

An Empirical Study on Design-Based vs. Traditional Approaches in Capstone Courses in Engineering Education*

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This study focuses on the two main design approaches applied to the guidance of student product development during capstone design courses through a comparison of two major approaches: traditional design process (TDP) and design thinking (DT). The objective of this paper is to discuss the impact of these design approaches on student activities, outcomes, and learning. Our research, conducted over three years, compared two courses offered at the same university, one applying TDP and the other DT. The research method consisted of three phases: (1) a comparison of the course structures and materials; (2) an analysis of deliverables from 50 design projects developed by 274 students, which was based on documentation and prototypes; and (3) a quantitative survey of the students. Results show that the DT-based course characteristics, such as extended time dedicated to prototyping cycles, limited the possibility of addressing some of the TDP methods (e.g. Quality Function Deployment) in the course timeframe shared by the two approaches. Results also suggest that, despite the shortcomings related to documentation, the DT-based course led to more innovative prototypes when compared to the TDP-based course. It was also notable that the DT course led to increased student self-efficacy in terms of innovation and increased technical knowledge. The results of this study are applicable for supporting the selection of design approaches and the definition of course activities in capstone design project courses.

Keywords: engineering design education; capstone design course; new product development process; design thinking

1. Introduction

One of the goals of engineering education is to support students in the development of the skills required to address complex design problems [1], and, accordingly, design has been an important topic in engineering education [2–4].

Several options may be considered in the organization of an engineering design course depending on the goals, many of which have been discussed in the literature. Engineering design courses may be directed either to students in their senior years through capstone design courses [2] or during their initial terms with cornerstone design courses [5–7]. Courses may involve students from a single university on a single campus or distributed internationally at two or more universities in multiple locations [8]. Such courses may also involve students from multidisciplinary backgrounds [9]; thus the creation of any particular course to design instruction entails an assessment of a number of different possibilities. The research presented here examines how the selection of the design approach determines the nature of the activities to be performed by students as well as the influence of such

curriculum choices on the student learning outcomes.

The present analysis considers the effect of two different design approaches applied to guide engineering development in engineering design courses, with attention to the two most widely disseminated approaches that are considerably distinct from each other. The first of these approaches, the “traditional design process” (TDP), is a highly structured, business-process oriented approach, which takes into account the thorough application of quality management methods. Conversely, the “design thinking” (DT) approach rests on a user-centric model. Our objective is to compare the impacts of these different approaches on students’ activities, outcomes, and learning in engineering design courses.

TDP is based on structured processes with carefully planned, sequenced, and documented activities and decisions. The approach was developed during the 1990s to manage parts of the design process that had theretofore been regarded as unstructured sets of activities, frequently leading to reduced efficacy and longer product development lead times [10–12]. TDP is grounded on the concepts of business process management [13], total quality manage-

ment [14], and lean manufacturing [15]; and, to increase the performance of design processes, it employs methods and tools such as concurrent engineering [16], the stage-gate process [17], and design for manufacturing and assembly (DFMA) [18]. TDP has been widely disseminated across the industry through business process reference models [19–21] and is heavily utilized in various industry sectors, including automotive and aeronautics. As a consequence of its applicability in industry, many engineering design courses employ a TDP approach.

However, customer interaction is limited in most cases; and companies applying TDP or TDP procedures face limitations in situations that call for disruption and faster customer feedback through shorter development and prototyping cycles. Alternatively, Design Thinking (DT) emphasizes both proximity to the user in order to deeply understand customers and their needs (empathy) and early prototyping of concepts on short trials and learning cycles to support more innovative solutions [22]. The DT approach has become increasingly popular and taught at engineering schools in capstone engineering courses [8]. In this article, we refer to Design Thinking as an application of the principles of project-based learning to capstone engineering courses, with a focus on designing real products.

At the university examined in the research presented here, a capstone design course based on TDP has been in place for many years. The course has evolved over time to incorporate ongoing developments in the TDP model, such as product lifecycle management [23], green design [24], and a stronger business-process orientation [25]. Nevertheless, the rising relevance of DT has led the authors to question whether the TDP course should be expanded to include the DT approach. Thus, a design education issue arose: should DT supplement or substitute TDP in engineering design courses? Due to the widespread application of TDP and the rapid emergence of DT, this issue is facing engineering educators worldwide.

In order to support a decision regarding such a change in curriculum direction, this research was undertaken to provide a better understanding of the impact of either design approach (TDP or DT) on students' activities, outcomes, and learning in engineering design courses. The main steps in this project are as follows: (1) identifying DT course characteristics; (2) deploying a novel DT course in parallel to an existing TDP curriculum at the same university; (3) gathering data on course characteristics and students outcomes in both courses; and (4) analyzing the data from both of these courses to understand the strengths and limitations of the two distinct approaches. Two research questions were

posed: how can TDP and DT course structures and content be compared; and what are the major differences in student outcomes? The research results are intended to support further discussion about engineering development approaches for engineering design courses and to facilitate curriculum choices in this regard.

The remainder of our study is structured as follows: Section 2 provides a brief summary of the literature on engineering design education as well as a discussion of the key characteristics of the TDP and DT approaches influencing design education. Section 3 then details the research method, and Section 4 provides an analysis of the data and a discussion of the results. Finally, Section 5 presents the conclusions of the study and offers suggestions for further research.

2. Engineering design education

Engineering activity involves the utilization of analysis and design to find solutions to problems [4], and it follows that training in design is a major goal of engineering education [3]. Consequently, engineering educators must employ design education methodologies through which students do not simply learn about design merely as some abstract set of principles; more importantly, they must also learn how to design [26].

Engineering design education has evolved significantly over the past twenty years following a broader dissemination of capstone design courses. These courses typically target senior-level students as training in the application of previously acquired learning to complex, open-ended, “real world” problems. And in such courses, students frequently encounter challenges including the creation design solutions delivered as prototypes, providing an end-to-end design experience [2, 3, 27].

There is already a relevant body of literature on this topic. A 1995 survey of 173 North American schools provided an overview of the main characteristics of capstone design courses including course duration, team size, faculty involvement, and industry sponsorship [2]. The survey was later complemented by an extensive literature review, which showed that although “the individual structures of capstone design courses are extremely diverse, the objective of nearly all such courses is to provide students with a real-life engineering design experience” [27].

