,* a previous knowledge of the problem allows experts to apply experience before proceeding to *problem scoping*. This previous knowledge also explains why no expert selected research as the first step.

Three design stages were represented, with *project realization* represented by the step to contact the client, under the communicate design activity. A refinement to the tool could be to change 'analyze idea' to 'perform technical analysis of idea' to clarify the difference between ideation and analysis.

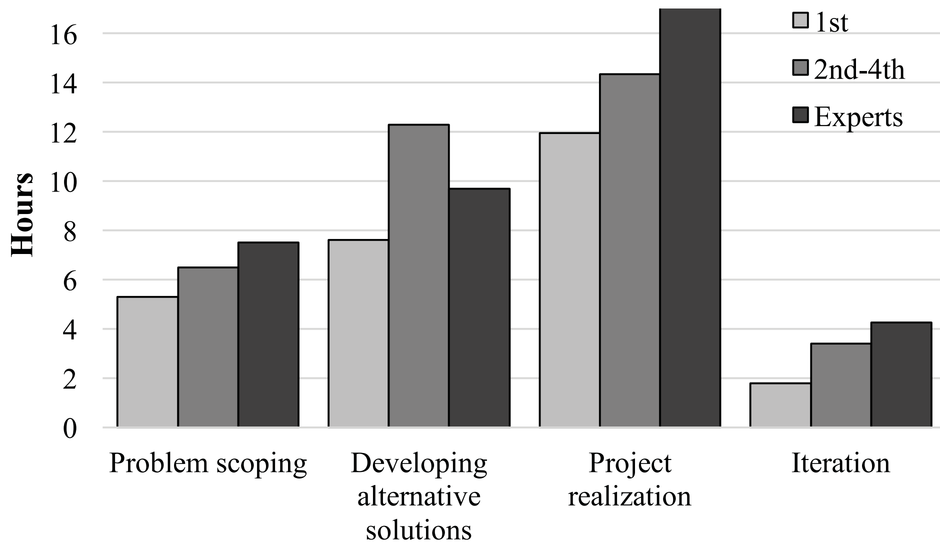
5.4.3. Number of Hours in Each Step

The total number of hours anticipated to complete the hypothetical project was computed for each participant group and expected to be 40 as the question requests. As shown in Table 5-2, first-year students had the lowest average at 28.4 hours. This indicates a lack of interest in completing the instrument, misunderstanding the directions, or a low DA, unaware of how to fill the 40 hours. Second- through fourth-year students were closer to the target with 38 hours, and experts met the target with 40.1 hours. The 40-hour target provided a second set of data to compare DA of only participants that followed the instructions and were 'within schedule', defined as 38 to 42 hours allowing for an error of +/- 5%. Table 5-2 shows the number of participants who were within schedule, with a large reduction in the number of first-year participants to one-third of the initial data set.

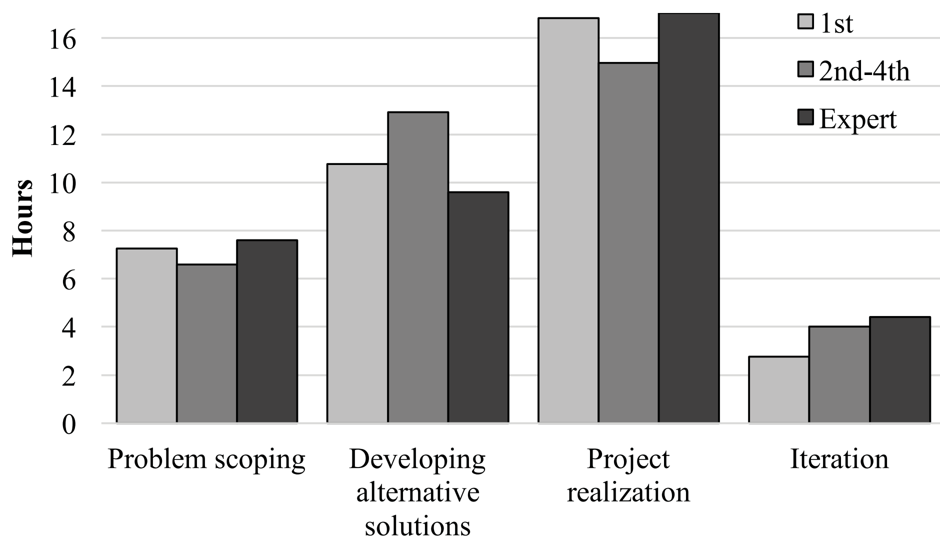
Table 5-2: Sample size by group for 2 data sets

	Completed		***Within schedule***	
	n	*Average hours*	*n*	*Average hours*
1st	203	28.4	73	39.7
2nd-4th	33	38.0	25	40.0
Expert	21	40.1	18	39.8
Total	*257*	*30.6*	*116*	*39.8*

The distributions of responses by design stage for the 2 data sets are shown in Figure 5-4 a for all data (n = 257) and b for data within schedule (n = 116). A one-way ANOVA confirmed a statistically significant difference in means between the groups for all data [$F(2,254) = 6.723$, $p < .001$], however the preconditions for ANOVA were not met.



a. All completed responses (n=257)



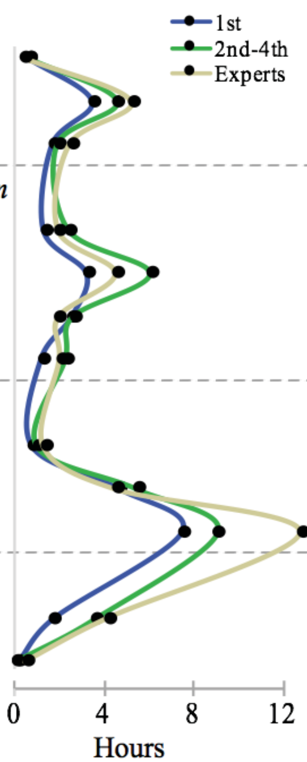
b. Responses within schedule (n=116)

Figure 5-4: Amount of time by design stage for 2 data sets

Figure 5-4 a shows a consistent trend where first-year students spent the least time at each stage and experts spent the most time. While experts spent more time in *problem scoping* than the student groups, the largest division of time for experts was spent in *project realization.* This reflects the lesson that students learn through experience in the last week of their design projects and experts know to anticipate: building the prototype and communicating the results takes a large amount of time. The 1 data point inconsistent to the trend was the increased amount of time second- through fourth-year students spent in *developing alternative solutions,* specifically modeling. This shows experience with the time required to produce a CAD model and inexperience with the tool. Table D-7 in Appendix D shows the significant differences between the groups and each stage from the one-way ANOVA, however the preconditions for normality were not met.

Figure 5-2 b confirms that the 40-hour target is a good indicator of DA, as the times are less distributed for each group. Using a one-way ANOVA, there are significant differences between the steps and groups for the within schedule data set [$F(2,113) = 3.982$, $p = .021$]. Table 5-3 provides more detail for each design activity and displays the distribution of time visually for the full data set and numerically for the within schedule data set. The percentages correspond to each participant group.

Table 5-3: Design stages and activities per group for all data

Design stages and activities	***Full data set (n=257)***	***Within schedule data set (n=116)***					
		1st		*2nd - 4th*		*Expert*	
Problem scoping		**7.3**		**6.6**		**7.6**	
Identification of need		0.8	2%	0.5	1%	0.4	1%
Problem definition		4.3	11%	4.6	12%	4.8	12%
Gathering information		2.2	6%	1.5	4%	2.4	6%
Developing alternative soln		**10.8**		**12.9**		**9.6**	
Generating ideas		1.5	4%	2.5	6%	1.9	5%
Modeling		4.3	11%	5.7	15%	4.1	11%
Feasibility analysis		3.5	9%	2.4	6%	1.5	4%
Evaluation		1.5	4%	2.3	6%	2.1	5%
Project realization		**16.8**		**15**		**17**	
Decision		1.1	3%	0.9	2%	1.3	3%
Communication		5.9	16%	5.1	13%	3.8	10%
Implementation		9.8	26%	9	23%	12	31%
Iteration		**2.8**		**4**		**4.4**	
Iterate		2.4	6%	4	10%	3.9	10%
Margin of safety		0.4	1%	0	0%	0.5	1%
Other		0.4	1%	0	0%	0.1	0%

Within *problem scoping*, all groups spent 12% of time for problem definition but experts and first-year students spent more time gathering data. As seen in the full data set, second- through fourth-year students estimated it will take 15% of the time to perform modeling while first-year students and experts spent only 11% of time. Students spent more time on communication while experts spent 31% on implementation. The *iteration* design stage was consistent between the 2 data sets; experts added a step for margin of safety and allotted more time than students for iteration. Tables D-2 to D-5 in Appendix D contain descriptive information for design stages, activities, and steps for the data sets.

5.4.4. Comparison to Independent Variables

The independent variables that were collected from participants were compared to the 20 dependent variables using 2 ANOVA techniques; the 6 independent and 20 dependent variables are shown in Table 5-4. The dependent variables are comprised of the total time to complete the project, number of steps selected, first step, categorization of first step into design stages, and total time spent in each design stage and activity. While the number of steps, total time, and first step were compared by group using descriptive statistics in the previous 2 sections, ANOVA allows each individual response to be organized into different groups defined by the independent variable, a time-consuming process if performed in a spreadsheet. A two-way ANOVA allows for the comparison of each data point by 2 independent variables, creating a matrix of potential groups and mean scores. All analyses were repeated for the 2 data sets.

Table 5-4: Variables for analysis

Independent variables	***Dependent variables***
Group: 1st, 2nd – 4th, experts	Total time to complete project
Discipline	Number of steps
Age	First step
Gender	Stage of first step
Identify as a minority	Time in each design stage (x4)
Years of experience of experts	Time in each design activity (x12)

Using one-way ANOVA, there were 26 significant effects for all data (n = 257) as shown in Tables D-6, D-7, and D-8 in Appendix D. However, there were no significant effects that met all preconditions for ANOVA; either the variance was too great, the data were too skewed, or the data were too peaked or flat. There were 14 significant effects for the data that were within schedule (n = 116), however 8 interactions did not meet one of the assumptions. While ANOVA is a robust analysis technique, the results are not completely reliable because assumptions were violated. There were 6 significant effects ($p < .05$) shown in Table 5-5 for the data that were within schedule and met all preconditions. The effect size and significance are listed for each combination of variables. There were no significant differences between the engineering discipline and dependent variables. This indicated the instrument can be applied to engineers from a variety of disciplines. There were 2 significant effects between the groups, the number of steps [$F(2,113) = 3.982$, $p = .021$], and communication design activity [$F(2,113) = 4.533$, $p = .013$]. The effect η^2 indicates the differences are medium effects ($.06 < \eta^2 < .14$ [65]).

Table 5-5: Significant effects for one-way ANOVA for within schedule data set

	Independent variables	*Number of effects*	*Dependent variables*	*F*	*p*	η^2
One-way	Group	2	**Number of steps**	F(2,113) = 3.982	.021	.07
			Communication activity	F(2,113) = 4.533	.013	.07
	Discipline	0				
	Age	1	*Problem scoping stage*	F(10,105) = 2.191	.024	.17
	Gender	1	Identification of need activity	F(1,114) = 4.278	.041	.04
	Minority	1	Communication activity	F(2,113) = 5.049	.008	.08
	Experience	1	**Number of steps**	F(4,13) = 3.236	.048	.50
Two-way	Group					
	& Discipline	0				
	& Age	0				
	& Gender	1	*Project realization stage*	F(2,110) = 3.953	.022	.06
	& Minority	1	*Project realization stage*	F(3,108) = 3.718	.014	.09

Figure 5-5 a and b display the mean number of steps and hours for communication for each group. The reduced number of steps supports the findings of the descriptive statistics from the previous section. Experts selected 5 fewer steps than first-year students, indicating a preference for a simplified design process. First-year students allocated 2 additional hours to communicate ideas and twice as much time to prepare the presentation than experts. One-third of first-year students and one-sixth of second- through fourth-year students allotted time to commercialize or market the device, whereas no experts selected this step. It was included as a red herring to show that some students did not appreciate the difference between consultation and commercialization.

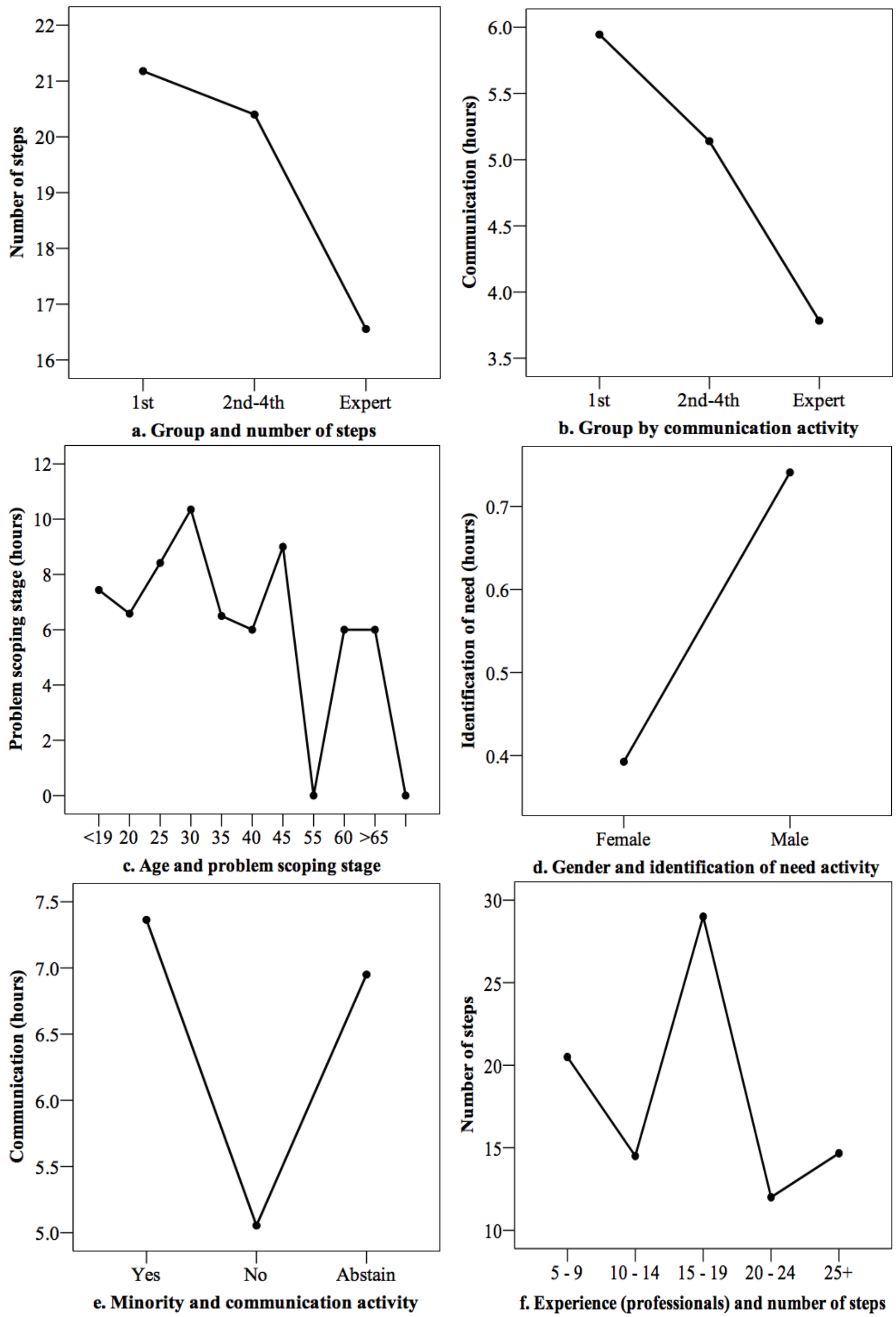


Figure 5-5: One-way ANOVA results for data within schedule

Figure 5-5 c shows the significant effect between age and *problem scoping* design stage [F(10,105) = 2.191, p = .024]. There was a large effect ($\eta^2 > .14$ [65]) where $\eta^2 = .17$, however because 85% of the participants were in the first 2 data points, the effect is exaggerated and there is no clear trend in the data. The participant who was 55 and selected no problem scoping steps selected 'evaluate ideas' as the first step, indicating prior experience with the subject. The difference between gender and the identification of need design activity was small ($\eta^2 < .06$ [65]) where $\eta^2 = .04$, but significant [F(1,114) = 4.278, p = .041]. As shown on Figure 5-5 d, there was only a difference of 18 minutes for men and women.