More recent research focuses on specific course characteristics. A detailed description of relevant course experience elements included project selection and mentorship, as well as course administration and assessment [28]. A comparative research analyzed the impacts of course duration and team

size on student outcomes, comparing a single-semester and a two-semester offering [29]. Course comparison has also been applied to compare students' achievements resulting from participation in mono-disciplinary and multidisciplinary student teams [9, 30].

Although many aspects of capstone design courses have been analyzed, a gap persists in the literature regarding the differences in the underlying design processes employed as well as the relative outcomes of the distinct approaches. Engagement in these processes is key to guiding student activities. Students need to acquire understandings of how the various stages of design fit together within the design process [31]. Also, students who have gained process knowledge are better able to generate creative solutions in their future design engagements [31].

In a 2001 study, project management techniques including milestone scheduling, project review meetings and the utilization of memos and design memos, were employed to improve the overall management of projects in a capstone design course [32]. While addressing such issues as time management and resource allocation, that study did not discuss the influence of the design process approach. One specific design process, Systems Engineering Design Process (SEDP), was discussed in the context of a capstone design course [33], however, without comparison to other process alternatives.

In terms of the course design process, two approaches are considered in the present research: TDP and DT. Although there might be various course-specific process variations—as well as industry-specific adaptations—TDP and DT offer alternative foundations for comprehensive process curricula. These two approaches are discussed in detail below, with attention to their implications for structuring courses and student activities.

2.1 Traditional design process

The curriculum of engineering design courses made significant advances in the 1990s. During the 1980s, academics and practitioners came to realize the competitive edge of Japanese industrial companies was based on manufacturing capabilities. The response was the emergence of total quality management and lean manufacturing [34], both of which have been adopted by many large companies, especially in the automotive industry.

Propositions for more efficient engineering design processes emerged in the 1990s, including those concerned with managing the development process and decision-making with the introduction of stage-gate [17], concurrent engineering [16], and a wide range of design methods, including QFD (quality

function deployment), DFMA, and FMEA (failure mode and effect analysis), among others [10, 35–38]. Due to their importance and widespread adoption across the industry, these process elements and characteristics have heavily influenced the implementation of the TDP approach within the curricula of many engineering design courses worldwide.

One of the major advances related to process management has been the stage-gate [17]. It acknowledges the progressive nature of activity flow while utilizing “gates,” or decision-making points, to guide the product development process. The original formulation employs five stages with their respective gates intervening between the initial idea and the final launching of the product. The process begins with a preliminary assessment and proceeds sequentially through the remaining four stages: business case preparation, development, testing and validation, full production, and market launch [17]. Each of these stages concludes with a formal assessment that constitutes the “gate” or decision as to whether the project should progress to the next stage. Consequently, the stage-gate process ensures a disciplined approach to product development and serves as a roadmap for control of the design activity. A design course utilizing the stage-gate approach follows a business-process centric view and is organized into phases—which may differ from the ones listed above—delimited by the gates. In simulation of the stage-gate method, the gates deployed in design curricula are usually bound to the students' specific course deliverables to be assessed.

The concurrent engineering approach envisions a parallel development of a product along with its manufacturing process. Detailed development activities are executed simultaneously in teams, which calls for more frequent and richer communications between team members in order to reduce error propagation and total product development lead-time through an anticipation of problems and agreement on tradeoff solutions [10, 16, 39]. Emulating concurrent engineering in design courses is not trivial, because some restrictions from later product lifecycle phases are not always present or students may be unaware of existing limitations that require consideration in terms of tradeoffs during decision making. However, development process specification of parallel activities, especially in detailed design phases, may create opportunities for practicing concurrent engineering. This requires class engagement in detailed engineering activities (e.g. detailed geometry design, material selection, and manufacturing process planning). Therefore, in the development of a curriculum for such a course, accommodation to this level of detail should be made when formulating course deliverables.

The widespread application of quality management-related methods, such as QFD, DFMA and FMEA, is another notable characteristic of TDP. It is important to mention that, because of product development theory evolution history and industry applications, many of the current relevant product development process guides chiefly reflect the TDP approach [10, 37, 38, 40].

One limitation of TDP for industrial application is the reduction in user interaction during the design process. An understanding of actual and often varied customer requirements is necessary to mitigate development risks, and this requires their input [36]. However, customer interaction is limited in many project situations [41].

2.2 Design thinking

The design discipline rests on the premise that solutions to real problems are best provided by approaches from a number of different angles and perspectives [22]. In this regard, design thinking utilizes an interdisciplinary approach for testing concepts and anticipating problems, facilitating the generation of richer contexts and faster prototyping [42], even when the problems are poorly defined. User-centered design is a popular approach to open-ended and complex problems because its solutions are built around user needs with the guidance of actual user input [36, 43–47]. Thus, design thinking is quintessentially a user-centered approach.

Design thinking has been translated into various frameworks that have been incorporated into engineering courses [8, 48–50]. Such frameworks usually emphasize three main groups of activities, which follow an iterative pattern: understanding the problem from the users' perspective, proposing solutions, and making those solutions concrete through the construction of prototypes.

To grasp problems from the users' point of view, students are encouraged to observe the problem in the field, to talk to different participants, and to observe or participate in the action [51]. Solutions arise from divergent and convergent thinking upon new data and previous knowledge concerning a given issue in the pursuit of multiple answers, which may be better or worse, in order to uncover new possibilities and open new paths for exploration [3].

Many authors consider that prototypes serve as means for designers to present their ideas [42, 45, 52, 53]. Prototypes are also tangible artifacts that have transposed a design from an abstract concept into an empirical object readily assessable by the users. Therefore, design thinking curricula should encourage students to prototype their solutions across multiple prototyping cycles.

Different kinds of prototypes may be considered, depending on the purpose, the focus, and the project phase. Among other objectives, prototyping may aim to support the students' exploration and learning, experimentation and assessment, or communication [54–56]; and the focus of the prototyping activity may cover a range of aspects including functionality, integration, assembly, and appearance [57, 58].

Examples of prototyping in design thinking courses include critical function prototypes (CFP) and "dark horse" prototypes. CFPs focus on the exploration and assessment of the main function of the product, which is central to overall solution generation. On the other hand, dark horse prototyping permits an investigation of "previously unexplored and potentially risky" solution concepts in the middle of a project, expanding the possibilities and "preventing the design space from shrinking too rapidly" [59]. Students are requested to develop an alternative concept that may either be innovative or should at least permit additional learning from user feedback.

The extended prototyping in design courses calls for access to prototyping facilities and to prototyping materials, which may constitute a barrier to the adoption of DT in design education, especially for institutions with limited resources.

3. Research method

This study was conducted over a period of approximately three years, from June 2013 to July 2016. In order to compare TDP and DT, a new DT course was created and offered concurrently with the pre-existing TDP course taught at the same university.

Research was structured in three main phases. The first phase, from June 2013 to June 2014, focused on planning the study and preparing the new DT course based on existing references, and included the participation of the curriculum designers in an actual DT course project taught at a partner university. The second phase, from February 2014 to July 2015, focused on offering the course and gathering data on students' project performance. The third phase, from February 2016 to July 2016, involved gathering quantitative data from a survey and statistical analysis.

The preexisting TDP course is a one-semester product development course offered to undergraduates in the seventh semester of Industrial Engineering. Each class has approximately 70 students and is essentially monodisciplinary (90% Industrial Engineering students), although a few students from other engineering programs take the class as an elective. During the second phase of this study, the TDP course was offered twice, once in the first

semester of 2014, and once in the first semester of 2015.

The TDP course follows the approach discussed in Section 2.1, and the main characteristics of the specific TDP-based course content are detailed in Section 4. Students work in teams to develop new product solutions and are expected to present final team prototypes at the end of the course. Ideas for the projects are proposed by each team of students and require justification in terms of real user needs and existing market demand. The first project deliverable is a project briefing and a proposal that requires validation by the faculty members. Team formation rules allow students to organize organically, with an initial recommendation of five students per team.

The course program calls for a single final prototype to be presented by each team. The class is supported by an equipped mechanical (metal and wood) and electronics prototyping lab freely accessible throughout the semester. Material expenses are the responsibility of the team members, although many of the necessary consumable prototyping materials are available at no cost through the prototyping lab (e.g. 3D-printing polymers, wood, fixtures, bearings, cables). Likewise, at the lab students may borrow at no cost more sophisticated electronic components (e.g. Arduino and Intel Galileo boards, sensors, breadboards, etc.).

In the deployment of the new DT course offering, the first phase of the study involved meeting an international benchmark through the collaboration of universities across national borders. The university where the research was conducted became part of an international network of engineering schools that is led by a university with extensive and renowned experience in DT courses. The aim of this network is to conduct bilateral collaborative DT projects, each involving two universities in different countries. The projects taking place under the network involve multidisciplinary teams of typically six to eight students working on a project proposed and sponsored by industry partners. Both course and the corresponding project are three academic quarters in duration.

During this first research phase, the faculty members from the university where the research was undertaken jointly supervised a team of students from the same university on a specific aeronautics project. The project participation allowed the faculty members to accumulate practical experience with the DT approach, and to conduct a literature review on DT practices, as discussed in Section 2.2. The participation of these faculty members in the international network inspired the novel DT course at their university.

During the second phase of the study, the DT

course designed during the first phase was deployed at the university. Because of the semester-based curriculum of the researched university, the initial reference course from the international benchmark had to be reduced from three quarters to fit into single semester product development course. In order to allow our experiment to proceed without affecting the structure of existing university course offerings, the course was initially offered as an elective. Although there was no fixed cohort linkage, the course was targeted to seventh semester students, as was the established TDP course.

The DT course followed the approach presented in Section 2.2 as experienced by the researchers during their international practical experience course. The adoption of a DT approach suggested a multidisciplinary class. Therefore, the course was designed to mix students from different programs at the Engineering School with students from other disciplines in equivalent (1:1) proportions. The team size recommendation was six students, in accordance with the DT benchmark and recommendations from the literature [29]. Team formation rules also followed the benchmark in allowing students to organize organically, according to project preference, because teams observed multidisciplinary rules, including mirroring at team level the 1:1 engineering/others ratio of the overall class. Finally, as suggested by the DT benchmark, project briefings were proposed by external partners (industry, ONGs, university departments), rather than the team itself.

Each class was designed for a population of approximately 60 students, although the first two offerings had lower enrollments as a result of their pilot character. During the second phase of this study, the DT course was offered three times – in both semesters of 2014 and during the first semester of 2015.

The DT course program called for three prototypes to be submitted by each team over the course of the semester. In order to offset the greater prototyping costs resulting from the higher number of prototypes, projects were funded by the university endowment. On average, the teams spent US\$ 195, and student costs were mitigated by the availability of many of the materials in the lab. The DT and TDP classes had access to the same prototyping facilities.

Table 1 summarizes the main TDP and DT characteristics and demographics from the second phase of this research (February 2014 to July 2015). During this three semester period, the TDP-based course enrolled a total of 141 students working on 28 different projects, while the DT-based course total was 133 students engaged in 22 different projects. The DT course average actual cohort was

Table 1. Course characteristics and demographics for the second phase of study (February 2014 to July 2015)

	TDP-based course	DT-based course
Semester offerings analyzed—semester/year (number of students)	1/2014 (69) 1/2015 (72)	1/2014 (35) 2/2014 (36) 1/2015 (62)
Total number of students	141	133
Number of teams	28	22
Multidisciplinarity prevalence	Monodisciplinary	Multidisciplinary
Number of engineering majors represented	5	11
Engineering students' most frequent major: number of engineering students in most frequent major (percentage of total)	Industrial Engineering: 127 (90.1%)	Electrical Engineering: 17 (12.8%)
Number of non-engineering students (percentage of total)	1 (0.7%)	66 (49.6%)
Average students' semester cohort (std. dev.)	7.4 (2.5)	6.3 (3.1)
Average team size (std. dev.)	5.0 (0.4)	6.1 (1.2)

6.3 semesters, with a higher dispersion compared to the TDP offerings.

The second phase of the research involved gathering data from the 2014 and 2015 course offerings. Two main data gathering methods were applied. To facilitate comparison, the first of these methods consisted of pairing teaching documentation on the courses' actual project phases, milestones, and content taught. The second method comprised an assessment of the students' final deliverables on the basis of five criteria.

For the comparison of actual course content and project phases, our first method was to compose from the syllabi a single, generic calendar and content table which presented, in parallel columns, the respective course data. During each course offering, based on real classroom data, actual course progress was documented following each class session. This data included TDP and DT project phases, report deliverables milestones, as well as milestones on prototype deliverables, and students' presentations, and the classroom teaching progress, thus registered, was used to compare course content.

To support further implementation, the second method's assessment of the students' deliverables—final reports and prototypes—focused on the innovation of their solutions and the completeness of their product documentation. Five criteria were defined. The first criterion, “(1) product documentation level of completeness for recommendation implementation” summarized the degree of completeness and the information quality of the following items: (1.1) market research and opportunity sizing; (1.2) conceptual product-solution definition (product functional definition, technology selection, and overall architecture); (1.3) detailed technical drawings; (1.4) detailed product structure.