Figure 5-5 e shows the significant difference between the communication activity and whether or not participants identified as a minority [F(2,113) = 5.049, p = .008]. Participants who identified as a minority spent 2 more hours in the communication design activity than those who do not identify as a minority, producing a medium effect, where $\eta^2 = .08$. There were 4 other significant effects for this independent variable, displayed in Appendix D as preconditions were not met.

A large effect, $\eta^2 = .50$, was seen between the experience of experts and number of steps as shown in Figure 5-5 f [F(4,13) = 3.236, p = .048]. The expert with 15-19 years of experience selected the maximum number of steps while 17 experts who were earlier or later in their career selected fewer steps. The effect size was exaggerated due to the low number of participants with this level of experience.

Using two-way ANOVA, the interaction between 2 independent variables was considered when analyzing the mean differences. The engineering discipline, age, gender, and whether participants identify as a minority were considered for each of the 3 groups of participants. The years of experience variable was not analyzed because it applies only to experts and therefore does not meet the assumption for independence of observations.

For the complete data set (n = 257), there were 15 significant effects between the 4 combinations of the independent variables and the 20 dependent variables, however the normality preconditions were not met for the effects and the results are listed in Tables D-6, D-7, and D-8 in Appendix D. There were 8 significant effects for the refined data set (n = 116), 2 of which met the required preconditions for ANOVA and are displayed in Table 5-5. The *project realization* design stage showed significant differences in the interaction between group and gender [F(2,110) = 3.953, p = .022], and group and identify as a minority [F(3,108) = 3.718, p = .014]. Figure 5-6 shows the differences in means for each group and independent variable.

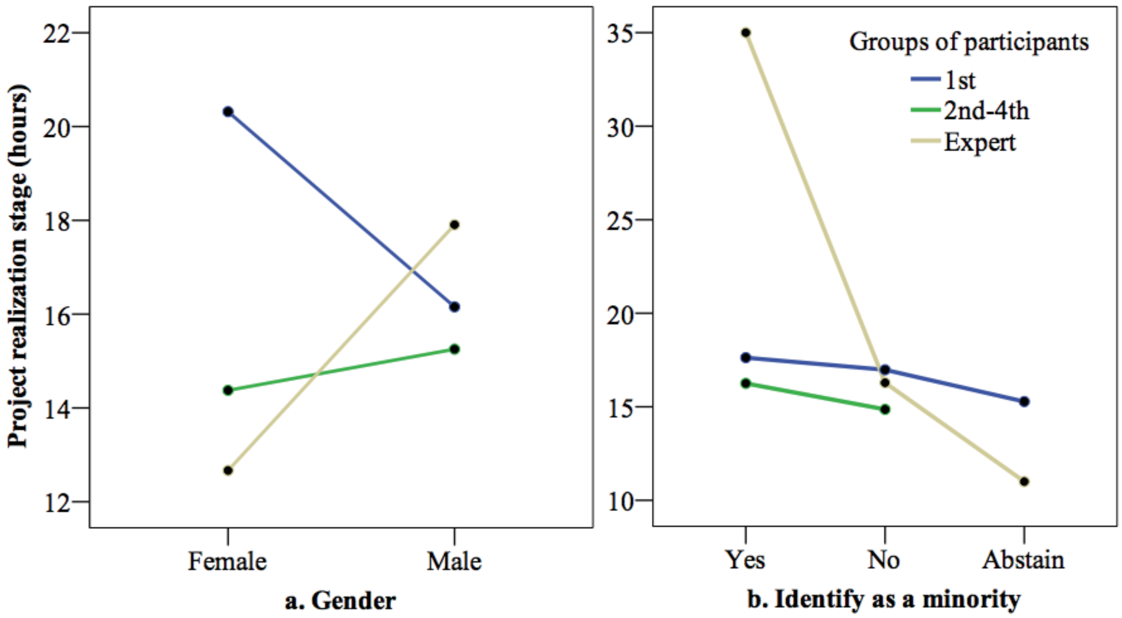


Figure 5-6: Two-way ANOVA results within schedule for project realization stage

The 3 female experts spent 6 fewer hours than the 15 male experts in the *project realization* design stage, while the 13 female first-year students allotted 5 more hours than their 60 male counterparts, as shown in Figure 5-6 a. There was a medium effect of $\eta^2 = .06$. There were 3 additional significant effects between group, gender and dependent variables ($p < .05$), but the normality requirements were not met.

The results for 2 of the *developing alternative solutions*: generating ideas and evaluation, help to explain the effect seen in Figure 5-6 a. Shown in Figure D-1 in Appendix D, female experts spent 5 hours more than male experts generating ideas and 2.5 hours more evaluating ideas. This indicates the 15 male experts rely more on immediate iteration and allot more time for building while the 3 female experts allow more time to plan the design and think through the details before building begins. First-year students spent 1 hour less than second- through fourth-year students for generating ideas and evaluation, but the difference between female and male students was small; this balances the higher time the female first-year students allotted for *project realization*.

The 1 expert who identifies as a minority spent nearly 20 hours more than the 17 experts who do not identify as a minority, as seen in Figure 5-6 b. Although there is a medium effect, $\eta^2 = .09$, it is exaggerated due to the small sample size.

5.5. DISCUSSION

Validation is the measure of how well the outcomes of the study accurately addressed the research question [115], and can be divided into construct, content, and concurrent validity. Construct validity asks whether the construct accurately measures the ability or concept addressed in the research question [116]. The construct for this study was a measure of understanding of the design process to determine DA. The literature review confirmed understanding of design process is a valid assessment for DA. Content validity considers whether the instrument accurately reflects the construct [116] and will be discussed in section 5.5.1. Concurrent validity asks whether the results of the instrument correlate with outside information [116], and will be discussed in section 5.5.2.

5.5.1. Addressing Study Objectives

The data addressed both objectives of the study and thus confirmed construct validity. Students selected different steps and durations than experts, and there were differences in the responses between participant demographics, as summarized in the following list. Significance is noted only if all preconditions for ANOVA were met using the data set of participants within schedule; remaining items were discovered using descriptive statistical analysis.

- Number of steps:
  → Experts used the fewest number of steps ($p < .05$), 5 less than first-year students
- Duration of steps:
  → First-year students allotted 2 more hours for communication than experts ($p < .05$)
  → Female experts spent 6 fewer hours than male experts in *project realization* ($p < .05$) and 5 more hours generating ideas in *developing alternative solutions*

→ Female first-year students allotted 5 more hours than male students in *project realization* design stage, the inverse of experts ($p < .05$)

→ Experts spent more time in each stage than first-year students

→ Second- through fourth-year students spent more time than other groups in *developing alternative solutions*, specifically modeling

→ All groups spent the most time in *project realization*, specifically implementation

→ An indicator of DA was whether the total number of hours was within the specified 40-hour limit (+/- 5%).

- Selection of steps:

→ Experts employed iteration more than first-year students ($p < .05$)

→ One-third of first-year students, one-sixth of second- through fourth-year students, and no experts selected commercialize or market the device

→ 2 experts and 1 second- through fourth-year student wrote-in 'margin of safety'

- First step:

→ Only students selected research as the first step, as experts relied on their previous experience

→ 5% of experts, 6% of second- through fourth-year students, and no first-year students selected specify requirements as the first step

→ Define the problem was the most common first step for all groups

→ 19% of experts chose a step within *developing alternative solutions* rather than *problem scoping* as the first step as they evaluated their previous experience

→ 5% of first-year students chose ideation or sketching as the first step

These findings are reasonable and contain no surprising data, indicating that this quantitative assessment delivery is a useful tool to measure understanding of the design process, and thus DA. In a future iteration of the instrument, the wording should be altered for the 'analyze idea' step to clarify the difference between ideation and analysis. Also, 'margin of error' and 'choose 1 idea' should be added as selectable steps.

The instrument was cumbersome to fill out using Opinio, which could account for the 40% of participants that began the survey but did not complete it. This large reduction in the number of responses could indicate a volunteer effect where the DA is higher in those participants willing to complete the survey. This effect will be reduced as the survey is delivered to more participants, the overall reliability will increase.

5.5.2. Comparison to the Literature

In order to ensure concurrent validity, the data must be compared to the literature. According to Fortier, expert designers take time to understand the problem and consider alternative solutions until the problem is well though out [112]. This is seen in the data as experts spent 7.6 hours on average in *problem scoping* and 9.6 hours in *developing alternative solutions.* Only 1 expert out of 18 skipped the *problem scoping* design stage to proceed to *developing alternative solutions*. According to the data, 45% of the time is spent planning the design, 45% is spent in *project realization* to build and test the device, and the remaining 10% is reserved for iteration.

Atman et al. [20] found that experts spent 24% of time in *problem scoping* whereas students spent only 18%. According to the data in this study, experts spent 20% of their time in *problem scoping* while students spent 18% of their time. This spread is not as large as the Atman et al. [20] study, but indicates a similar result. Figure 5-7 shows the percentage of time spent in each stage for both of these studies.

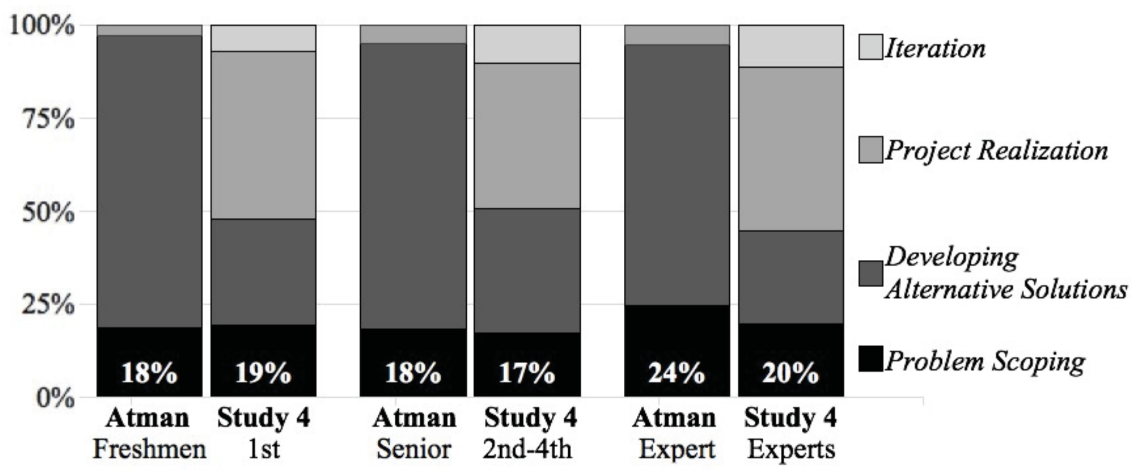


Figure 5-7: Time spent in design stages according to 2 studies

One key difference between the studies is the maturity of the design at the end of the task. In Atman et al. [20], participants developed a design on paper, but did not build. In this study, participants planned the necessary steps to complete the design, which included building. This accounts for the difference for time spent in the *project realization* between the 2 studies, and why an extra design stage for *iteration* was necessary. Despite differences between the structure of the studies, there is similarity in the results.

Statistical threats to validity such as Type I and II errors [66] were documented throughout the chapter. Data were not included in the summary of results if the sample size, effect, or assumptions were questionable. Experts were consulted to ensure an accurate measure of the design process was employed to compare against student responses. This increased the reliability [117] of results. A representative sample was sought to reduce the heterogeneity bias, however more experts who are 50 – 59 years old and identify as a minority would improve the distribution. Validity is confirmed for this study, as a repeatable, precise, and consistent answer to the objective was established.

5.6. CONCLUSION

An instrument was developed, piloted, and validated to assess students' understanding of the design process, one aspect of DA. This instrument can be deployed in design courses using a customized online tool or phone application, which could output student scores immediately comparing their results to other students and experts based on the 20 dependent variables. This immediate feedback could encourage students to complete the assessment, increase the sample size, and aid instructors in the optimization of design project delivery. Multiple design scenarios could be developed to allow students to take the assessment multiple times.

It was shown that experts selected fewer steps and used more time in the design process than students. Experts spent more time than students to iterate the design and second- through fourth-year students spent more time modeling the idea than first-year students or experts. There was a significant difference between how male and female experts allocated time for designing and building. The study objectives were met and an instrument was validated.

CHAPTER 6: CONCLUSION AND RECOMMENDATION

6.1. CONCLUSION

The objective of this research was to develop an instrument that could measure the design ability (DA) of engineering students to aid instructors in optimizing the execution of design projects. An online instrument that could provide immediate results would be desirable for students to receive instant feedback and facilitate simple delivery for instructors. Chapters 2 and 3 described the development of DA assessment techniques, including lessons learned in the delivery and validation of the instrument. Presented in chapter 2, study 1 presented a sample design scenario that was expanded upon in study 2. Study 3 used qualitative techniques to determine the characteristics of skilled design engineers according to experts. Study 4 focused on 1 design scenario to assess DA in terms of the design process. This simplified instrument was delivered to students and experts, validated, and provided an online assessment of DA. In order to maximize the utility of the instrument, the results should be displayed immediately to provide formative feedback for students.

This dissertation provided a range of contributions to the academic body of knowledge, all related to DA. Literature reviews were performed to better understand DA: the design process, the application of the design process to DA, existing DA measurement tools, ethical awareness tools, service-learning, existing measures of abilities, skills and qualities, and measures of the design process. Multiple quantitative statistical techniques were employed, including factorial analysis, one- and two-way analyses of variance, analysis of covariance, reliability assessment, and 2 tests for normality. Two quantitative, 1 qualitative, and 1 mixed-method instruments were developed.

Studies 1 and 2 produced reliable constructs for DA ($\alpha = .729$ and .712, respectively). In study 2, DA was shown to change consistently based on the age of participant ($p = .003$), source of client ($p = .021$) and length of project ($p = .001$), as well as 22 other significant findings (summarized in Table 3-8).

In chapter 3, a classification was developed of the source of client for design projects (Figure 3-1). If instructors considered the available options for the source of project and intentionally selected that appropriate one for their desired learning objectives, the projects could be more focused and tailored so students realize better outcomes. In chapter 4, a classification of the relationship between design and engineering based on responses from engineering professionals was provided (Figure 4-3). There were 3 themes to describe the relationship: the level of tasks, balance between design and engineering, and amount of design with the position. This matrix explored the system- and detailed-level design tasks and documented commonality at intersections in participant data. This classification highlighted that there are many expectations and definitions of a design engineer.

In chapter 4, the 9 qualities of design engineers as described by the 12 participants were compiled: collaborative, confident, creative, driven, engaged, intuitive and perceptive, inquisitive, systematic and efficient and have versatile and broad interests. Design engineers are team-oriented, driven by innovation and a common goal, self-motivated, aware of their limitations, constantly learning, willing to talk to anyone about a range of topics, but can have an ego and be blunt to rudeness. Conflicting information was collected regarding a design engineers' ability and desire to perform management tasks, warranting further study. The data was then triangulated with the literature.

In chapter 5, the design stages and activities proposed by Atman et al. [20], were developed (Figure 5-1), with the addition of a fourth design stage and 2 design activities. The study 4 instrument was validated considering construct, content, and concurrent validity methods. Notable findings from study 4 relate to the number of steps, duration of steps, first step selected, and selection of steps. Specifically, experts selected significantly less steps for a sample design scenario than the number of steps selected by first- or second- through fourth-year students ($p < .05$). The first-step in the design process selected by experts and students was to define the problem (Table 5-1). Experts also selected 'specify requirements' as the first step where first-year students did not, and students selected 'research' where experts did not. Experts spent significantly ($p < .001$) more hours on each design stage than first-year students, specifically during the ‘implementation’ design activity and *iteration* design stage, whereas second- through fourth-year students had the highest time for modeling the idea (Figure 5-4). There were a total of 8 significant effects that met all preconditions for analysis of variance (Table 5-5). There was a significant difference ($p < .05$) between how female and male engineering experts planned their time. Female experts spent 5 more hours ‘generating’ and ‘evaluating ideas’ where male experts spent 8 more hours in the *project realization* design stage. This indicates that men allot more time for an iterative build process whereas women prefer to think through the details before implementation. These results should be confirmed in future studies with a larger sample of experts.

6.2. RECOMMENDATION

In a future study, the instrument from study 4 could be expanded to assess the qualities derived in study 3 of expert design engineers. The steps that the participants select in the study 4 instrument can open new online pages to ask questions tailored to the design scenario the students created. The questions will be based on the qualities of design engineers defined by the experts. This reflexive tool will allow for the same instrument to be deployed multiple times to build upon students’ understanding and knowledge, but never have the same outcome, similar to a ‘choose your own adventure’ book. This will require extensive programming and careful selection and validation of DA assessment items, but provide a wealth of DA data.

After 4 studies, a quantitative instrument was successfully validated to measure DA, meeting the research objective.

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APPENDIX A: STUDY 1 INSTRUMENT & RESULTS

1. DESIGN ABILITY INSTRUMENT 122

2. ETHICAL AWARENESS INSTRUMENT 125

3. INDEPENDENT VARIABLES ON INSTRUMENT 126

4. NORMALITY RESULTS 128

1. DESIGN ABILITY INSTRUMENT

The items below assess design ability (DA) from high (1) to low (4).

1.1 Proposed Design Scenario Items

You were asked to design a chair for a person over 6 feet tall, for their office. Answer the following 3 questions with this information.

DD1 - You just finished the first meeting with the client to discuss the problem, which lasted 15 minutes. Of the following, the first task you should complete is:

1 a. Develop a schedule of all tasks to be completed.
2 b. Find out more about chair design and background information.
3 c. Brainstorm ideas based on what the client said was important.
4 d. Write requirements to define the problem.

DD2 - When developing ideas, the chair should be:

1 a. Treated as one unit.
2 b. Broken up by sections: base, armrest, and seat.
3 c. Broken up by components: wheels, stem, seat, backrest, armrest, screws, bolts, and springs.
4 d. Broken up by function: height adjustment, mobility, back support, and arm support.

DD3 - The best requirement for the chair would be:

1 a. The chair seat must be 2 feet plus or minus 3 inches from the floor.
2 b. The chair height should be adjustable.
3 c. The chair must fit a 6 ft tall person.
4 d. The chair should be tested before delivery.

DC4 - When presenting to a large audience for a formal design presentation, it is most appropriate to:

1 a. Read your speech off a piece of paper.
2 b. Glance at notecards.
3 c. Focus on one person in the audience.
4 d. Read from the screen behind you.

1.2 DA Self-Assessment Items

1.2.1 Define the Problem

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know
DD22 - My ability to define client specifications or requirements improved during this project.	1	2	3	4	5
DD23 - My ability to determine the tasks required to complete a design during a limited time improved during this project.	1	2	3	4	5
DD25 - This project helped me gain a better understanding of the engineering design process.	1	2	3	4	5

1.2.2 Evaluate Alternatives

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know
DE17 – My ability to compare the advantages and disadvantages of different designs improved during this project.	1	2	3	4	5

1.2.3 Communicate the Design

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know
DC18 - When I make oral presentations, I say 'um' a lot.	4	3	2	1	5
DC19 - I know the necessary components of a professional engineering report.	1	2	3	4	5
DC20 - I feel comfortable sharing ideas with my teammates.	1	2	3	4	5
DC21 - In my last engineering report, there were at least 3 errors.	4	3	2	1	5
DC24 - My ideas were heard and incorporated nicely into this project.	1	2	3	4	5
DC26 - My ability to communicate in oral presentations improved during this project.	1	2	3	4	5
DC27 - In my last oral presentation, I confidently explained how the product was designed.	1	2	3	4	5

1.3 DA Assessment Items

1.3.1 Define the Problem

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know
DD5 - Research is not necessary to develop product requirements.	4	3	2	1	5
DD7 - Requirements are measureable and specific pieces of information.	1	2	3	4	5

1.3.2 Evaluate Alternatives

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know
DE8 – When evaluating possible designs, it is best to choose the least expensive design.	4	3	2	1	5
DE13 – A decision matrix is optional when deciding which design to select.	4	3	2	1	5
DE14 – The disadvantages should be considered as well as the advantages when deciding which design is best.	1	2	3	4	5

1.3.3 Communicate the Idea

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know
DC6 - Only one person in each group needs to work on the design document.	4	3	2	1	5
DC9 - It is necessary to rehearse before a presentation for the client.	1	2	3	4	5
DC10 - A design document has sections with headings.	1	2	3	4	5
DC11 - When working on a team, my teammates contribute less than I do.	4	3	2	1	5
DC12 - Tables are a concise way to display data.	1	2	3	4	5
DC15 - There are never too many slides in a presentation for the client.	4	3	2	1	5
DC16 - My client was pleased with my design	1	2	3	4	5

2. ETHICAL AWARENESS INSTRUMENT

2.1 Ethical Awareness Self-Assessment Items

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know
E8 - I am more engaged in a project that helps the community.	1	2	3	4	5
E9 - My design for this project is more meaningful to society than other design projects I worked on.	1	2	3	4	5
E10 - If I was hired today as an engineer in my field, I could do whatever is asked of me.	1	2	3	4	5

2.2 Ethical Awareness Assessment Items

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know
E1 - Acting ethically is the most important part of being an engineer.	1	2	3	4	5
E2 - I don't need to worry about ethics until after I graduate.	4	3	2	1	5
E3 - The best teams have at least one female.	1	2	3	4	5
E4 - Men make better engineers than women.	4	3	2	1	5
E5 - It is better for society if people who are part of a minority isolate themselves.	4	3	2	1	5
E6 - Engineers have a responsibility to protect society.	1	2	3	4	5
E7 - The best teams have people who think and feel the same way.	4	3	2	1	5

3. INDEPENDENT VARIABLES ON INSTRUMENT

3.1 Participant Variables

Engineering discipline: What department are you in or intending to go into?

a. Aerospace
b. Chemical
c. Civil
d. Electrical
e. Environmental
f. Industrial
g. Material
h. Mechanical
i. Mining Resources
j. Other
k. Not Declared

Gender: Indicate your gender.

a. Male b. Female c. I prefer not to answer.

Identifies as a racial minority: Do you identify yourself as part of a racial minority?

a. Yes b. No c. I prefer not to answer.

Age: Indicate your age.

a. 17 or under
b. 18 - 21
c. 22 - 25
d. 26 – 29
e. 30 or over
f. I prefer not to answer

Year in studies: What year are you in your studies at university?

a. 1^{st} b. 2^{nd} c. 3^{rd} d. 4^{th} e. 5^{th} or higher

Time travelled internationally: How much time have you spent travelling outside of Canada or the US during your lifetime?

a. None
b. Up to 1 month
c. 2 – 6 months
d. 7-12 months
e. More than 1 year
f. International Student

3.2 Project Variables

Source of project: For the design project you just completed, there was:

a. A client from industry or a private company.
b. A client from a non-profit organization or the community.
c. No external client or the instructor acted as the client.

Maturity of the product: What was the final product for this project? Select only one.

a. Paper design only, nothing was built
b. Non or partially functioning prototype or proof of concept was built
c. Functioning prototype was built
d. Fully functioning, delivered product was built
e. Don't know

Whether the course was mandatory: Was this a required course for your degree?

a. Yes b. No

Project length: How many weeks did you spend on this project?

1-3 4-6 7-9 10-12 13-15 16-18 19-21 22-24 25+

Amount of time spent with the professor: How many hours did you spend with the faculty member advising you on this project, outside of class?

1-3 4-6 7-9 10-12 13-15 16-18 19-21 22-24 25+

Amount of time spent with the client: If you had a client, how many hours did you spend with your client during this project (include any in-class meetings)? Select 0 if no client.

1-3 4-6 7-9 10-12 13-15 16-18 19-21 22-24 25+

Rate project length, time with professor, time with client:

	More time needed		About right		Less time needed	
Rate the length of this project.	1	2	3	4	5	-
Rate the amount of involvement of the faculty member who advised you on this project.	1	2	3	4	5	-
If you had a client, rate the amount of involvement of your client on this project. If you did not have a client, skip this question.	1	2	3	4	5	N/A

4. NORMALITY RESULTS

Tables A-1, A-2, and A-3 contain descriptive information organized by dependent variables, independent variables, and items, respectively. Variables and items that meet normality requirements are marked with '*'.

Table A-1: Descriptive statistics of dependent variables

	Dependent variable	*n*	*Mean*	*σ*	*Range*	*Skewness*	*Kurtosis*
Constructs	Design ability (DA)*	19	1.88	0.45	[1.12, 3.07]	0.84 (0.52)	1.66 (1.01)
	DA define*	19	2.16	0.36	[1.63, 2.86]	0.21 (0.5)	-0.95 (0.97)
	DA evaluate*	19	1.76	0.50	[1, 3]	0.66 (0.52)	0.68 (1.01)
	DA communicate	19	1.98	0.43	[1.46, 3.08]	1.35 (0.52)	1.38 (1.01)
	Ethics*	19	1.99	0.32	[1.4, 2.67]	0.19 (0.51)	-0.35 (0.99)
Factors	F1*	19	1.87	0.36	[1.27, 2.82]	0.58 (0.52)	1.17 (1.01)
	F2*	19	1.91	0.45	[1.21, 2.85]	0.61 (0.52)	0.06 (1.01)
	F3	19	2.02	0.45	[1.5, 3.25]	1.29 (0.52)	1.6 (1.01)
	F4*	19	2.12	0.48	[1.11, 2.78]	-0.31 (0.52)	-0.55 (1.01)
	F5*	19	2.31	0.44	[1.44, 3.11]	-0.4 (0.52)	-0.48 (1.01)

* Signifies an item that meets normality requirements

Table A-2: Descriptive statistics of independent variables

	Independent variable	*n*	*Mean*	*σ*	*Range*	*Skewness*	*Kurtosis*
Participant	VS1.Travel*	19	2.58	1.68	[1, 6]	0.91 (0.52)	-0.08 (1.01)
	VS2.Discipline	19	6.79	2.30	[2, 9]	-1.21 (0.52)	-0.17 (1.01)
	VS4.Age	19	2.42	0.77	[2, 4]	1.53 (0.52)	0.72 (1.01)
	VS5.Minority	16	1.94	0.25	[1, 2]	-4 (0.56)	16 (1.09)
	VS6.Gender	19	1.84	0.38	[1, 2]	-2.04 (0.52)	2.41 (1.01)
Project	VP4.LengthProj*	19	2.21	0.86	[1, 3]	-0.45 (0.52)	-1.51 (1.01)
	VP5.InvolvFaculty*	19	2.53	0.91	[1, 4]	-0.34 (0.52)	-0.5 (1.01)
	VP7.NumWeeks*	19	2.58	0.84	[1, 4]	0.36 (0.52)	-0.48 (1.01)
	VP8.NumHrsProf	19	1.84	2.12	[1, 9]	2.83 (0.52)	7.8 (1.01)

* Signifies an item that meets normality requirements

Table A-3: Descriptive statistics of items

	Items	*n*	*Mean*	*σ*	*Range*	*Skewness*	*Kurtosis*
Define items	DD1.FirstTask*	19	2.68	0.89	[2, 4]	0.71 (0.52)	-1.37 (1.01)
	DD2.Comp	19	1.53	1.02	[1, 4]	1.85 (0.52)	2.21 (1.01)
	DD3.Req*	19	3.21	0.79	[2, 4]	-0.41 (0.52)	-1.21 (1.01)
	DD5.Research	18	1.44	0.62	[1, 3]	1.09 (0.54)	0.39 (1.04)
	DD7.ReqMeas*	19	2.42	1.17	[1, 5]	0.68 (0.52)	-0.27 (1.01)
	DD22.ClientSpec	19	2.58	1.35	[1, 5]	1.19 (0.52)	0 (1.01)
	DD23.Tasks	19	1.74	0.45	[1, 2]	-1.17 (0.52)	-0.72 (1.01)
	DD25.DesignProcess*	19	1.58	0.61	[1, 3]	0.5 (0.52)	-0.5 (1.01)
Evaluate items	DE8.Cheapest*	18	1.83	0.51	[1, 3]	-0.32 (0.54)	0.92 (1.04)
	DE13.DecisionMatrix*	15	2.27	0.80	[1, 4]	0.42 (0.58)	0.38 (1.12)
	DE14.Disadvantages	19	1.21	0.42	[1, 2]	1.55 (0.52)	0.42 (1.01)
	DE17.Compare	19	1.84	0.90	[1, 5]	2.39 (0.52)	8.64 (1.01)
Communicate items	DC4.Pres	19	1.21	0.71	[1, 4]	3.77 (0.52)	14.7 (1.01)
	DC6.OnePerson*	19	1.32	0.48	[1, 2]	0.86 (0.52)	-1.42 (1.01)
	DC9.Rehearse	19	1.68	0.95	[1, 5]	2.48 (0.52)	8.35 (1.01)
	DC10.Sections	19	1.79	1.23	[1, 5]	2.06 (0.52)	3.8 (1.01)
	DC11.Team*	19	2.37	0.96	[1, 4]	0.42 (0.52)	-0.54 (1.01)
	DC12.Tables	19	1.95	0.85	[1, 5]	2.55 (0.52)	9.94 (1.01)
	DC15.Slides	18	1.50	0.86	[1, 4]	1.89 (0.54)	3.38 (1.04)
	DC18.Um*	15	2.13	0.74	[1, 3]	-0.23 (0.58)	-0.97 (1.12)
	DC19.Doc	19	2.16	0.90	[1, 5]	1.72 (0.52)	5.03 (1.01)
	DC20.ShareIdea	19	1.79	1.08	[1, 5]	1.93 (0.52)	3.93 (1.01)
	DC21.ReportErr*	16	3.06	0.68	[2, 4]	-0.07 (0.56)	-0.49 (1.09)
	DC24.IdeasIncorp*	19	1.68	0.67	[1, 3]	0.47 (0.52)	-0.57 (1.01)
	DC26.OralPres	19	2.47	0.84	[1, 5]	1.34 (0.52)	3.63 (1.01)
	DC27.Explain	19	2.42	1.26	[1, 5]	1.31 (0.52)	0.89 (1.01)
Ethical awareness items	E1.MostImp*	19	1.32	0.48	[1, 2]	0.86 (0.52)	-1.42 (1.01)
	E2.Graduate*	19	1.32	0.48	[1, 2]	0.86 (0.52)	-1.42 (1.01)
	E3.BestTeams*	19	3.68	1.20	[2, 5]	-0.17 (0.52)	-1.57 (1.01)
	E4.MenWomen	14	1.43	0.65	[1, 3]	1.3 (0.6)	0.95 (1.15)
	E5.Isolate	18	1.22	0.55	[1, 3]	2.57 (0.54)	6.36 (1.04)
	E6.Resp	19	1.26	0.45	[1, 2]	1.17 (0.52)	-0.72 (1.01)
	E7.ThinkSame*	19	1.63	0.60	[1, 3]	0.31 (0.52)	-0.55 (1.01)
	E8.Engaged	19	1.84	0.96	[1, 5]	2.04 (0.52)	6.07 (1.01)
	E9.Meaningful*	19	3.11	1.41	[1, 5]	-0.07 (0.52)	-1.24 (1.01)
	E10.Hired*	19	2.95	1.03	[1, 5]	-0.23 (0.52)	0.2 (1.01)

* Signifies an item that meets normality requirements

APPENDIX B: STUDY 2 INSTRUMENT & RESULTS

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1. QUANTITATIVE ITEMS ON INSTRUMENT

The following sections contain the quantitative items from study 2 divided into instrument parts 1 and 2, subdivided by subconstruct: *understand the problem, ideate,* and *build & test.* The items below assess design ability (DA) from high (1) to low (4).

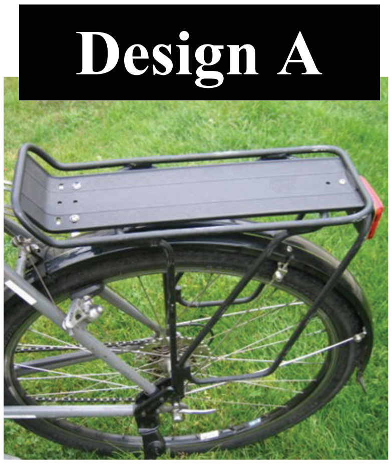
1.1 Part 1 Quantitative Items

1.1.1 Understand the Problem

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know
A client asks you to build a permanent stream crossing on their property for logging.					
Research: *Research must be gathered on the following items*					
a. Duck migration patterns	Poor	2	3	4	5
b. Provincial water crossing regulations	Great	2	3	4	5
c. Height of trucks used	Poor	2	3	4	5
d. Environmental impact of deforestation	Poor	2	3	4	5
e. Permits required	Great	2	3	4	5
f. Required safety factors	Great	2	3	4	5
g. Weight of trees	Great	2	3	4	5
h. Logging restrictions	Great	2	3	4	5
Gather data: *On the initial site visit, the following must be measured*					
a. Bank height	Great	2	3	4	5
b. Average rainfall	Poor	2	3	4	5
c. Soil density	Great	2	3	4	5
d. Slope	Great	2	3	4	5
e. Distance across the crossing	Great	2	3	4	5
f. Water depth	Great	2	3	4	5
g. Water temperature	Poor	2	3	4	5
h. Height of trees	Poor	2	3	4	5
Define requirements: *Appropriate specifications or requirements for the bridge are:*					
a. The bridge shall support a tractor towing 10 logs	Great	2	3	4	5
b. The bridge shall be strong enough to hold 20kN.	Great	2	3	4	5
c. The bridge shall have a maximum deflection of 30mm.	Great	2	3	4	5
d. The bridge shall not touch the water.	Great	2	3	4	5
e. The bridge shall be safe during all seasons.	Great	2	3	4	5
f. The bridge shall be 4m wide.	Poor	2	3	4	5
g. The bridge shall withstand -20 degrees C to 40 degrees C without deformation.	Great	2	3	4	5
h. The bridge shall have a factor of safety of at least 2.	Great	2	3	4	5

1.1.2 Ideate

Assume a client wants an inexpensive way to carry his laptop, groceries, and sports equipment to and from work on his bicycle. There are 3 prospective designs, A, B, and C.