Each element was individually assessed using a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). The second criterion, “(2) Prototype innovation degree,” considered a three-point innovation scale based on the literature [10], which registered: (1) incremental innovation; (2) new for the market; and (3) radical innovation. The third criterion evaluated the “Prototype level of functionality”; and the fourth criterion, “(4) Prototype multidisciplinarity level,” took into account the actual number of disciplines used to implement the final prototype (mechanical, electric, electronic, software, ergonomics, other). Finally, the fifth criterion, “(5) Patents” enumerates the patents requested as well as patent requests in the process of being submitted because the assessment was conducted only shortly after the course conclusion and the patenting process might have been underway by the time the analysis was conducted. Table 2 summarizes criteria for the assessment of students' deliverables.

The students' final deliverables (final reports, presentations, and photos of prototypes) were stored in a database and graded on each of the criteria independently by two evaluators who are also co-authors of the present report.

The third phase of this research consisted of a pre-post survey applied to students of both courses in the first semester of 2016: The main purpose of the survey was to assess the student evolution in terms of gains in knowledge of the tools and skill in tool use, innovative posture, and career goals. The evolution and results of the TDP and DT students were then compared. Table 3 presents the numbers of students surveyed and response rates.

The questionnaire contains eight main questions related to the survey objectives as well as additional questions regarding respondents' demographical

Table 2. Criteria for the assessment of students' deliverables

Criteria	Details
(1) Product documentation level of completeness for recommendation implementation	Composed of 4 items: (1.1) Market research and opportunity sizing (1.2) Conceptual product solution definition (product functional definition, technology selection, and overall architecture) (1.3) Detailed technical drawings (1.4) Detailed product structure Question: Is the documentation item complete and of high quality?
(2) Prototype innovation degree	Scale: three-point based on the literature [10] (1) incremental innovation (2) new for the market (3) radical innovation.
(3) Prototype's level of functionality	Are the prototype's critical functions operational and capable of supporting product user assessment?
(4) Prototype's multidisciplinary level	Count of actual number of disciplines used to implement the physical final prototype: <ul style="list-style-type: none"> • Mechanical • Electric • Electronic • Software • Ergonomics • Other: textile, chemical
(5) Patents	Number of patents requested (percentage of the projects) / number of patent requests in the process of being submitted (percentage of the projects)

Table 3. Survey respondents

	TDP-based course	DT-based course
Total number of students	83	62
Number of teams	13	9
Survey respondents—beginning (%)	56 (67.5%)	56 (90.3%)
Survey respondents—end (%)	73 (88.0%)	57 (91.9%)

data. These questions were adapted from existing questionnaires in the field. The first three questions, based on a study by Blikstein [60], measure confidence towards the use of certain tools. Students were asked about their confidence in the repair of electromechanical equipment with diverse levels of assistance. Students were also asked to rate their knowledge of 21 different tools and appliances divided into the following three categories: Basic (typically encountered in daily living, such as email); Manufacturing (used in this context to reflect the knowledge necessary to build prototypes); and Office (employed to design documents and presentations). Both of the questions were assessed on a 6-point Likert scale ranging from “Not Confident” to “Totally Confident.” The third question employed “Yes” and “No” answers to assess the students' knowledge of 19 different technical components as well as their performance in guessing the component presence in a toaster. Students were also asked to rate their level of certainty towards the answer on a 1 to 10 scale.

Innovative behavior and interests were assessed with questions based on the Engineering Majors

Survey (EMS) questionnaire [61]. The EMS is an initiative of the Epicenter (National Center for Engineering Pathways to Innovation) led by professor Sheri Sheppard and based at Stanford University. The instrument relies on career theories to formulate questions that “ask students about their ‘innovation self-efficacy’, expectations for the outcomes of innovative behaviors, innovation interests, and goals around doing innovative work in their early careers” [61].

We used our adaptation of the EMS survey to analyze student outcomes in project-related situations (such as “Lead a team of people” and “Generate new ideas from world observations”) in terms of confidence (question four), interests (question five) and perception of importance (question six). Questions seven and eight assess future plans and career goals by inquiring into the probability of the students following any of eight different career paths, as well as the probability of working in engineering-related jobs at different intervals following graduation. Responses to questions four through eight were given on a five-point Likert scale.

Table 4. Indicators extracted from survey's questions

Indicator	Details	Number of sub-items	Scale
(1) Technical confidence	Assesses confidence to fix or build an equipment.	Nine	Six-point Likert
(2) Basic tools domain	Assesses level of knowledge towards daily life tools (i.e. Email).	Five	Six-point Likert
(3) Manufacturing tools domain	Expresses level of knowledge towards prototyping tools (i.e. 3D Printer).	Nine	Six-point Likert
(4) Office tools domain	Assesses level of domain towards documentation tools (i.e. MS Office).	Seven	Six-point Likert
(5) Basic components confidence	Evaluates students' level of certainty on guessing the presence of known components in a toaster.	Ten	Ten-point
(6) Complex components confidence	Evaluates students' level of certainty in guessing the presence of the more complex components of a toaster.	Nine	Ten-point
(7) Innovation self-efficacy	Assesses confidence towards the creative aspect of innovation.	Six	Five-point Likert
(8) Engineering task self-efficacy	Measures confidence towards engineering project-related activities.	Five	Five-point Likert
(9) Professional self-efficacy	Analyzes confidence in interpersonal and teamwork activities.	Two	Five-point Likert
(10) Place financial value	Measures students' willingness to monetize ideas.	One	Five-point Likert
(11) Innovation interests	Analyzes interest towards common innovation-related activities (i.e. Giving an "elevator pitch").	Seven	Five-point Likert
(12) Innovation work scale	Measures willingness to overcome major innovating difficulties.	Six	Five-point Likert

Finally, the survey concluded with a series of background questions regarding demographical data, including financial situation and contact with innovation in private life.

The complete survey contains a total of 122 sub-items. The theoretical framework suggests that indicators can be compiled from the survey questions and answers [60, 61], and Table 4 provides a summary of the 12 indicators we consider. These indicators were calculated as an average of their sub-items.

In order to foster honesty in answers, the survey was anonymous. The research was conducted on paper in the classroom. Data was collected at the beginning of the first class prior to any other activity following the completion of the final class. Data collected on paper was entered into the software Qualtrics and analyzed with the IBM SPSS 17.0 software package [62] and Microsoft Excel.

The level of statistical significance for t-tests is $p < 0.05$, and the size effect was measured through Cohen's d . Results below 0.2 were considered small; those from 0.2 to 0.5, medium; and values above 0.5 were considered high.

Since respondents attended different courses, we conducted a Kolmogorov-Smirnov test for two samples, with $\alpha = 0.01$ to verify that the equality between populations holds to the indicators

assessed. Skewness and kurtosis were also calculated in order to assure the validity of the models used, with ± 2 as the acceptable range. Lastly, Cronbach's alpha was computed for each of the indicators in order to check its consistency, with values over 0.65 regarded as acceptable.

4. Results and discussion

This section provides an analysis and discussion of the results related to our study's two research questions. Section 4.1 examines the comparison between TDP and DT course structures and content, and Section 4.2 treats the major differences between student outcomes in the TDP and DT courses. Finally, Section 4.3 discusses the improvement in student design knowledge and facility as determined from an analysis of the quantitative survey.

4.1 TDP and DT course structures comparison

Throughout the study, we documented the actual progress of the courses, including teaching activities and student deliverables. Fig. 1 is a calendar comparing the major project phases of the TDP and DT courses as well as student deliverables for each phase.

The TDP course was structured in three sequen-

	Week	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15	W16	W17	W18	W19
TDP	Project phases			Informational Project					Conceptual Project					Detailed Project						
	Report (R#)								R1				R2		R3					R4R5
	Prototype (PRO#)																			PRO1
	Presentation (PRE#)		PRE1																	PRE2
DT	Project phases			Critical Function Prototype								"Dark Horse" Prototype		Functional Prototype						
	Report (R#)			R1					R2											R3
	Prototype (PRO#)											PRO1		PRO2						PRO3
	Presentation (PRE#)						PRE1					PRE2		PRE3						PRE4

R - Report
 PRO - Prototype
 PRE - Presentation

Fig. 1. Comparison of TDP and DT course schedules.

tial phases, namely: Informational Project, Conceptual Project, and Detailed Project. A stage-gate process was employed and Reports R1 through R4 were due at each of the gates allowing progress to the subsequent phase. Exceptionally, R2 was an intermediary gate established to prevent excessive work on progress toward the final concept (R3). The DT course in the study was also structured in three phases, but phases related to prototyping cycles: critical function prototyping, "dark horse" prototyping, and functional prototyping.

With regard to deliverables, there were eight for TDP course, while the DT course required ten. More important than the quantity of deliverables, was their type and nature; and the distribution by type of deliverable (report, prototype, presentation) differed significantly in each course (Fig. 1). The TDP course called for five technical reports, one prototype, and two presentations, whereas the DT course required three technical reports, three prototypes, and four presentations. Consequently, the TDP course tended to focus more on formal documentation (reports), while the DT course emphasized hands-on prototyping experience. As discussed in Section 4.2, the difference in the deliverable types influenced the students' time allocation and outcomes.

Table 5 presents in considerably greater detail the account of student deliverables provided in Fig. 1.

The TDP course in our study followed a linear approach. Students committed earlier (between Weeks 7 and 11) to a conceptual solution that was

developed in progressively increasing detail throughout the conceptual and detailed project phases, and a unique final prototype was presented at the end of the course (Fig. 1). The DT course, on the other hand, employed a cyclical approach in which students advanced through three prototyping phases during each of which prototypes were tested with potential users. This cyclical approach permitted students to identify misconceptions and design issues, which were then addressed in the following cycle. The intervention of the "dark horse" prototyping cycle between Weeks 11 and 14 stimulated innovation by encouraging the students to seek and to implement an alternative concept; and the final concept might combine elements of CFP and "Dark Horse" in different degrees, depending on the success of either approach with regard to user feedback. Therefore, in the DT course, the final concept was fully defined only at the beginning of the third cycle, later than in the TDP course (Fig. 1).

The analysis of the deliverables content (Table 5) indicates that the TDP course requires the preparation of more documentation items, including the application of various product development methods (QFD, DFMA, FMEA) and the definition of manufacturing process plans. On the other hand, in addition to the gathering of data on user needs conducted in both courses, the DT course specifies three contacts with potential users for feedback: one following each of the prototyping cycles.

Given the time and effort constraints, which are

Table 5. Description of students' deliverables

Course	Deliverable (according to calendar)	Content description
• TDP	PRESENTATION 1	<ul style="list-style-type: none"> • Problem to be addressed • Hypothesis for market demand • Project briefing
	REPORT 1	<ul style="list-style-type: none"> • Market segmentation and focus • User needs • QFD matrix – product requirements • Preliminary sketches
	REPORT 2	<ul style="list-style-type: none"> • Technical benchmarking • Commercial benchmarking • FAST (function analysis system technique) diagram • Product concept draft • Distribution and logistics strategy
	REPORT 3	<ul style="list-style-type: none"> • Product assembly draft • Product structure (preliminary) • Materials selection • DFMA • Macro manufacturing process planning (for critical items)
	REPORT 4	<ul style="list-style-type: none"> • Technical drawings • Sourcing specification for item purchase • Manufacturing process planning and tooling • Product FMEA and process FMEA • Quality control plan
	REPORT 5	<ul style="list-style-type: none"> • Executive summary • Final items from R1–R4 • Product costing
	PROTOTYPE 1	<ul style="list-style-type: none"> • Functional prototype
	PRESENTATION 2	<ul style="list-style-type: none"> • Final solution presentation
DT	REPORT 1	<ul style="list-style-type: none"> • Personas • Empathy map • Customer journey • Service blueprint
	PRESENTATION 1	<ul style="list-style-type: none"> • User needs assessment • Benchmarking
	REPORT 2	<ul style="list-style-type: none"> • Ideation • Idea selection for critical function prototype (CFP)
	PROTOTYPE 1	<ul style="list-style-type: none"> • CFP
	PRESENTATION 2	<ul style="list-style-type: none"> • CFP attributes • User feedback on CFP
	PROTOTYPE 2	<ul style="list-style-type: none"> • Dark horse prototype
	PRESENTATION 3	<ul style="list-style-type: none"> • Dark horse prototype attributes • User feedback on dark horse prototype
	PROTOTYPE 3	<ul style="list-style-type: none"> • Functional prototype
	PRESENTATION 4	<ul style="list-style-type: none"> • Final solution presentation • User feedback on functional prototype
	REPORT 3	<ul style="list-style-type: none"> • Documentation of findings on user interactions • Product specification (product structure, drawings, materials specification etc.)

equivalent for both courses, course deliverables express decisions made reflecting each course's emphasis on its respective development approach (discussed in Sections 2.1 and 2.2). The approach chosen (TDP or DT) also influenced the actual course content that was presented during class hours. Table 6 summarizes the actual course content for TDP and DT based on classroom notes.