Synthesize components: *When developing ideas, the carrier should be:*
(1) a. Broken up by function: attachment device and holding device
(2) b. Broken up by sections: rack and support arms
(3) c. Broken up by components: screws, support arms, holding beams, holding cross-beams, rim
(4) d. Treated as one unit.
(5) e. Don't know.

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know
Conceptualize alternatives: *When evaluating designs:*					
a. If Design A is selected, steel is the best choice for this design.	Great	2	3	4	5
b. If Design B is selected, it should be constructed with plastic because that will make it light.	Poor	2	3	4	5
c. Design C is the most versatile design.	Poor	2	3	4	5
d. The cheapest design should be selected.	Poor	2	3	4	5
e. For Design B, a lid would help keep the items in the basket.	Great	2	3	4	5
f. For Design B, a lid would restrict what can be placed inside.	Great	2	3	4	5
g. It is not possible to design a lid for Design B that allows items of varying sizes and shapes.	Poor	2	3	4	5

1.1.3 Build & Test

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know
Verification: *The following actions are necessary to ensure the user need is met.*					
a. Perform an analysis of the maximum weight the device can hold.	Great	2	3	4	5
b. Attach the device to 3 different bike models.	Poor	2	3	4	5
c. While the device is not attached to a bike, put items in the device until it breaks. Then measure size and weight of items.	Poor	2	3	4	5
d. While the device is attached to a bike, put different types of sports equipment in the device and ride the bike.	Great	2	3	4	5
e. Not enough information is provided to accurately test the device.	Great	2	3	4	5
Prototype: *For a general design project:*					
a. A site visit is always necessary.	Poor	2	3	4	5
b. Sketches and drawings convey the same information.	Poor	2	3	4	5
c. Dimensions are not required on drawings.	Poor	2	3	4	5
d. A prototype can be built using a different material than the device will be made of.	Great	2	3	4	5
e. Analysis is one method to verify the design meets requirements.	Great	2	3	4	5
f. The purpose of testing is to ensure the device doesn't break.	Poor	2	3	4	5

1.2 Part 2 Quantitative Items

1.2.1 Understand the Problem

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know
Consider you were asked to design an office chair for a person over 6ft tall.					
First Steps: *You just finished the first meeting with the client, which lasted 15 minutes. The following steps should be taken before you begin to brainstorm ideas*					
a. Find out more about chair design	Great	2	3	4	5
b. Write requirements	Great	2	3	4	5
c. Sketch the idea	Poor	2	3	4	5
d. Build a prototype	Poor	2	3	4	5
e. Talk to people over 6 feet tall	Great	2	3	4	5
f. Measure the height of a normal desk	Great	2	3	4	5
g. Research average weights of people over 6 feet tall	Great	2	3	4	5
h. None of the above. Start with a clear mind	Poor	2	3	4	5

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know
Define requirements: *The following are appropriate requirements.*					
a. The chair seat shall be 2 ft +/- 3 inches from the floor.	Great	2	3	4	5
b. The chair seat shall fit a 6 ft tall person.	Great	2	3	4	5
c. The chair height shall be adjustable.	Great	2	3	4	5
d. The chair shall be tested before delivery.	Poor	2	3	4	5
e. The chair shall withstand up to 350lb without deformation.	Great	2	3	4	5
f. The chair shall not tip.	Great	2	3	4	5
g. The chair shall be comfortable.	Poor	2	3	4	5
h. The chair shall have arms.	Great	2	3	4	5

1.2.2 Ideate

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know

Conceptualize alternatives: *Consider you have a client who lives on a remote island where wood is scarce and supplies arrive by plane. Her daughter loves dogs and princesses. She wants a doghouse for her german shepherd for the backyard. There are 3 prospective designs, A, B, and C. State how strongly you agree or disagree with each statement for this situation:*

Design A

Design B

Design C

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know
a. Design A is a poor selection because the client doesn't want wood.	Poor	2	3	4	5
b. Design A should be selected because the daughter's taste is important to the client.	Great	2	3	4	5
c. Design B should be selected because it can be moved easily.	Poor	2	3	4	5
d. Design C provides the most strength so it should be selected.	Poor	2	3	4	5
e. There is not enough information given to determine whether a door is necessary.	Great	2	3	4	5
f. None of the designs are ideal.	Great	2	3	4	5
g. A site visit is necessary.	Poor	2	3	4	5

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know
Consider you were asked to design an office chair for a person over 6ft tall.					
Synthesize Components: *When developing ideas, the chair should be:*					
a. Treated as one unit.	Poor	2	3	4	5
b. Broken up by sections: base, armrest, and seat.	Great	2	3	4	5
c. Broken up by components: wheels, stem, seat, backrest, armrest, screws, bolts, and springs.	Poor	2	3	4	5
d. Broken up by function: height adjustment, mobility, back support, and arm support.	Great	2	3	4	5

1.2.3 Build & Test

	Strongly agree	Agree	Disagree	Strongly disagree	Don't know
Consider you were asked to design an office chair for a person over 6ft tall.					
Build Chair: *Once the design is complete,*					
a. In order to ensure the user need has been met, a person over 6 ft tall must sit in the chair to check comfort level.	Great	2	3	4	5
b. No other tasks must be performed to prove the design meets the user need.	Poor	2	3	4	5
c. After the chair is build, there can be no changes made to the design.	Poor	2	3	4	5
Prototype: *For a general design project.*					
a. A prototype is always required.	Great	2	3	4	5
b. Assuming requirements accurately reflect the client need, the purpose of a test is solely to ensure requirements are met.	Great	2	3	4	5
c. Every requirement can be tested.	Poor	2	3	4	5
Drawing: *The following items must be included on every drawing for a general design project: State how strongly you agree or disagree with each.*					
a. Title block	Great	2	3	4	5
b. Units	Great	2	3	4	5
c. Notes	Poor	2	3	4	5
d. Detailed view of a section	Poor	2	3	4	5
e. Dimensions	Great	2	3	4	5
f. Author	Great	2	3	4	5
g. Isometric view	Poor	2	3	4	5

2. QUALITATIVE ITEMS ON INSTRUMENT

The following sections contain the qualitative items from study 2 divided into parts 1 and 2, subdivided by subconstruct: *understand the problem, ideate,* and *build & test.*

2.1 Part 0 Qualitative Items

These items are included in part 1 for the 2-part instrument.

	Design Ability			***Ethical***		
	Under -stand	***Ideate***	***Build & test***	***aware- ness***	***SL***	***Non- SL***
For the purposes of this survey, assume you are a Professional Engineer with your own business.						
1. A client asks you to build a deck for them. Use the space provided to list the questions you would ask your client.	X					X
2. List the steps you would take to provide your client a deck.		X				X
3. A client who uses an electric wheelchair for mobility asks you to design a desk for them. What are the questions you would ask?	X				X	
4. Consider that you are designing a playground for a school. The drawings are due tomorrow and there is no room in the schedule to slip. Unless you stay on schedule, the playground will not be completed in time for school to start. A second project you are working on is a new addition to the mall. The drawings are also due tomorrow and you have no room in the schedule to slip. Unless you stay on schedule, the mall addition will not be completed on time. You only have time to complete one set of drawings and your boss is insisting you have to set your own priorities. Which do you work on first? Please explain why you chose this.				X		

2.2 Part 1 Qualitative Items

	Design ability			***Ethical awareness***	***SL***	***Non-SL***
	Under-stand	***Ideate***	***Build & test***			
1. For the purposes of this survey, assume you are a Professional Engineer with your own business. A client asks you to design something to hold jewelry that will keep the necklaces from knotting when travelling. Sketch a design to meet the client need. If more information is needed, state any assumptions or hypothetical answers you ‘received’ from the client.		X				X
2. Assume a client asks you to build a permanent stream crossing on their property for logging. What environmental and ethical considerations could there be for this project?				X		

2.3 Part 2 Qualitative Items

	Design ability			***Ethical awareness***	***SL***	***Non-SL***
	Under-stand	***Ideate***	***Build & test***			
For the purposes of this survey, assume you are a Professional Engineer with your own business.						
1. A client asks you to build a bridge for a stream crossing on their property. What questions do you ask?	X					X
2. List the steps you would take to provide your client a stream crossing.		X				X
3. Company ABC is known to cut corners, but nothing has been proven. They are asking you to design a device for them to detect shoplifters. An analysis is due tomorrow and there can be no delays in the schedule. You are also working on Corp XYZ to add a pedway over a street for the city. An analysis is due tomorrow and there can be no delays in the schedule. Both analyses cannot be thoroughly completed in time. Your boss is insisting that you manage your own work and set your own priorities. Which do you work on first? Please explain why you chose this.				X		

3. INDEPENDENT VARIABLES ON INSTRUMENT

The following sections contain the items from study 2 that comprise the independent variables and are divided into participant and project independent variables.

3.1 Participant Variables

Engineering discipline: What department are you in or intending to go into?

a. Aerospace
b. Chemical
c. Civil
d. Electrical
e. Environmental
f. Industrial
g. Material
h. Mechanical
i. Mining resources
j. Other
k. Not Declared

Gender: Indicate your gender.

a. Male b. Female c. I prefer not to answer.

Identifies as a racial minority: Do you identify yourself as part of a racial minority?

a. Yes b. No c. I prefer not to answer.

Age: Indicate your age.

a. 17 or under
b. 18 - 21
c. 22 - 25
d. 26 – 29
e. 30 or over
f. I prefer not to answer

Year in studies: What year are you in your studies at university?

a. 1st b. 2nd c. 3rd d. 4th e. 5th or higher

Time travelled internationally: How much time have you spent travelling outside of Canada or the US during your lifetime?

a. None
b. Up to 1 month
c. 2 – 6 months
d. 7-12 months
e. More than 1 year
f. International Student

Logbook score, design report score, and overall score. Recoded as follows:

Recoded	Score
1	88-100
2	75-87
3	63-74
4	50-62
5	<50

Course: [Recorded by survey software] Which course is the participant enrolled in?

a. Dal 2nd b. UPEI 1st c. UPEI 2nd d. High School

3.2 Project Variables

Source of project: For the design project you just completed, there was:

a. A client from industry or a private company.
b. A client from a non-profit organization or the community.
c. No external client or the instructor acted as the client.

Maturity of the product: What was the final product for this project? Select only one.

a. Paper design only, nothing was built
b. Non or partially functioning prototype or proof of concept was built
c. Functioning prototype was built
d. Fully functioning, delivered product was built
e. Don't know

Whether the course was mandatory: Was this a required course for your degree?

a. Yes   b. No

Project length: How many weeks did you spend on this project?

1-3   4-6   7-9   10-12   13-15   16-18   19-21   22-24   25+

Amount of time spent with the professor: How many hours did you spend with the faculty member advising you on this project, outside of class?

1-3   4-6   7-9   10-12   13-15   16-18   19-21   22-24   25+

Amount of time spent with the client: If you had a client, how many hours did you spend with your client during this project (include any in-class meetings)? Select 0 if no client.

1-3   4-6   7-9   10-12   13-15   16-18   19-21   22-24   25+

Rate project length, time with professor, time with client:

	More time needed		About right		Less time needed	
Rate the length of this project.	1	2	3	4	5	-
Rate the amount of involvement of the faculty member who advised you on this project.	1	2	3	4	5	-
If you had a client, rate the amount of involvement of your client on this project. If you did not have a client, skip this question.	1	2	3	4	5	N/A

4. PROJECT VARIABLE DATA FOR 3-PART INSTRUMENT

This section contains the results for the subset of participants that received the 3-part instrument. Figure B-1 contains the project results for the 3-week project.

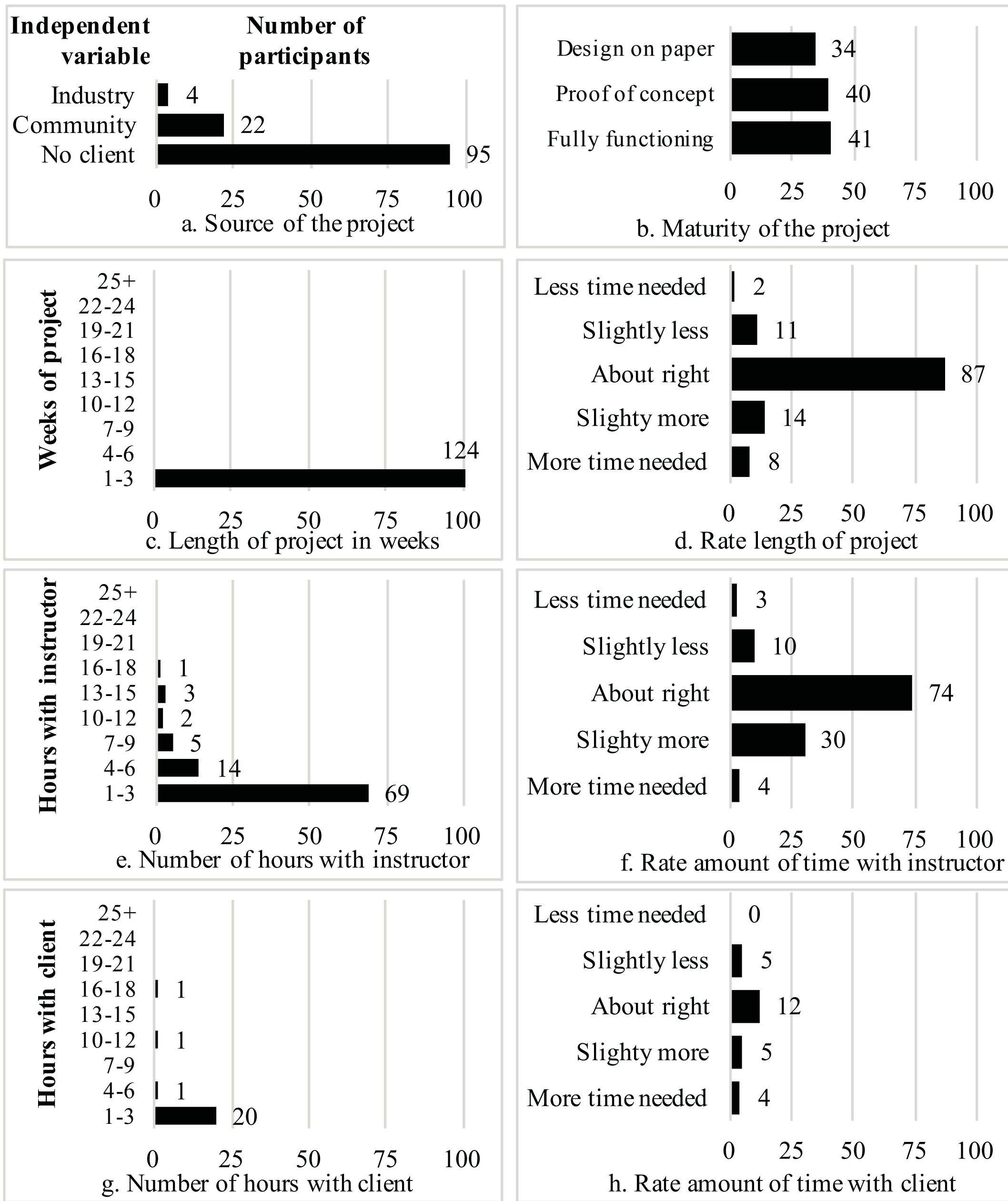
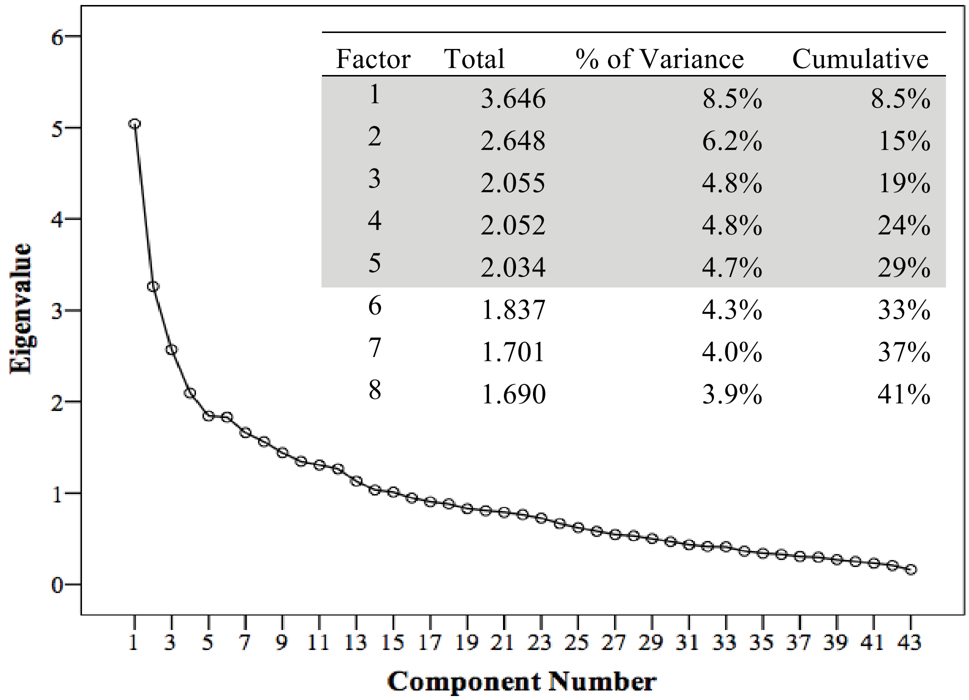