The documentation of the actual class content (Table 6) indicates a stronger emphasis on product development methods originated from total quality management, lean manufacturing, and business

process management of the TDP approach. Many of these methods were taught only during the TDP course, which also covers manufacturing process planning. On the other hand, manufacturing process planning was not considered during the DT course, but content related to prototyping types, process and user testing, as well as user needs documentation, was exclusive for the DT course. Common to both courses were fundamental information gathering and analysis and the generation of product information (e.g. user needs data gathering, product benchmarking, product requirements,

Table 6. Summarized course syllabus—actual content presented and discussed during class hours on each course

Syllabus item	TDP	DT
Successful products and the importance of innovation	X	X
Business process perspective on product development	X	
Stage-gate process	X	
User needs data gathering	X	X
User needs documentation (personas, empathy map, customer journey, service blueprint)		X
Quality Function Deployment (QFD)	X	
Product benchmarking	X	X
Product requirements	X	X
Functional structure	X	X
Function analysis system technique (FAST) diagram	X	
Product architecture	X	X
Product structuring	X	X
Prototyping types		X
Prototyping manufacturing processes and materials		X
User testing		X
Lifecycle perspective	X	X
Product-service systems (PSS)		X
Product lifecycle management (PLM)	X	
Design for manufacturing and assembly (DFMA)	X	
Manufacturing process planning	X	
“Make or buy” process and suppliers classification	X	
Failure mode and effect analysis (FMEA)	X	
Quality control plans	X	

functional structure, product architecture, product structure) (Table 6).

4.2 TDP and DT students' performance and outcomes

This section provides assessments of student outcomes drawn from analyses of presentations, prototypes, and final reports. Results for student deliverables assessments are presented in Table 7.

Product documentation performance was assessed through an examination of the technical reports delivered by each project team. Overall, the TDP course in the study yielded more highly detailed project reports. The overall difference with regard to this metric was observed chiefly in the shortcomings of student technical drawings and product structure documentation in the DT reports (respectively items 1.3 and 1.4 of Table 7). Likewise, some DT reports lacked the necessary level of detail and completeness of design specifications. Results for market research and conceptual product solution definition (items 1.1 and 1.2 on Table 7) were more balanced between TDP and DT.

TDP reports had higher page counts, and an analysis of the final reports confirmed the presence of more comprehensive technical information. The DT reports were shorter, but presented comparatively more data on user feedback as well as richer descriptions of the as-built prototypes.

Since both courses have the same timeframe and require the same amount of student involvement, differences in documentation completeness may result from the design process, the derived activity emphasis, and the time allocation. The linear approach of the TDP course, with its earlier concept

definition and a stage-gate process structured around formal reports, enforces continuous documentation by the students. Conversely, the cyclical approach of the DT course and its later concept definition, coupled with a higher number of prototypes and presentations, tended to restrict the emphasis placed on documentation to later project phases.

Prototype assessment indicates that the DT course resulted in more innovative solutions compared to the TDP (item 2 on Table 7). DT prototypes also displayed a higher level of functionality and included input from a greater number of disciplines (items 3 and 4 in Table 7). The higher number of disciplines brought into the construction of the DT course prototypes can be partially attributed to the multidisciplinary enrollment of the DT course, compared to monodisciplinary (Industrial Engineering) on TDP. However, it should be noticed that the multidisciplinary class had fewer engineering students per team—on average three of the six members of the DT teams were engineering students in comparison with the five-member TDP teams, which consisted exclusively of engineering students.

The differences in innovation level and prototype functionality likely are attributable mainly to the design process. The later concept definition in DT and the dark horse prototyping allowed additional time for innovative thinking. Likewise, the cyclical production of prototypes allows students to reuse previously constructed subassemblies when possible. Also, the iteration of the process grants students an opportunity to improve their technical facility with the infrastructure provided for the prototyp-

Table 7. Assessment of students' deliverables

Criteria	Details	TDP	DT
(1) Product documentation level of completeness for recommendation implementation <i>Is the documentation item complete and of a high quality?</i> Scale: five-point Likert scale (1 = strongly disagree to 5 = strongly agree)	(1) Overall product documentation	4.07	2.26
	(1.1) Market research and opportunity sizing	4.00	2.70
	(1.2) Conceptual product solution definition (product functional definition, technology selection, and overall architecture)	4.16	2.75
	(1.3) Detailed technical drawings	3.96	1.64
	(1.4) Detailed product structure	4.16	1.95
(2) Prototype innovation degree	Scale: three-point based on [10]: (1) incremental innovation, (2) new for the market, (3) radical innovation.	1.57	2.20
(3) Prototype level of functionality	Are the prototype's critical functions functional and capable of supporting product user assessment? Scale: five-point Likert scale (1 = strongly disagree to 5 = strongly agree)	2.89	3.39
(4) Prototype multidisciplinary level	Count of actual number of disciplines used to implement the physical final prototype (mechanical, electric, electronic, software, ergonomics, other).	2.32	3.07
(5) Patents	Number of patents requested (percentage of the projects) / number of patents in the process of being requested (percentage of the projects)	1 (3.6%) / 0 (0%)	2 (9.1%) / 1 (4.5%)

Note: $\alpha = 0.05$.

ing, which helps account for the improved results observed in the final prototyping cycle of the DT course. The differences in the innovation level observed during the study are apparent in the tally of patent applications: the 28 TDP projects resulted in a single patent application, while the 22 DT projects resulted in two patent requests and one patent application was not yet submitted.

4.3 Third phase: survey data analysis

As noted in section 3, our survey was distributed to students of both courses in February and July of 2016 at the beginning and end of the term; the sample size and response rates are detailed in Table 3.

To check the indicators' consistency with a minimum requirement of 0.65, our analysis began with a calculation of Cronbach's alpha for samples from both courses. Table 8 indicates the results for indicators with two or more sub-items. All alphas satisfy the condition just specified, and normality was tested for both populations through assessments of skewness and kurtosis (with ± 2 as acceptable values). The totality of indicators other than "basic components confidence" were found to be normal, and thus statistical tests were not undertaken to assess this particular exception. In order to correctly compare students from these different courses, Kolmogorov-Smirnov tests were con-

ducted to rate the equality of populations. With $\alpha = 0.01$, all indicators fit the equal population hypotheses, which allowed us to conduct the t-tests. The results are elaborated in Table 8.

In the sequence, t-tests were performed regarding the factors specified in Table 8 for TDP and DT post samples, since pre-samples were demonstrated to be equal according to the Kolmogorov-Smirnov test. The results are listed in Table 9.

At the completion of the courses, a significant difference in favor of the DT students was verified among the tool-related indicators. Increases were noted in technical confidence ($p < 0.001$ and $d = 0.641$), in the manufacturing tools domain ($p < 0.001$ and $d = 0.905$) and in complex components confidence ($p < 0.005$ and $d = 0.479$) among the DT students; and we attribute this to their more extensive laboratory experience and equipment usage which created opportunities to manufacture a greater number of prototypes than the TDP students. In the DT course, prototypes were followed by presentations (in Microsoft PowerPoint or Prezi, which included photographs and video recording); reports (generally in Microsoft Word); and eventually videos. This expanded emphasis on presentations and their multimedia possibilities also led to a facility increase in the office tools domain ($p < 0.001$ and $d = 0.621$).

Results also indicate an increase in innovation

Table 8. Results for alpha, skewness, kurtosis and Kolmogorov-Smirnov tests

	TDP alpha	DT alpha	Skewness TDP	Kurtosis TDP	Skewness DT	Kurtosis DT	KS test (p-value)
Technical confidence	0.899	0.912	-0.677	1.447	-0.640	0.475	0.060
Basic tools domain	0.895	0.850	-0.108	-0.112	-0.126	-0.811	0.905
Manufacturing tools domain	0.856	0.926	0.619	-0.204	1.186	0.903	0.465
Office tools domain	0.862	0.857	0.216	-0.273	-0.045	-0.701	0.905
Basic components confidence	0.769	0.847	-0.870	1.103	-1.419	3.121	0.298
Complex components confidence	0.750	0.838	-0.307	-0.772	-0.174	-0.421	0.961
Innovation self-efficacy	0.778	0.877	0.180	0.445	0.319	0.582	0.334
Engineering task self-efficacy	0.832	0.891	0.163	-0.572	0.520	0.381	0.153
Professional self-efficacy	0.819	0.857	-0.102	-0.592	-0.498	-0.177	0.979
Place financial value	–	–	-0.423	-0.392	-0.348	-0.465	1.000
Innovation interests	0.677	0.781	-0.109	0.905	-0.165	-0.713	0.036
Innovation work scale	0.837	0.774	-0.287	0.097	-0.066	-1.090	0.021

Table 9. Results from t-tests

		Mean	Std Dev	N	t	p-value	Cohen's d
Technical confidence	TDP	4.008	0.781	73	-3.570	0.00027	0.641
	DT	4.559	0.938	57			
Basic tools domain	TDP	4.482	0.825	73	-2.747	0.00345	0.483
	DT	4.856	0.725	57			
Manufacturing tools domain	TDP	2.497	0.744	73	-4.915	< 0.001	0.905
	DT	3.333	1.102	57			
Office tools domain	TDP	3.960	0.819	73	-3.525	0.00030	0.622
	DT	4.466	0.805	57			
Complex components confidence	TDP	5.962	1.490	73	-2.663	0.00448	0.479
	DT	6.760	1.841	57			
Innovation self-efficacy	TDP	3.413	0.553	71	-5.962	< 0.001	1.077
	DT	4.053	0.637	56			
Engineering task self-efficacy	TDP	3.068	0.647	71	-4.015	0.00006	0.729
	DT	3.593	0.791	56			
Professional self-efficacy	TDP	3.859	0.723	71	-1.140	0.12831	0.206
	DT	4.018	0.820	56			
Place financial value	TDP	3.356	1.046	73	-1.668	0.04897	0.296
	DT	3.661	1.014	56			
Innovation interests	TDP	3.753	0.548	71	-5.026	< 0.001	0.893
	DT	4.236	0.534	57			
Innovation work scale	TDP	3.675	0.871	73	-5.044	< 0.001	0.889
	DT	4.310	0.556	57			

self-efficacy ($p < 0.001$ and $d = 1.077$) and engineering task self-efficacy ($p < 0.001$ and $d = 0.729$) in DT students as opposed to the TDP population, which may be due to the hands-on development of new products, instead of the more abstract conceptualization of the TDP approach. Professional self-efficacy ($p < 0.15$ and $d = 0.206$) was not found to differ significantly between the TDP and DT students, a result that was expected because team leadership and effective communication of ideas were present among the indicator's sub-items. A tendency to place financial value ($p < 0.05$ and $d = 0.296$) was greater among DT students, probably because the team had to manage its own and limited budget by itself.

Innovation interests ($p < 0.001$ and $d = 0.893$) and innovation work scale ($p < 0.001$ and $d = 0.889$) values were also greater among DT students, which adds weight to the hypothesis that the course,

through hands-on and client-oriented work, would motivate students to perform innovation-related activities.

Finally, Table 10 summarizes results for the query on willingness to work in engineering-related positions after specified intervals following from graduation. A significant difference between samples was verified for one ($p < 0.05$ and $d = 0.298$), five ($p < 0.01$ and $d = 0.446$) and ten ($p < 0.001$ and $d = 0.609$) year intervals. The results indicate that the DT course was more successful in motivating students to pursue careers that involve engineering.

5. Conclusion

This study is part of research efforts aimed at understating and improving capstone design courses. More specifically, our research examines underlying approaches in engineering design

Table 10. Tendency to work as engineers after graduation

		Mean	Std Dev	N	t	p-value	Cohen's d
One year after graduating	TDP	3.356	1.183	73	-1.692	0.047	0.298
	DT	3.702	1.133	57			
Five years after graduating	TDP	3.370	1.208	73	-2.540	0.006	0.446
	DT	3.860	0.990	57			
Ten years after graduating	TDP	3.110	1.242	73	-3.467	< 0.001	0.609
	DT	3.825	1.104	57			

courses, the course structure that results from the choice of either a TDP or DT process, as well as the similarities and differences to be found among the course activities, deliverables, and related course content.