Figure B-1: Project data for first project for Dalhousie students

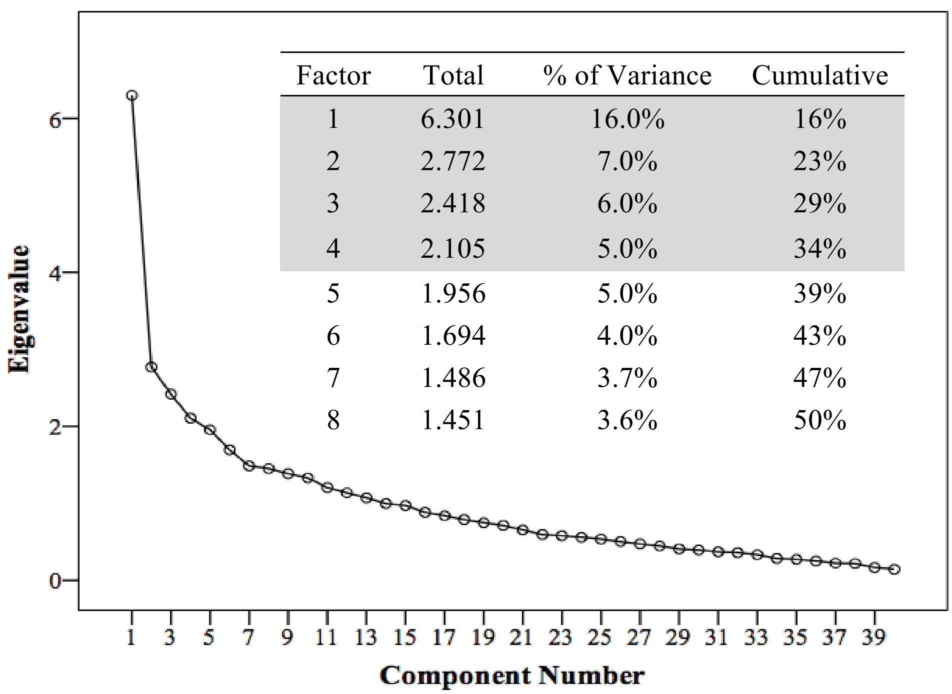
5. FACTORIAL ANALYSIS RESULTS

This section contains the detailed data and results for the factorial analysis. Figures B-2 and B-3 contain the part 1 and part 2 scree plots, respectively.



Factor	Total	% of Variance	Cumulative
1	3.646	8.5%	8.5%
2	2.648	6.2%	15%
3	2.055	4.8%	19%
4	2.052	4.8%	24%
5	2.034	4.7%	29%
6	1.837	4.3%	33%
7	1.701	4.0%	37%
8	1.690	3.9%	41%

Figure B-2: Scree plot and variance data for part 1



Factor	Total	% of Variance	Cumulative
1	6.301	16.0%	16%
2	2.772	7.0%	23%
3	2.418	6.0%	29%
4	2.105	5.0%	34%
5	1.956	5.0%	39%
6	1.694	4.0%	43%
7	1.486	3.7%	47%
8	1.451	3.6%	50%

Figure B-3: Scree plot and variance data for part 2

6. DEPENDENT VARIABLES COMPOSITION

The items for each dependent variable in Table B-1 are denoted using ‘x’. The ‘+’ sign signifies an item that was in the factor, but was removed to increase the reliability.

Table B-1: Items in dependent variables

		Part 1									Part 2								Total			
		Part 1 DA	*Understand*	*Ideate*	*Build & test*	*Factor 1a*	*Factor 1b*	*Factor 1c*	*Factor 1d*	*Factor 1e*	*Part 2 DA*	*Understand*	*Ideate*	*Build & test*	*Factor 2a*	*Factor 2b*	*Factor 2c*	*Factor 2d*	*Total DA*	*Understand*	*Ideate*	*Build & test*
	n items	23	16	4	6	13	8	12	9	7	30	12	8	9	13	7	12	9	75	32	13	16
Part 1 - *Understand the problem*																						
Research	a.								x										x	x		
	b.	x	x			x													x	x		
	c.							+											x	x		
	d.								x	x									x			
	e.	x	x			x													x	x		
	f.	x	x			x													x	x		
	g.	x	x					x											x	x		
	h.	x	x			x				+									x	x		
Gather data	a.	x	x			x													x	x		
	b.					+																
	c.	x	x			x													x	x		
	d.	x	x			x													x	x		
	e.	x	x			x													x	x		
	f.	x	x			x													x	x		
	g.								x										x			
	h.						+		x										x			
Define requirements 1	a.	x	x					+	+										x	x		
	b.		x				x												x	x		
	c.	x	x				x												x	x		
	d.									+									x	x		
	e.		x							x										x		
	f.						+															
	g.	x	x				x												x	x		
	h.	x	x				x												x	x		
Part 1 - *Ideate*																						
Synthesize comp	1			x						x									x		x	
Conceptualize alternatives 1	a.	x					x		+										x			
	b.			x				x											x		x	
	c.	x						x											x		x	
	d.	x		x				x											x		x	
	e.																		x			
	f.								x										x		x	
	g.			x					x										x			
Part 1 - *Build & test*																						
Verification	a.	x				x													x			x
	b.				x	x		x											x			
	c.	x			x			x											x			
	d.																		x			x
	e.						+		+													

Table B-1: Items in dependent variables (cont)

		Part 1									**Part 2**								**Total**			
		Part 1 DA	*Understand*	*Ideate*	*Build & test*	*Factor 1a*	*Factor 1b*	*Factor 1c*	*Factor 1d*	*Factor 1e*	*Part 2 DA*	*Understand*	*Ideate*	*Build & test*	*Factor 2a*	*Factor 2b*	*Factor 2c*	*Factor 2d*	*Total DA*	*Understand*	*Ideate*	*Build & test*
Part 1 -*Build&test*	a.				x			x														
Prototype 1	b.	x			x			x											x			x
	c.	x			x	x		x											x			x
	d.									x									x			x
	e.	x																	x			x
	f.	x			x			x		x									x			x
Part 2 - *Understand the problem*																						
First steps	a.										x	x					x		x	x		
	b.										x	x					x		x	x		
	c.										x							x	x			
	d.										x							x	x			
	e.										x	x					x	x	x	x		
	f.										x	x					x	+	x	x		
	g.										x	x			x		x		x	x		
	h.										x	x							x	x		
Define requirements 2	a.										x	x				x			x	x		
	b.										x	x				+			x	x		
	c.										x	x				+			x	x		
	d.										x					x			x			
	e.										x	x			x				x	x		
	f.											x				+				x		
	g.										x					x			x			
	h.										x	x							x	x		
Part 2 - *Ideate*	a.										x		x					x	x		x	
Conceptualize alternatives 2	b.										x		x						x		x	
	c.										x		x						x		x	
	d.										x		x					x	x		x	
	e.												x								x	
	f.										x		x				x		x		x	
	g.																+					
Synthesize components 2	a.										x		x				x	x	x	x		
	b.										x						x		x		x	
	c.										x						+		x			
	d.										x		x				x		x		x	
Part 2 - *Build & test*																						
Build chair	a.										x			x			x		x			x
	b.										x			x	x			x	x			x
	c.										x			x	x				x			x
Prototype 2	a.										x			x	x				x			x
	b.										x			x				+	x			x
	c.										x				+				x			
Drawing	a.										x			x	x				x			x
	b.										x			x	x				x			x
	c.										x				+				x			
	d.										x				+	x			x			
	e.										x			x	x				x			x
	f.										x			x	x				x			x
	g.										x				+				x			

7. DESCRIPTIVE STATISTICS FOR VARIABLES AND ITEMS

Tables B-2 through B-5 contain descriptive information of the dependent variables, independent variables, and items, respectively. Items that meet normality requirements are marked with '*' and dependent variables that meet reliability are marked with '+'.

Table B-2: Descriptive information of dependent variables

	Dependent variable	*n*	*Mean*	σ	*Range*	*Skewness*	*Kurtosis*
Total constructs	Total design ability *+	211	2.03	0.15	[1.6, 2.5]	0.19 (0.17)	0.2 (0.33)
	Subtotal und. the prob. +	210	1.74	0.24	[1.1, 2.7]	0.6 (0.17)	0.94 (0.33)
	Subtotal ideate	211	2.2	0.35	[1, 3.4]	0.15 (0.17)	1.05 (0.33)
	Subtotal build & test *+	208	1.81	0.32	[1, 2.9]	-0.22 (0.17)	0.17 (0.34)
Difference constructs	Design ability	150	0.29	0.33	[-0.3, 1.2]	0.4 (0.2)	-0.33 (0.39)
	Understand the problem *	142	0.2	0.49	[-1, 1.5]	0.28 (0.2)	-0.01 (0.4)
	Ideate	137	-0.82	0.59	[-2.4, 0.7]	-0.44 (0.21)	0.49 (0.41)
	Build & test *	150	0.2	0.27	[-0.5, 0.9]	0.06 (0.2)	0.13 (0.39)
Part 1 constructs	Design ability +	190	1.69	0.27	[1.1, 2.6]	0.38 (0.18)	0.48 (0.35)
	Understand the problem +	189	1.49	0.31	[1, 2.8]	0.93 (0.18)	1.28 (0.35)
	Ideate	181	2.02	0.37	[1, 3]	-0.31 (0.18)	0.72 (0.36)
	Build & test	178	2.54	0.44	[1.5, 4]	0.57 (0.18)	1.26 (0.36)
Part 1 factors	Factor 1a +	190	1.55	0.29	[1, 2.4]	0.58 (0.18)	-0.22 (0.35)
	Factor 1b	187	1.75	0.52	[1, 3.4]	0.57 (0.18)	-0.1 (0.35)
	Factor 1c	189	2.39	0.43	[1, 3.6]	-0.48 (0.18)	1.96 (0.35)
	Factor 1d *	190	2.56	0.45	[1.5, 3.7]	0.11 (0.18)	-0.38 (0.35)
	Factor 1e *	190	2.27	0.46	[1, 4]	0.14 (0.18)	0.49 (0.35)
Part 2 constructs	Design ability *+	171	1.87	0.23	[1.3, 2.4]	-0.07 (0.19)	-0.33 (0.37)
	Understand the prob. *+	171	1.77	0.32	[1, 2.8]	0.33 (0.19)	0.32 (0.37)
	Ideate *	171	2.2	0.35	[1.2, 3.1]	0.08 (0.19)	-0.08 (0.37)
	Build & test +	167	1.68	0.35	[1, 2.6]	0.01 (0.19)	-0.76 (0.37)
Part 2 factors	Factor 2a +	171	1.65	0.38	[1, 2.7]	0.08 (0.19)	-0.87 (0.37)
	Factor 2b +	171	2.87	0.56	[1, 4]	-0.78 (0.19)	0.76 (0.37)
	Factor 2c *	171	1.86	0.34	[1, 2.6]	-0.14 (0.19)	-0.43 (0.37)
	Factor 2d *	171	2.17	0.39	[1, 3.3]	-0.09 (0.19)	0.01 (0.37)

Table B-3: Descriptive information of independent variables

	Independent variables	*n*	*Mean*	σ	*Range*	*Skewness*	*Kurtosis*
Participant variables	Course	240	2.68	0.47	[2, 3]	-0.79 (0.16)	-1.38 (0.31)
	Discipline	230	5.9	2.91	[1, 11]	0.27 (0.16)	-1.18 (0.32)
	Year	233	2.33	1.22	[1, 6]	2.18 (0.16)	4 (0.32)
	Age	233	2.2	0.76	[1, 6]	2 (0.16)	6.68 (0.32)
	Gender	233	1.3	0.47	[1, 3]	1 (0.16)	-0.66 (0.32)
	Minority	233	1.94	0.43	[1, 3]	-0.33 (0.16)	2.41 (0.32)
	Travel	232	3.18	1.72	[1, 6]	0.47 (0.16)	-1.08 (0.32)
	Logbook score	212	2.83	1.35	[1, 5]	0.16 (0.17)	-1.18 (0.33)
	Report score	212	2.18	0.97	[1, 5]	0.78 (0.17)	0.46 (0.33)
	Overall report score	213	2.27	0.7	[1, 5]	0.64 (0.17)	1.49 (0.33)
Main project variables	Source of client	171	2.43	0.6	[1, 3]	-0.53 (0.19)	-0.61 (0.37)
	Final product	167	2.48	0.5	[2, 3]	0.09 (0.19)	-2.02 (0.37)
	Length	171	2.38	1.52	[1, 7]	2.62 (0.19)	5.44 (0.37)
	Rate length *	170	2.39	0.87	[1, 5]	-0.16 (0.19)	-0.27 (0.37)
	Prof	171	2.86	3.04	[1, 11]	1.61 (0.19)	1.08 (0.37)
	Rate prof	170	2.76	0.9	[1, 6]	0.6 (0.19)	2.32 (0.37)
	Rate client	171	4.12	1.95	[1, 6]	-0.24 (0.19)	-1.66 (0.37)
	Time with client	171	5.9	4.39	[1, 10]	-0.15 (0.19)	-1.97 (0.37)
3-week project variables	Source of client 0	121	3.57	1.2	[1, 5]	-0.23 (0.22)	-1.1 (0.44)
	Final product 0	119	2.13	0.87	[1, 4]	0.07 (0.22)	-1.08 (0.44)
	Length 0	124	2.93	0.82	[1, 6]	0.32 (0.22)	3.6 (0.43)
	Rate length 0	124	2.9	0.87	[1, 6]	1.03 (0.22)	3.16 (0.43)
	Prof 0	114	5.25	1.47	[1, 6]	-1.67 (0.23)	1.35 (0.45)
	Rate prof 0 *	124	1	0	[1, 1]	0 (0.22)	0 (0.43)
	Rate client 0	124	3.56	3.77	[1, 10]	1.06 (0.22)	-0.75 (0.43)
	Time with client 0	124	8.4	3.4	[1, 10]	-1.7 (0.22)	0.95 (0.43)

Table B-4: Descriptive information of Part 1 items

	Part 1 items	*n*	*Mean*	σ	*Range*	*Skewness*	*Kurtosis*
Understand the problem	Research a.*	174	2.76	0.8	[1, 4]	-0.36 (0.18)	-0.2 (0.37)
	Research b.	188	1.23	0.49	[1, 4]	2.57 (0.18)	9.02 (0.35)
	Research c.	175	3.06	0.85	[1, 4]	-0.41 (0.18)	-0.81 (0.37)
	Research d.	185	3.17	0.87	[1, 4]	-0.69 (0.18)	-0.47 (0.36)
	Research e.	187	1.16	0.41	[1, 3]	2.55 (0.18)	6.11 (0.35)
	Research f.	187	1.16	0.37	[1, 2]	1.87 (0.18)	1.5 (0.35)
	Research g.	184	1.72	0.78	[1, 4]	1.02 (0.18)	0.85 (0.36)
	Research h.	185	1.65	0.78	[1, 4]	0.97 (0.18)	0.22 (0.36)
	Gather data a.	185	1.39	0.58	[1, 4]	1.51 (0.18)	3 (0.36)
	Gather data b.	183	3.23	0.8	[1, 4]	-0.71 (0.18)	-0.27 (0.36)
	Gather data c.	187	1.52	0.6	[1, 3]	0.69 (0.18)	-0.48 (0.35)
	Gather data d.	185	1.43	0.54	[1, 3]	0.72 (0.18)	-0.65 (0.36)
	Gather data e.	185	1.24	0.44	[1, 3]	1.43 (0.18)	0.6 (0.36)
	Gather data f.	182	1.61	0.72	[1, 4]	1.01 (0.18)	0.65 (0.36)
	Gather data g.*	178	2.54	0.86	[1, 4]	0.07 (0.18)	-0.66 (0.36)
	Gather data h.	178	2.69	0.88	[1, 4]	-0.05 (0.18)	-0.79 (0.36)
	Define requirements 1 a.	168	2.07	0.97	[1, 4]	0.47 (0.19)	-0.83 (0.37)
	Define requirements 1 b.	160	1.76	0.89	[1, 4]	0.99 (0.19)	0.13 (0.38)
	Define requirements 1 c.	152	1.8	0.77	[1, 4]	0.81 (0.2)	0.48 (0.39)
	Define requirements 1 d.	174	1.84	0.94	[1, 4]	0.8 (0.18)	-0.43 (0.37)
	Define requirements 1 e.	181	1.29	0.6	[1, 4]	2.27 (0.18)	5.12 (0.36)
	Define requirements 1 f.*	163	3.03	0.78	[1, 4]	-0.37 (0.19)	-0.48 (0.38)
	Define requirements 1 g.	176	1.58	0.79	[1, 4]	1.32 (0.18)	1.23 (0.36)
	Define requirements 1 h.	156	1.38	0.67	[1, 4]	1.75 (0.19)	2.67 (0.39)
Ideate	Synthesize components 1	180	1.89	1.09	[1, 4]	0.75 (0.18)	-0.93 (0.36)
	Conceptualize alt. 1 a.*	167	2.19	0.8	[1, 4]	0.29 (0.19)	-0.32 (0.37)
	Conceptualize alt. 1 b.*	169	2.66	0.68	[1, 4]	-0.13 (0.19)	-0.11 (0.37)
	Conceptualize alt. 1 c.	164	2.65	0.91	[1, 4]	0.03 (0.19)	-0.88 (0.38)
	Conceptualize alt. 1 d.	175	2.05	0.67	[1, 4]	0.86 (0.18)	1.75 (0.37)
	Conceptualize alt. 1 e.*	174	1.89	0.63	[1, 4]	0.23 (0.18)	0.11 (0.37)
	Conceptualize alt. 1 f.*	178	1.96	0.71	[1, 4]	0.25 (0.18)	-0.39 (0.36)
	Conceptualize alt. 1 g.	177	2.16	0.84	[1, 4]	0.63 (0.18)	0.05 (0.36)
Build & test	Verification a.	177	1.34	0.5	[1, 3]	0.96 (0.18)	-0.43 (0.36)
	Verification b.	173	3.18	0.74	[1, 4]	-0.57 (0.19)	-0.12 (0.37)
	Verification c.*	174	2.74	0.82	[1, 4]	-0.25 (0.18)	-0.41 (0.37)
	Verification d.	170	1.88	0.74	[1, 4]	0.55 (0.19)	0.11 (0.37)
	Verification e.*	156	2.62	0.82	[1, 4]	-0.31 (0.19)	-0.38 (0.39)
	Prototype 1 a.	173	2.39	0.72	[1, 3]	-0.75 (0.19)	-0.72 (0.37)
	Prototype 1 b.	172	2.24	0.79	[1, 4]	0.6 (0.19)	0.14 (0.37)
	Prototype 1 c.	172	1.76	0.71	[1, 4]	0.89 (0.19)	1.21 (0.37)
	Prototype 1 d.*	167	2.17	0.78	[1, 4]	0.31 (0.19)	-0.2 (0.37)
	Prototype 1 e.	169	1.71	0.58	[1, 4]	0.51 (0.19)	1.5 (0.37)
	Prototype 1 f.*	170	2.85	0.8	[1, 4]	-0.28 (0.19)	-0.38 (0.37)

Table B-5: Descriptive information of Part 2 items

	Part 2 items	*n*	*Mean*	σ	*Range*	*Skewness*	*Kurtosis*
Understand the problem	First steps a.	169	1.72	0.67	[1, 4]	0.64 (0.19)	0.42 (0.37)
	First steps b.	170	1.47	0.6	[1, 4]	1.04 (0.19)	0.97 (0.37)
	First steps c.	169	2.94	0.96	[1, 4]	-0.37 (0.19)	-1.01 (0.37)
	First steps d.	170	2.02	1.01	[1, 4]	0.73 (0.19)	-0.55 (0.37)
	First steps e.	169	1.91	0.72	[1, 4]	0.52 (0.19)	0.22 (0.37)
	First steps f.	170	1.83	0.69	[1, 4]	0.68 (0.19)	0.88 (0.37)
	First steps g.	169	1.91	0.73	[1, 4]	0.52 (0.19)	0.09 (0.37)
	First steps h.	154	1.75	0.75	[1, 4]	1.1 (0.2)	1.55 (0.39)
	Define requirements 2 a.*	121	2.28	0.78	[1, 4]	0.33 (0.22)	-0.13 (0.44)
	Define requirements 2 b.	170	1.64	0.77	[1, 4]	1.11 (0.19)	0.8 (0.37)
	Define requirements 2 c.	167	1.64	0.65	[1, 4]	0.65 (0.19)	0.04 (0.37)
	Define requirements 2 d.	171	3.51	0.73	[1, 4]	-1.5 (0.19)	1.87 (0.37)
	Define requirements 2 e.	154	1.62	0.69	[1, 4]	0.9 (0.2)	0.59 (0.39)
	Define requirements 2 f.	166	1.66	0.75	[1, 4]	0.99 (0.19)	0.63 (0.38)
	Define requirements 2 g.	170	3.22	0.76	[1, 4]	-0.81 (0.19)	0.43 (0.37)
	Define requirements 2 h.*	140	2.05	0.66	[1, 4]	0.4 (0.21)	0.6 (0.41)
Ideate	Conceptualize alt. 2 a.*	159	2.4	0.84	[1, 4]	-0.23 (0.19)	-0.71 (0.38)
	Conceptualize alt. 2 b.*	162	2.36	0.75	[1, 4]	0.29 (0.19)	-0.12 (0.38)
	Conceptualize alt. 2 c.*	165	2.42	0.81	[1, 4]	0.21 (0.19)	-0.39 (0.38)
	Conceptualize alt. 2 d.*	162	2.16	0.76	[1, 4]	0.25 (0.19)	-0.23 (0.38)
	Conceptualize alt. 2 e.	164	1.98	0.91	[1, 4]	0.9 (0.19)	0.23 (0.38)
	Conceptualize alt. 2 f.*	160	2.45	0.85	[1, 4]	0 (0.19)	-0.58 (0.38)
	Conceptualize alt. 2 g.	164	2.95	0.9	[1, 4]	-0.31 (0.19)	-0.9 (0.38)
	Synthesize components 2 a.	161	2.07	0.69	[1, 4]	0.97 (0.19)	1.86 (0.38)
	Synthesize components 2 b.*	163	1.9	0.72	[1, 4]	0.36 (0.19)	-0.33 (0.38)
	Synthesize components 2 c.	163	2.75	0.84	[1, 4]	0.05 (0.19)	-0.86 (0.38)
	Synthesize components 2 d.	164	1.81	0.71	[1, 4]	0.5 (0.19)	-0.19 (0.38)
Build & test	Build chair a.	166	1.58	0.6	[1, 4]	0.65 (0.19)	0.46 (0.38)
	Build chair b.*	163	1.67	0.55	[1, 4]	0.26 (0.19)	0.67 (0.38)
	Build chair c.	165	1.66	0.59	[1, 4]	0.44 (0.19)	0.41 (0.38)
	Prototype 2 a.*	160	2.05	0.66	[1, 3]	-0.05 (0.19)	-0.69 (0.38)
	Prototype 2 b.	162	2.28	0.75	[1, 4]	-0.33 (0.19)	-0.84 (0.38)
	Prototype 2 c.*	160	2.71	0.78	[1, 4]	0.15 (0.19)	-0.7 (0.38)
	Drawing a.	162	1.43	0.54	[1, 3]	0.77 (0.19)	-0.52 (0.38)
	Drawing b.	161	1.45	0.58	[1, 3]	0.86 (0.19)	-0.24 (0.38)
	Drawing c.*	158	2.97	0.75	[1, 4]	-0.13 (0.19)	-0.76 (0.38)
	Drawing d.	159	2.16	0.75	[1, 3]	-0.27 (0.19)	-1.18 (0.38)
	Drawing e.	162	1.45	0.57	[1, 3]	0.81 (0.19)	-0.35 (0.38)
	Drawing f.	159	1.53	0.58	[1, 3]	0.55 (0.19)	-0.64 (0.38)
	Drawing g.	157	2.15	0.77	[1, 4]	-0.08 (0.19)	-0.93 (0.39)

8. ANOVA & ANCOVA RESULTS

Table B-6 contains the ANOVA results of dependent variables that have statistical significance but do not meet all assumptions required for a valid ANOVA.

Table B-6: ANOVA results for significant variables that do not meet assumptions

Variables			***Assumptions***			***ANOVA results***			
	Dependent	***Independent***	***Reliability of scale***	***Normality***	***Homogeneity of variance***	***df***	***F***	η^2	***p***
Total	Understand the problem	Age	x		x	5	2.67	.06	.023
		Rate amount of time with client	x		x	5	2.31	.07	.047
	Ideate	Class			x	3	4.90	.07	.003
		Identify as minority			x	2	3.62	.03	.029
		Year in studies			x	5	3.55	.08	.004
		Report score			x	4	2.58	.05	.039
Difference in part 2 and 1	Understand the problem	Class	x		x	3	2.93	.06	.036
		Year in studies	x		x	5	4.58	.14	.001
		Overall score	x		x	4	2.47	.07	.048
		Source of project	x		x	2	4.71	.06	.010
		Time with client	x		x	5	3.07	.10	.012
		Rate amount of time with client	x			4	2.60	.07	.039
		Rate amount of time with professor proj 0	x		x	5	2.43	.11	.041
	Ideate	Hours with professor	x	x		9	2.08	.12	.036
	Build & test	Age	x		x	4	2.53	.07	.044
		Identify as minority	x		x	2	4.69	.07	.011
		International travel	x		x	5	2.64	.09	.026
		Overall score	x		x	4	2.87	.09	.026
		Hours with professor proj 0	x		x	6	3.60	.20	.003
Part 1	Design ability	Class	x			3	2.96	.05	.034
		Age	x			5	2.31	.06	.046
		Identify as minority	x		x	2	3.23	.03	.042
		Gender	x		x	2	4.33	.04	.015
		Project length	x		x	2	3.31	.04	.039
		Rate length of project	x		x	4	2.61	.07	.038
		Hours with professor proj 0	x		x	6	2.39	.11	.033
	Understand the problem	Class	x		x	3	3.12	.05	.027
		Age	x		x	5	2.52	.06	.031
		Gender	x		x	2	3.37	.04	.037
	Ideate	International travel		x	x	5	3.75	.10	.003
		Hours with professor		x		9	2.59	.15	.009
		Rate length of project proj 0			x	5	2.29	.09	.050
		Rate length of project proj 0		x	x	5	2.41	.10	.041
		Hours with professor proj 0				6	3.78	.16	.002
	Build & test	Time with client proj 0			x	4	2.65	.08	.037
		Identify as minority			x	2	4.57	.05	.012
		International travel			x	5	2.42	.07	.038
		Logbook score			x	4	2.49	.06	.045
		Report score			x	4	4.32	.10	.002
		Overall score			x	4	3.43	.08	.010
		Hours with professor proj 0			x	6	3.26	.15	.006

Table B-6: ANOVA results for sign. variables that do not meet assumptions (cont)

	Variables		Assumptions			ANOVA results			
	Dependent	***Independent***	***Reliability of scale***	***Normality***	***Homogeneity of variance***	***df***	***F***	η^2	***p***
Part 2	Understand the problem	Rate amount of time with client	x	x		5	2.60	.07	.027
	Ideate	Logbook score		x	x	4	2.46	.06	.048
	Build & test	Discipline	x		x	10	2.38	.14	.012
		Rate length of project	x		x	4	3.00	.07	.020
Factors	Factor 1a	Class	x		x	3	2.66	.04	.050
		Age	x			5	2.41	.06	.038
		Gender	x		x	2	3.77	.04	.025
		Source of project	x		x	2	3.46	.04	.034
		Hours with professor proj 0	x		x	6	2.40	.11	.032
	Factor 1b	Age			x	5	3.72	.09	.003
		Rate amount of time with professor			x	5	3.02	.10	.013
	Factor 1c	Class			x	3	4.00	.06	.009
		Age			x	5	2.53	.06	.031
		Gender			x	2	3.31	.03	.039
		Year in studies			x	5	3.02	.08	.012
		Project length			x	2	3.05	.04	.050
		Hours with professor proj 0			x	6	3.33	.15	.005
		Time with client proj 0			x	4	3.20	.10	.016
	Factor 1d	Discipline		x	x	10	2.07	.11	.029
		Identify as minority		x	x	2	4.98	.05	.008
		International travel		x	x	5	6.17	.14	.000
	Factor 1e	Class		x	x	3	6.31	.09	.000
		Year in studies		x	x	5	3.13	.08	.010
		Report score		x	x	4	5.10	.11	.001
		Rate amount of time with professor		x	x	5	3.27	.10	.008
		Rate amount of time with client proj 0		x	x	4	2.78	.09	.030
	Factor 2b	Class	x		x	3	14.50	.21	.000
		Source of project	x		x	2	9.78	.10	.000
		Project length	x		x	2	20.90	.20	.000
		Rate amount of time with client	x			5	2.99	.08	.013
		Maturity of product proj 0	x		x	3	3.18	.09	.028
	Factor 2c	Gender		x	x	2	3.82	.05	.024
	Factor 2d	Class		x	x	3	5.91	.10	.001
		Year in studies		x	x	5	3.81	.11	.003
		Project length		x	x	2	6.23	.07	.002
		Hours with professor		x	x	10	4.15	.21	.000

Table B-7 contains the ANCOVA results of dependent variables that have statistical significance but do not meet all assumptions required for a valid ANCOVA. Figure B-4 shows the plots of part 1 compared to part 2 for each of these variables. Ideally data are grouped in the bottom right quadrant going from 4.00 to 1.00.