Students in the TDP course followed a stage-gate process and were directed to commit to a conceptual solution earlier in their semester, after which solutions were progressively detailed in reports. A more extensive application of design methods originated from the total quality management and lean manufacturing was noted for the TDP course. Methods such as QFD, DFMA, and FMEA were included in the TDP classroom content as well as in reports. On the other hand, the DT in the study course adopted an iterative, cyclical process. There was an earlier construction of prototypes as well as more frequent structured feedback from potential users. During the DT course, students progressed through three prototyping cycles, compared to the single final prototyping session of the TDP course.

The comparison of the outcomes indicates that TDP students generated more comprehensive and detailed product documentation, whereas the DT students were able to create prototypes with higher degrees of functionality and their solutions were also rated as more innovative. The results appear to indicate that the TDP course tends to be more effective for teaching the application of specific design methods and product documentation preparation. On the other hand, the DT course may be of greater value for teaching students how to come up with more innovative solutions.

Additionally, quantitative data from the survey provides evidence that confidence and awareness with regard to both tool and equipment use increased more in the DT course. Likewise, the DT approach was also found to instill greater confidence in innovative abilities and project engineering-related activities than the TDP approach. Finally, the greater inclination towards future employment within engineering professions found among the DT students indicates that the DT course was better able to motivate students to follow a STEM path.

Nevertheless, the study has the following limitations. First, the DT course is an elective discipline

that was created within the scope of this research. Because of its elective nature, students applied to participate and could not be assigned randomly. Second, project comparisons were based on different sets of projects in each course. TDP projects were proposed by the members of student teams, while the DT projects were assigned by external partners. In order to balance project efforts, all projects briefings were evaluated by faculty to equalize project complexity. Student-proposed projects were required to prove that they addressed a real problem and targeted a relevant demand. Third, team size averaged five members in TDP and six in DT—and in the latter case, the six member teams consisted of three engineering and three non-engineering students. This difference resulted from the emphasis in the DT course on multidisciplinary, which required that engineering students be evenly balanced by students from other areas.

One shortcoming of this study results from the limitations of generalizing from the conclusions of research conducted on a university-level student population. Therefore, conclusions drawn from a comparison of these two courses cannot be extrapolated to the actual design approaches (TDP and DT) in their application within other contexts, including corporate applications. Similarly, the comparison that grounds this study rests on an assumption of the equivalence of the timeframes and levels of student involvement required by each approach. Increased effort in a particular design aspect in either of the courses required that the same course reduce efforts in some other aspect.

Despite their limitations, the results presented here generated insights, allowed discussion, and supported decision-making at the university where the research was conducted. The study's findings supported the decision to maintain two distinct design courses at that institution. The TDP course as we have described it will continue to be offered to Industrial Engineering students. This decision was based on the assessment that the course offers the formal training necessary to manage relatively large and complex projects in traditional industrial sectors (e.g. automotive and aeronautics) that are particularly relevant in the region where the uni-

versity is located. Likewise, the DT course will continue to be offered as an elective discipline to students who desire additional experience in alternative development processes. Finally, the option to replace the existing TDP course with the DT course was rejected. Along with these findings, discussions of this sort may also be useful at other universities.

Two additional results from this study may also find application. The two distinct course calendars and the table of contents presented here might serve as reference for future comparisons. Our study demonstrates that the chosen design approach influences students' deliverables and potentially their learning experience as well. Future research might compare students' knowledge on product development at the beginning and at the end of each course based on standard assessment tools. It is also worth noting that this research has not analyzed the differences in motivation and self-efficacy in terms of gender and socioeconomic status differences. Further research might examine this data more closely and discover additional patterns.

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Appendix I: Indicators

Below we evidence indicators used in this analysis, as stated in section 3. The number in parenthesis indicates the question from which the sub-item was taken from. Indicators were calculated as averages from their sub-items.

Technical confidence	If there was someone to give me step-by-step instructions (3) If there was nobody close to tell me what to do as I advance (3) If I had a book or website as reference (3) If I had seen someone fixing it before (3) If I could call someone when I was unable to proceed (3) If someone helped me starting (3) If I had a lot of time to finish fixing the device (3) If someone showed me how to fix it previously (3) If I had used a similar device before (3)
Basic tools confidence	Computers (4) Smartphones (4) Email (4) Videoconference (4) Tablets (4)
Prototyping tools confidence	Multimeter (4) Construction of programmable robots (4) Construction of electronic devices (4) Woodwork tools (4) Laser cutters (4) Soldering and metalwork (4) 3D printer (4) Electric soldering (4) Microcontrollers (4)

Office tools confidence	Designing a webpage (4) Text editors (e.g. MS Word) (4) Spreadsheets (e.g. MS Excel) (4) Elaboration of presentations (e.g. MS PowerPoint) (4) Movie making (4) Edition of digital pictures (4) Blog writing (4)
Basic components confidence	Motors (5) Gears (5) Wires (5) LEDs (5) Lamps (5) Screws (5) Light sensors (5) Resistors (5) Microphone (5)
Complex components confidence	Thermostats (5) Microcontrollers (5) AC/DC converter (5) Heat element (5) Switches (5) Transistors (5) Capacitors (5) Transducers (5) Solenoids (5)
Innovation self-efficacy	Ask a lot of questions (6) Generate new ideas by observing the world (6) Experiment as a way to understand how things work (6) Actively search for new ideas through experimenting (6) Build a large network of contacts with whom you can interact to get ideas for new products or services (6) Connect concepts and ideas that appear, at first glance, to be unconnected (6)
Engineering task self-efficacy	Design a new product or project to meet specified requirements (6) Conduct experiments, build prototypes, or construct mathematical models to develop or evaluate a design (6) Develop and integrate component sub-systems to build a complete system or product (6) Analyze the operation or functional performance of a complete system (6) Troubleshoot a failure of a technical component or system (6)
Professional self-efficacy	Lead a team of people (6) Communicate your ideas effectively to people in different positions or fields (6)
Place financial value	Take the steps needed to place a financial value on a new business venture (6)
Innovation interests	Experimenting in order to find new ideas (7) Giving an “elevator pitch” or presentation to a panel of judges about a new product or business idea (7) Finding resources to bring new ideas to life (7) Developing plans and schedules to implement new ideas (7) Conducting basic research on phenomena in order to create new knowledge (7) Working on products, projects, or services that address societal challenges (7) Working on products, projects, or services that have significant financial potential (7)
Innovation work scale	Searching out new technologies, processes, techniques, and/or product ideas (8) Generating creative ideas (8) Promoting and championing ideas to others (8) Investigating and securing resources needed to implement new ideas (8) Developing adequate plans and schedules for the implementation of new ideas (8) Selling a product or service in the marketplace (8)

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