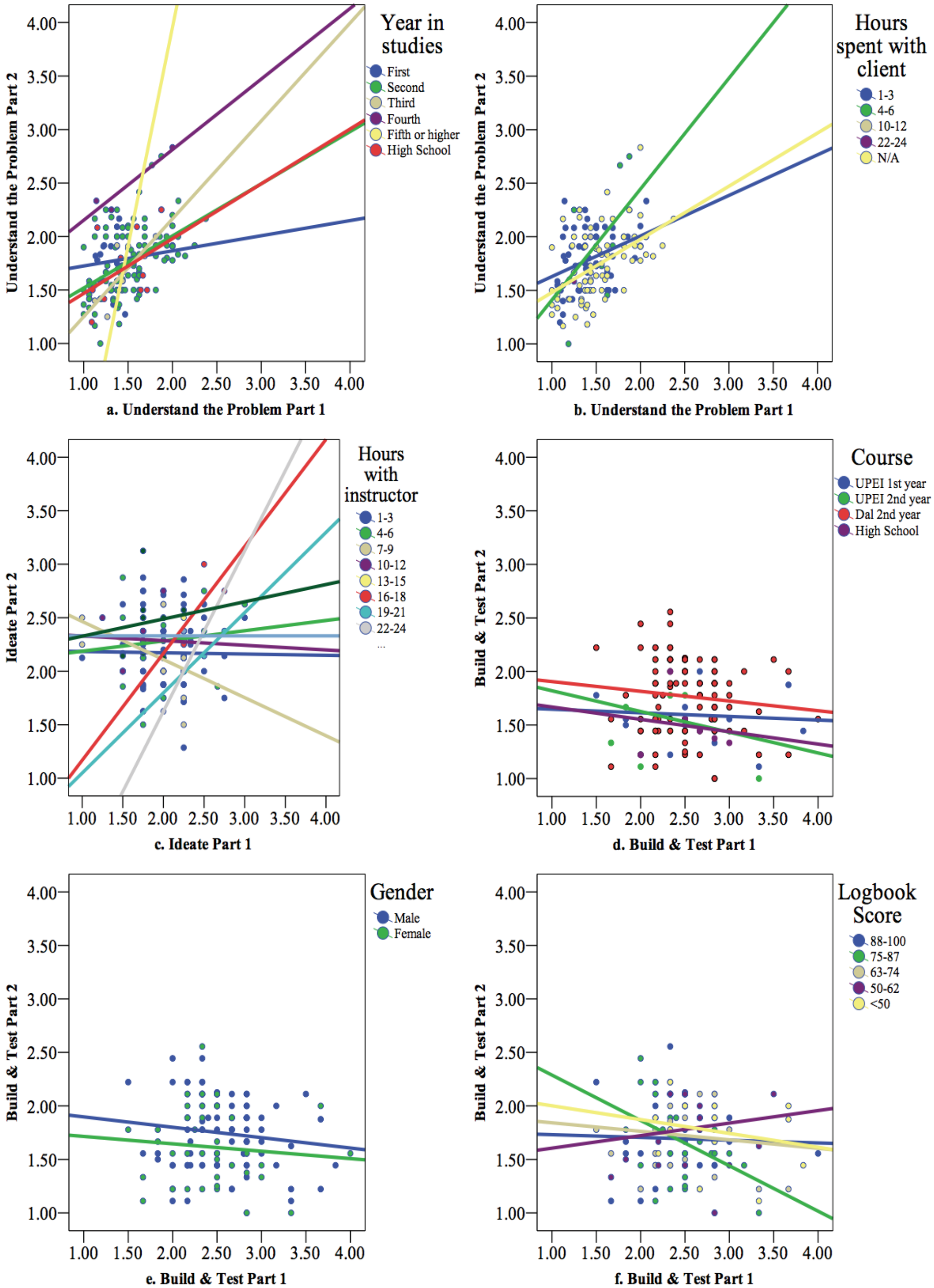


Figure B-4: Scatter plot for part 2 ANCOVA results

Table B-7: ANCOVA results for significant variables that do not meet assumptions

Variables		***Assumptions***					***ANOVA results***			
Dependent = part 2 ***Covariate = part 1***	***Independent variable***	***Reliability of scale of part 1 & 2***	***Part 1 ANOVA***	***Normality***	***Homogeneity of variances***	***Homogeneity of regression slopes***	***df***	***F***	η^2	***p***
Understand the problem	Year	x		x	x	x	5	4.56	.16	.001
	Client time	x	x			x	4	2.54	.07	.043
Ideate	Prof time			x	x	x	9	1.97	.14	.048
Build & test	Course		x		x	x	3	3.73	.09	.013
	Gender		x	x	x	x	1	4.95	.04	.028
	Logbook				x	x	3	4.27	.09	.006

APPENDIX C: STUDY 3 PARTICIPANT DATA & RESULTS

1. PARTICIPANT DATA 153

2. THE RELATIONSHIP BETWEEN DESIGN & ENGINEERING 153

1. PARTICIPANT DATA

The following table contains detailed information about each of the 12 participants.

Table C-1: Participant data

Location	*Gender*	*Terminal education*	*Years of experience*	*Industry*	*Teaching experience*	*Discipline*
France	M	Bachelor	30 - 39	Aerospace	No	Electrical
Southern US	F	Masters	10 - 19	Mass production	No	Industrial
Atlantic Canada	F	PhD	20 – 29	Marine robotics	Yes	Mechatronics
Western US	M	PhD	20 – 29	Aerospace	Yes	Systems
Midwest US	M	Bachelors	40 – 49	Petro-chemical	No	Mechanical
Eastern US	M	Bachelors	20 – 29	Aerospace	No	Systems
Atlantic Canada	M	Bachelors	10 – 19	Utilities	Yes	Mechanical
Atlantic Canada	M	Bachelors	10 – 19	Renewable power	No	Electrical
Atlantic Canada	F	Bachelors	20 – 29	Utilities	No	Civil
Western Canada	M	PhD	20 – 29	Acoustics	Yes	Mechanical
Atlantic Canada	M	Bachelors	20 – 29	Utilities	Yes	Civil
Eastern US	M	Bachelors	10 - 19	Aerospace	No	Software

2. THE RELATIONSHIP BETWEEN DESIGN & ENGINEERING

The following table contains a summary of the beliefs of participants regarding design and engineering. The categorization of the 3 themes are listed in the table: *balance* between engineering and design, *amount* of design within a position, and the *level* of the design work, as well as whether participants currently *identify* as design engineers. The cell corresponds to the column and row of cells in Figure 4-3.

Table C-2: Relationship between design and engineering

Balance	***Cell***	***Amount***	***Level***	***Identify***	***How design and engineering relate***
Separate	A1	Full	System	No	Design is creative. A designer comes up with the overall system design and hands it off to engineers.
	C1	Full	Detailed	No	Designers work under engineers. They are good with CAD, creativity, make recommendations to engineers on what's possible. Engineers parse out sections to designers.
	C1	Full	Detailed	No	Designers are focused on software, a part. An engineer looks at whole picture, assesses, come up with the design that meets the intent. The designer runs a tool, but rely on the input they've been given.
Design is a subset of eng.	A2	Partial	System	No	Not all engineers can be designers, but designers are a subset of engineers.
	A2	Full	System	Yes	Designers have the ability to see beyond limitations while engineers work within limits.
	B2	Full	Both	Yes	Design engineers see problems that have no solution. They go from broad to narrow in scope.
	B2	Full	Both	Yes	Design is about synthesis, not analysis. Design is combining things in innovative unique ways to create something new, moving from fuzziness to clarity.
	C2	Partial	Detailed	Yes	Design is creativity. Take nothing and make it something. Engineering is take something and make it work with something else.
	C2	Partial	Detailed	No	Design is one side of an engineer, project management is the other side. Design is primarily troubleshooting.
	C2	Full	Detailed	No	Design is one piece of the whole engineering puzzle. It is a critical portion, but not a large portion. Engineers start as designers doing detailed work and some move on to project management.
Eng. is a subset of design	B3	Un-known	Both	Yes	Design is the ability to come up with a solution to a problem or an improvement on an existing solution, whereas engineering is a specific part of a design. To be an engineer, you are a designer. It is an integral part of engineering.
Balance	A4	Full	System	No	There is one lead engineer/designer who would be creative, break down the problem, and supervise the engineers.

APPENDIX D: STUDY 4 INSTRUMENT & RESULTS

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2. DESCRIPTIVE STAISTICS FOR VARIABLES AND ITEMS 157

3. ANOVA RESULTS 161

1. INSTRUMENT FOR STUDY 4

The following sections contain the instrument and quantitative results from study 4.

1.1 Quantitative Item

The following quantitative item requests the steps and time within each step for a sample design scenario.

On Monday morning, your boss at Melodious Consulting Engineers asks you to design a musical device for Jennifer, a new client to the firm. You immediately head into the conference room where your client is waiting, and learn that the client requests a new way to play music. You are asked to design a new musical instrument out of materials from a grandfather clock that was in the client's family for generations. There is a family reunion on Saturday that the client would like to bring a prototype to get the family's approval before destroying the clock.

So, you have approximately 1 week (40 work hours) to build a prototype for your client. You have up to 5 minutes (now) to plan your week to ensure you will have the prototype ready in time. Choose which steps you will take, put them in order, and approximate how much time you plan to spend on each step. Not all steps are necessary. Put responses on next page

Analyze idea
Build device
Build prototype
Commercialize/market device
Communicate idea to client
Contact client
Define Problem
Detailed sketch of idea(s)
Develop CAD model(s)
Develop decision matrices
Develop program management plan

Document design decisions
Estimate material and cost
Evaluate ideas
Gather data/information
Ideate
Identify need
Iterate
Make a powerpoint presentation
Observe users
Other
Perform market analysis

Perform risk analysis
Perform sustainability impact analysis
Present idea to client
Produce final document
Reevaluate design
Reflect on process
Research
Specify requirements
Test device
Test prototype
Verify design meets client need

Step 1: ________ Time: ______ hr	Step 11: _______ Time: ______ hr	Step 21: _______ Time: ______ hr
Step 2: ________ Time: ______ hr	Step 12: _______ Time: ______ hr	Step 22: _______ Time: ______ hr
Step 3: ________ Time: ______ hr	Step 13: _______ Time: ______ hr	Step 23: _______ Time: ______ hr
Step 4: ________ Time: ______ hr	Step 14: _______ Time: ______ hr	Step 24: _______ Time: ______ hr
Step 5: ________ Time: ______ hr	Step 15: _______ Time: ______ hr	Step 25: _______ Time: ______ hr
Step 6: ________ Time: ______ hr	Step 16: _______ Time: ______ hr	Step 26: _______ Time: ______ hr
Step 7: ________ Time: ______ hr	Step 17: _______ Time: ______ hr	Step 27: _______ Time: ______ hr
Step 8: ________ Time: ______ hr	Step 18: _______ Time: ______ hr	Step 28: _______ Time: ______ hr
Step 9: ________ Time: ______ hr	Step 19: _______ Time: ______ hr	Step 29: _______ Time: ______ hr
Step 10: _______ Time: ______ hr	Step 20: _______ Time: ______ hr	

1.2 Independent Variables

The following questions comprise the independent variables on the instrument for study 4. Items 5-7 apply only to experts and are denoted with a '*'.

1 - What type of engineering do you most identify with?

a. Aerospace
b. Chemical
c. Civil
d. Electrical
e. Environmental
f. Industrial
g. Material
h. Mechanical
i. Mining Resources
j. Other
k. Not Declared

2 – Indicate your age.

a. 19 or under
b. 20 – 24
c. 25 - 29
d. 30 – 34
e. 35 – 39
f. 40 – 44
g. 45 – 49
h. 50 – 54
i. 55 – 59
j. 60 – 64
k. 65 or older
l. I prefer not to answer

3 – Indicate your gender

a. Male
b. Female
c. I prefer not to answer

4 - Do you identify yourself as part of a racial minority?

a. Yes
b. No
c. I prefer not to answer

*5 – Where do you work? (Leave blank if you do not want to answer)

*6 – How many years have your worked as an engineer?

a. 4 or less
b. 5 – 9 years
c. 10 – 14 years
d. 15 – 19 years
e. 20 – 24 years
f. 25 or more years

*7 – Do you hold any of the following professional designations:

a. Engineer-In-Training
b. Professional Engineer
c. No

2. DESCRIPTIVE STAISTICS FOR VARIABLES AND ITEMS

The following table contains that number of participants for study 4: all completed responses, responses with 38-42 total estimated time, the number of surveys that were started, and the number of surveys that did not include any times.

Table D-1: Participant sample size

Group	*All completed responses*		*Responses within schedule*		*Incomplete responses*	*No times included*
	n	*Average*	*n*	*Average*	*n*	*n*
1st	203	28 [0 - 139]	73	39.7 [38 - 42]	400	37
2nd-4th	33	38 [0 - 100]	25	40.0 [38 - 42]	69	3
Expert	21	40 [23 - 69]	18	39.8 [38 - 42]	37	0
Total	*257*	*30.6 [0 - 139]*	*116*	*39.8 [38 - 42]*	*490*	*40*

ANOVA * = all data (n = 257), + = within schedule (n = 116)

Tables D-2 through D-5 contain descriptive information for the dependent variables, independent variables, and steps, for the full data set and data set within schedule.

Table D-2: Descriptive information for variables for all data

Variables	*n*	*Mean*	σ	*Range*	*Skewness*	*Kurtosis*
Group	257	1.29	0.61	[1, 3]	1.94 (0.15)	2.43 (0.3)
Discipline	257	5.3	2.71	[1, 10]	0.21 (0.15)	-1.24 (0.3)
Age	257	1.88	1.78	[1, 12]	3.59 (0.15)	14.23 (0.3)
Gender	257	1.81	0.4	[1, 3]	-1.43 (0.15)	0.65 (0.3)
Identify as minority	257	1.95	0.52	[1, 3]	-0.07 (0.15)	0.69 (0.3)
Experience	257	3.05	1.63	[1, 5]	0.15 (0.5)	-1.75 (0.97)
Total time for project	257	30.57	19.12	[0, 132.5]	0.71 (0.15)	4.45 (0.3)
Number of steps	257	19.44	7.57	[3, 29]	-0.2 (0.15)	-1.12 (0.3)
First step	257	7.7	7.19	[1, 22]	0.97 (0.15)	-0.39 (0.3)
Stage of first step	257	1.54	0.74	[1, 3]	0.97 (0.15)	-0.51 (0.3)
Problem scoping	*257*	*5.63*	*4.46*	*[0, 35]*	*1.35 (0.15)*	*6.36 (0.3)*
Identification of need	257	0.53	0.68	[0, 4]	1.57 (0.15)	3.34 (0.3)
Problem definition	257	3.46	3.04	[0, 25]	1.84 (0.15)	9.13 (0.3)
Gathering information	257	1.64	1.91	[0, 13]	1.83 (0.15)	5.66 (0.3)
Developing alternative solutions	*257*	*8.37*	*6.21*	*[0, 45]*	*1.49 (0.15)*	*6.83 (0.3)*
Generating ideas	257	1.37	2.4	[0, 24]	5.57 (0.15)	44.32 (0.3)
Modelling	257	3.4	2.97	[0, 20]	1.31 (0.15)	3.67 (0.3)
Feasibility analysis	257	2.32	3.12	[0, 40]	7.1 (0.15)	82.23 (0.3)
Evaluation	257	1.27	1.32	[0, 6]	0.97 (0.15)	0.52 (0.3)
Project realization	*257*	*12.69*	*9.04*	*[0, 57]*	*0.79 (0.15)*	*2.37 (0.3)*
Decision	257	0.77	0.99	[0, 6]	2.1 (0.15)	5.88 (0.3)
Communication	257	4.41	3.66	[0, 21]	0.96 (0.15)	1.72 (0.3)
Implementation	257	7.51	6.53	[0, 44]	1.47 (0.15)	4.56 (0.3)
Iteration	*257*	*2.2*	*3.01*	*[0, 26]*	*3.21 (0.15)*	*17.41 (0.3)*
Iterate	257	2.02	2.57	[0, 16]	2.12 (0.15)	6.33 (0.3)
Margin of safety	257	0.18	1.66	[0, 26]	14.84 (0.15)	230.12 (0.3)

Table D-3: Descriptive information for design steps for all data

Steps	*n*	*Mean*	σ	*Range*	*Skewness*	*Kurtosis*
Identify need	257	0.53	0.68	[0, 4]	1.57 (0.15)	3.34 (0.3)
Define Problem	257	0.93	1.08	[0, 8]	2.53 (0.15)	10.09 (0.3)
Develop program mgmt plan	257	0.35	0.67	[0, 4]	2.17 (0.15)	5.23 (0.3)
Research	257	1.64	2.24	[0, 20]	3.18 (0.15)	18.63 (0.3)
Specify requirements	257	0.54	0.76	[0, 4]	1.75 (0.15)	3.61 (0.3)
Gather data/information	257	1.17	1.58	[0, 10]	2.04 (0.15)	5.54 (0.3)
Observe users	257	0.47	0.88	[0, 6]	2.6 (0.15)	9.09 (0.3)
Ideate	257	1.37	2.4	[0, 24]	5.57 (0.15)	44.32 (0.3)
Develop CAD model(s)	257	1.5	1.68	[0, 10]	1.35 (0.15)	2.54 (0.3)
Detailed sketch of idea(s)	257	1.24	1.32	[0, 10]	1.8 (0.15)	7.02 (0.3)
Estimate material and cost	257	0.67	0.88	[0, 6]	1.93 (0.15)	5.9 (0.3)
Analyze idea	257	1.32	2.69	[0, 40]	11.71 (0.15)	167.11 (0.3)
Perform market analysis	257	0.34	0.66	[0, 4]	2.46 (0.15)	7.77 (0.3)
Perform risk analysis	257	0.39	0.63	[0, 4]	1.83 (0.15)	4.24 (0.3)
Perform sustain. impact analysis	257	0.27	0.52	[0, 2]	1.91 (0.15)	2.9 (0.3)
Evaluate ideas	257	0.86	1.06	[0, 5]	1.52 (0.15)	2.33 (0.3)
Develop decision matrices	257	0.41	0.66	[0, 4]	1.75 (0.15)	3.49 (0.3)

Table D-3: Descriptive information for design steps for all data (cont.)

Steps	*n*	*Mean*	σ	*Range*	*Skewness*	*Kurtosis*
Verify design meets client need	257	0.74	0.94	[0, 5]	1.93 (0.15)	4.66 (0.3)
Choose 1 idea	257	0.03	0.21	[0, 2]	7.48 (0.15)	60.37 (0.3)
Commercialize/market device	257	0.54	1.23	[0, 6]	2.79 (0.15)	7.59 (0.3)
Communicate idea to client	257	0.67	0.79	[0, 5]	1.55 (0.15)	3.96 (0.3)
Contact client	257	0.59	0.82	[0, 6]	2.39 (0.15)	9.39 (0.3)
Document design decisions	257	0.59	0.87	[0, 4]	1.73 (0.15)	2.97 (0.3)
Make a powerpoint presentation	257	0.64	1.02	[0, 5]	1.81 (0.15)	3.39 (0.3)
Present idea to client	257	0.6	0.79	[0, 5]	1.56 (0.15)	3.59 (0.3)
Produce final document	257	0.78	1.35	[0, 10]	2.53 (0.15)	9.8 (0.3)
Build device	257	2.22	3.29	[0, 25]	2.78 (0.15)	12.36 (0.3)
Build prototype	257	3.13	3.43	[0, 24]	2.3 (0.15)	8.34 (0.3)
Test device	257	0.77	1.24	[0, 10]	2.73 (0.15)	12.82 (0.3)
Test prototype	257	1.39	1.59	[0, 10]	2.01 (0.15)	6.77 (0.3)
Iterate	257	1.03	1.91	[0, 13]	2.99 (0.15)	11.32 (0.3)
Reevaluate design	257	0.64	0.91	[0, 5]	1.45 (0.15)	2.1 (0.3)
Reflect on process	257	0.35	0.7	[0, 6]	3.33 (0.15)	17.92 (0.3)
Margin of safety	257	0.03	0.32	[0, 4]	11.06 (0.15)	126.08 (0.3)
Other	257	0.15	1.63	[0, 26]	15.6 (0.15)	247.42 (0.3)

Table D-4: Descriptive information for variables for responses within schedule

Variables	*n*	*Mean*	σ	*Range*	*Skewness*	*Kurtosis*
Group	116	5.36	2.89	[1, 10]	0.12 (0.23)	-1.3 (0.45)
Discipline	116	2.3	2.31	[1, 12]	2.63 (0.23)	6.84 (0.45)
Age	116	1.8	0.4	[1, 2]	-1.53 (0.23)	0.36 (0.45)
Gender	116	1.99	0.43	[1, 3]	-0.05 (0.23)	2.69 (0.45)
Identify as minority	116	2.94	1.66	[1, 5]	0.27 (0.54)	-1.74 (1.04)
Experience	18	39.81	0.71	[38, 42]	-0.01 (0.23)	3.26 (0.45)
Total time to complete project	116	20.29	6.39	[7, 29]	-0.04 (0.23)	-1.23 (0.45)
Number of steps	116	7.06	7.53	[1, 22]	1.17 (0.23)	-0.19 (0.45)
First step	116	1.47	0.76	[1, 3]	1.23 (0.23)	-0.15 (0.45)
Stage of first step	116	7.17	3.13	[0, 16]	0.23 (0.23)	0.53 (0.45)
Problem scoping	116	0.67	0.73	[0, 4]	1.54 (0.23)	3.72 (0.45)
Identification of need	116	4.46	2.38	[0, 13]	0.82 (0.23)	1.56 (0.45)
Problem definition	116	2.04	1.62	[0, 8]	0.81 (0.23)	0.95 (0.45)
Gather	116	11.05	4.39	[3, 40]	2.45 (0.23)	15.9 (0.45)
Developing alternative solutions	116	1.79	1.77	[0, 10]	1.68 (0.23)	4.39 (0.45)
Generating ideas	116	4.59	2.87	[0, 20]	1.55 (0.23)	6.16 (0.45)
Modelling	116	2.93	4.02	[0, 40]	6.92 (0.23)	63.36 (0.45)
Feasibility analysis	116	1.73	1.36	[0, 6]	0.76 (0.23)	0.32 (0.45)
Evaluation	116	16.47	5.36	[0, 35]	0.02 (0.23)	1.34 (0.45)
Project realization	116	1.07	1.1	[0, 6]	2.04 (0.23)	5.39 (0.45)
Decision	116	5.44	2.87	[0, 14]	0.25 (0.23)	-0.45 (0.45)
Communication	116	9.96	4.84	[0, 30]	0.79 (0.23)	2.21 (0.45)
Implementation	116	3.28	3.5	[0, 26]	3.05 (0.23)	15.37 (0.45)
Iteration	116	2.96	2.74	[0, 15]	1.53 (0.23)	3.25 (0.45)
Iterate	116	0.32	2.46	[0, 26]	10.12 (0.23)	105.97 (0.45)
Margin of safety	116	0	0	[0, 0]	0 (0)	0 (0)

Table D-5: Descriptive information for design steps for responses within schedule

Steps	***n***	***Mean***	**σ**	***Range***	***Skewness***	***Kurtosis***
Identify need	116	1.19	1.16	[0, 8]	2.57 (0.23)	10.57 (0.45)
Define Problem	116	0.36	0.68	[0, 3]	1.85 (0.23)	2.53 (0.45)
Develop program mgmt plan	116	2.16	2.03	[0, 10]	1.65 (0.23)	4.31 (0.45)
Research	116	0.76	0.79	[0, 3]	1 (0.23)	0.43 (0.45)
Specify requirements	116	1.45	1.53	[0, 8]	1.58 (0.23)	3.24 (0.45)
Gather data/information	116	0.59	0.95	[0, 6]	2.33 (0.23)	8.31 (0.45)
Observe users	116	1.8	1.77	[0, 10]	1.68 (0.23)	4.39 (0.45)
Ideate	116	2.05	1.79	[0, 10]	1 (0.23)	2.16 (0.45)
Develop CAD model(s)	116	1.62	1.39	[0, 10]	2.08 (0.23)	10.12 (0.45)
Detailed sketch of idea(s)	116	0.92	0.9	[0, 4]	1.1 (0.23)	1.32 (0.45)
Estimate material and cost	116	1.7	3.79	[0, 40]	9.14 (0.23)	92.68 (0.45)
Analyze idea	116	0.4	0.6	[0, 2]	1.29 (0.23)	0.64 (0.45)
Perform market analysis	116	0.48	0.72	[0, 4]	1.77 (0.23)	4.18 (0.45)
Perform risk analysis	116	0.36	0.6	[0, 2]	1.56 (0.23)	1.39 (0.45)
Perform sust. impact analysis	116	1.26	1.24	[0, 5]	1.09 (0.23)	0.77 (0.45)
Evaluate ideas	116	0.47	0.63	[0, 2]	1.11 (0.23)	0.23 (0.45)
Develop decision matrices	116	1	1	[0, 5]	1.85 (0.23)	4.45 (0.45)
Verify design meets client need	116	0.07	0.31	[0, 2]	4.9 (0.23)	25.33 (0.45)
Choose 1 idea	116	0.66	1.38	[0, 5]	2.21 (0.23)	3.98 (0.45)
Commercialize/market device	116	0.8	0.75	[0, 3]	0.77 (0.23)	0.36 (0.45)
Communicate idea to client	116	0.66	0.79	[0, 4]	1.66 (0.23)	4.06 (0.45)
Contact client	116	0.78	0.99	[0, 4]	1.41 (0.23)	1.59 (0.45)
Document design decisions	116	0.7	0.92	[0, 3]	1.12 (0.23)	0.15 (0.45)
Make a powerpoint presentation	116	0.84	0.85	[0, 5]	1.5 (0.23)	4.24 (0.45)
Present idea to client	116	1	1.28	[0, 6]	1.25 (0.23)	1.39 (0.45)
Produce final document	116	2.44	2.79	[0, 13]	1.2 (0.23)	1.35 (0.45)
Build device	116	4.54	3.48	[0, 20]	1.76 (0.23)	4.47 (0.45)
Build prototype	116	0.92	1.17	[0, 5]	1.13 (0.23)	0.58 (0.45)
Test device	116	2.07	1.63	[0, 10]	1.65 (0.23)	5.08 (0.45)
Test prototype	116	1.62	2.3	[0, 13]	2.27 (0.23)	6.67 (0.45)
Iterate	116	0.9	0.96	[0, 4]	0.76 (0.23)	-0.27 (0.45)
Reevaluate design	116	0.44	0.67	[0, 3]	1.65 (0.23)	2.82 (0.45)
Reflect on process	116	0.07	0.47	[0, 4]	7.37 (0.23)	55.54 (0.45)
Margin of safety	116	0.25	2.42	[0, 26]	10.65 (0.23)	114.19 (0.45)
Other	116	0	0	[0, 0]	0 (0)	0 (0)

3. ANOVA RESULTS

Table D-6 contains a summary of the ANOVA results of dependent variables that have statistical significance. * represents significant effect for the whole data set. ^ represents significant effects for the data set that was within schedule (38 – 42 hours). Tables D-7 and D-8 contain the ANOVA results from the full data set and data within schedule, respectively. Items that meet all preconditions and p < .05 have a border.

Table D-6: Summary of one-way and two-way ANOVA results for both data sets

	One-way						*Two-way*			
	Group	**Discipline**	**Age**	**Gender**	**Minority**	**Experience**	**Group &Discipline**	**& Age**	**& Gender**	**& Minority**
Total time to complete project	*		+					*		+
Number of steps	+					+				
First step										
Stage of first step					*					
Problem scoping	*	*	+				*			
Identification of need				*+			*			
Problem definition	*	*				*+	*			
Gathering information									+	
Developing alternative solutions	*+						*	*		
Generating ideas			+		*			*+	*+	
Modelling	*						*			
Feasibility analysis						+				
Evaluation	*+	*	+				*	*	*+	
Project realization	*		*					*	+	+
Decision			*							
Communication	+				+			*		
Implementation	*		*							*+
Iteration	*	*	*		*					
Iterate	*+	*	*		*					
Margin of safety										
Significant interactions for:										
All data (n=257)	10	5	5	1	4	1	6	6	2	1
Data within schedule (n=116)	5	1	3	1	1	3	0	1	4	3
Met all assumptions (n=116)	2	0	1	1	1	1	0	0	1	1

p > .05 = all data (n = 257), + = within schedule (n = 116)*

Table D-7: One-way and two-way ANOVA results for all data

Variables		***Preconditions***		***ANOVA results***			
Independent	***Dependent***	***Normality***	***Homogeneity of variance***	***df***	***F***	η^2	***p***
Group	**Total time to complete project**			2	6.72	.05	.001
	Problem scoping		x	2	3.13	.02	.046
	Problem definition		x	2	4.07	.03	.018
	Developing alternative solutions		x	2	9.10	.07	.000
	Modelling			2	13.10	.09	.000
	Evaluation		x	2	11.03	.08	.000
	Project realization		x	2	3.95	.03	.020
	Implementation		x	2	6.07	.05	.003
	Iteration		x	2	10.01	.07	.000
	Iterate			2	13.35	.10	.000
Discipline	*Problem scoping*		x	9	2.74	.09	.005
	Problem definition		x	9	2.83	.09	.003
	Developing alternative solutions						
	Evaluation		x	9	2.53	.08	.009
	Iteration		x	9	2.05	.07	.035
	Iterate		x	9	2.66	.09	.006
Age	*Project realization*		x	10	2.00	.08	.034
	Decision		x	10	1.98	.07	.036
	Implementation		x	10	2.18	.08	.020
	Iteration		x	10	1.89	.07	.047
	Iterate		x	10	2.30	.09	.014
Gender	*Problem scoping*						
	Identification of need			2	4.17	.03	.017
Identify as minority	**Stage of first step**		x	2	3.18	.02	.043
	Developing alternative solutions						
	Generating ideas			2	4.87	.04	.008
	Iteration			2	5.26	.04	.006
	Iterate			2	5.82	.04	.003
Experience	*Problem scoping*						
	Problem definition		x	4	3.03	.43	.049
Group & Discipline	*Problem scoping*			12	1.94	.08	.031
	Identification of need			12	2.08	.09	.019
	Problem definition			12	2.16	.09	.014
	Developing alternative solutions		x	12	1.99	.08	.026
	Modelling			12	3.38	.13	< .001
	Evaluation			12	2.36	.09	.007
Group & Age	**Total time to complete project**			3	5.46	.06	.001
	Developing alternative solutions		x	3	6.78	.07	< .001
	Generating ideas			3	6.74	.07	< .001
	Evaluation			3	3.91	.04	.009
	Project realization			3	2.73	.03	.045
	Communication			3	4.00	.04	.008
Group & Gender	Generating ideas		x	2	5.49	.04	.005
	Evaluation		x	2	4.41	.03	.013
Group & Minority	Implementation		x	3	3.99	.04	.008

Table D-8: One- and two-way ANOVA results for responses within schedule

Variables		***Preconditions***		***ANOVA results***			
Independent	***Dependent***	***Normality***	***Homogeneity of variance***	***df***	***F***	η^2	***p***
Group	**Number of steps**	x	x	2	3.98	.07	.021
	Developing alternative solutions		x	2	3.59	.06	.031
	Evaluation		x	2	4.62	.08	.012
	Communication	x	x	2	4.53	.07	.013
	Iterate		x	2	4.70	.08	.011
Age	**Total time to complete project**		x	10	2.25	.18	.020
	Problem scoping	x	x	10	2.19	.17	.024
	Generating ideas		x	10	2.39	.19	.013
	Evaluation			10	1.96	.16	.046
Gender	Identification of need	x	x	1	4.28	.04	.041
Identify as minority	Communication	x	x	2	5.05	.08	.008
Experience	**Number of steps**	x	x	4	3.24	.50	.048
	Problem definition		x	4	3.21	.50	.049
	Feasibility analysis		x	4	4.07	.56	.024
Group & Age	Generating ideas			2	4.37	.06	.015
Group & Gender	Project Realization	x	x	2	3.95	.06	.022
	Gathering information		x	2	3.16	.05	.046
	Generating ideas		x	2	10.88	.15	< .001
	Evaluation		x	2	4.01	.06	.021
Group & Minority	Total time to complete project		x	3	5.28	.12	.001
	Project Realization	x	x	3	3.72	.09	.014
	Implementation			3	7.21	.15	< .001

Figure D-1 shows the ANOVA results for the generating ideas and evaluation design activities compared to gender. While there is statistical significance ($p < .05$), they do not meet assumptions of normality.

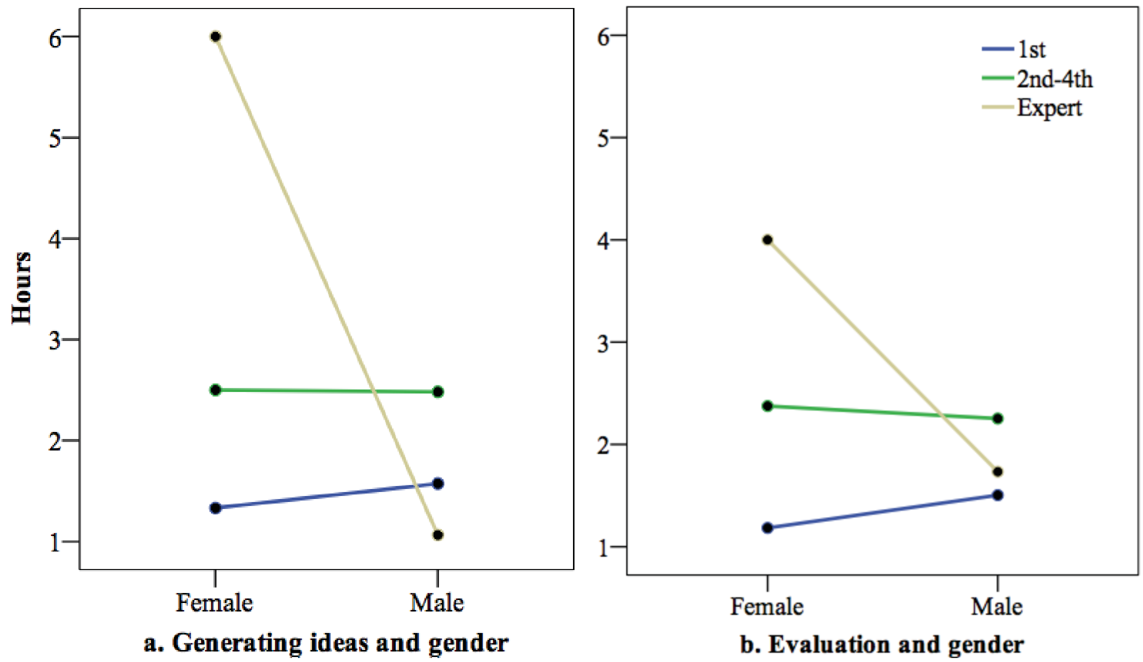

Figure D-1: Significant effects of gender and developing alternative solutions for data within schedule