WIP: Developing Novice Design Thinkers

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***Abstract*— This work-in-progress research-to-practice paper describes a study of the effects of early introduction of Electrical and Computer Engineering students to design problem solving. Design problems promote design thinking which entails students thinking about how to deploy new knowledge to come up with solutions. The courses in this study are sophomore-level, core courses which entail classical lecturing and analytical problems that only end with a unique solution. Design problem solving modules are introduced to sophomore courses and the student's performance and satisfaction are gaged.**

Keywords—design thinking, design problem solving.

I. Introduction

Engineering design problems promote design thinking which entails thinking and conceptualizing about how to deploy knowledge to create inventive solutions for real-life problems [1]. Design problems allow engineering students to use their higher order cognitive skills and demonstrate their personality in their solutions. Engineering design students experience decision making, and quality control, which improve their academic performance in engineering courses [2].

A design problem comprises a set of system requirements and applicational constraints. The design problem solution can be as fleshed-out as a detailed list of values for component; an illustration through schematics, block diagrams, and/or flowcharts; or can be a written software code or implemented hardware [3]. Unlike analytical problems where solutions are unique and uniform, design problems can have many feasible solutions that satisfy the design requirements or specifications [4].

Engineering design problem solving, and design processes are well accounted for in literature [5], especially in Architectural Engineering Education which leans heavily on design [6-9]. Malhotra et al., postulated, in 1980, that design problem solving enhances the cognitive skills of students in a software design class [10]. In a similar study in 1994, this time through an empirical study on semi-expert electronics engineers, Ball et al. correlated the improvement of the software engineers' cognitive skills to use of design modules [11]. While design problems are structured by customers' needs or wants [12], design solutions are structured both by constraints and by the designer's own cognitive map [2]. To produce intelligible designs, the designer must fully recognize the design problem's system requirements and constraints.

The majority of engineering freshman courses, and Electrical and Computer Engineering (ECE) sophomore courses are usually analytical in nature, where engineering students will experience design problems in more advanced courses later in their years of study as junior and senior-level students. The systematic and passive application of theory to solve problems, although necessary for learning, doesn't include design thinking. Unpracticed in design thinking, the majority of ECE students will struggle to apply their analytical skills and theoretical knowledge towards design and invention in design-related courses. Most students will be strangers to the format of a design problem with system requirements that specify ranges instead of values and ask for a solution that can be one of many valid answers [13].

It is a specific aim and a research question of this research work to determine the impact of solving design problems both systematically and frequently; in particular using design problems in exams; laboratory, and classroom exercises; and homework assignments; on the professional formation of engineers with respect to design thinking outcomes and technical course performance. The courses adopted in this study are sophomore-level courses where almost all problems are in nature theoretical and analytical. The researchers will introduce design problems for students to complete in lectures, laboratory experiments, homework assignments, and exams.

Previous research in the area included the work of Rodriguez et al, who studied the experiences of students engaged in a course which has been redesigned to enhance student development through design thinking pedagogy [14]. Otherwise, the application of similar concepts in introductory circuits analysis courses has included Moreno and Diaz's 2021 study on the development of critical thinking for an electrical circuits course [15]. Critical thinking also involves the use of cognitive skills to make decisions and produce outcomes [16], but does not customarily include the structure and processes of design thinking that ends in a design solution [17]. Critical thinking outcomes better suite literary arts and sciences, like history [18], while design thinking structure is better suited to practical applications in engineering [4, 19-21]. As Moreno and Diaz reported, there was no improvement of critical thinking nor academic performance following their effort to apply didactic methods to integrate science, technology, engineering, art, and mathematics in the circuits class [15]. The researchers in this work propose that design thinking offers a more promising method to enhance academic performances in the Electrical and Computer Engineering courses.

In this article, two elementary core courses were revamped to include systematic design problem solving. The courses are ECE 101: Linear Circuits and System, and ECE 202: Embedded

Systems and Interfacing. Prior to this study, the two courses were theoretical in nature with lab experiments that instruct students, through step-by-step instructions, to carry out lab procedures and do not induce design thinking. Often students of these core courses complain that they do not understand why they are being introduced to all those theoretical and analytical methods and fail to see any applications of the circuits or programmed microcontrollers. Instructors of subsequent advanced topics in Electrical and Computer Engineering often complained that most students do not remember the basics of their respective electrical or computer disciplines owing to weak foundations from the elementary sophomore courses.

The students in this study were introduced to elements of the engineering design problem; and have experienced systematic design problem solving in lectures, laboratory, and homework assignments of an elementary electronic circuits course. The students' performance on a design test problem is compared the performance of another population of sophomore students who had taken the same test problem. The results of the student surveys will also reveal how the students perceived the design problem solving.

II. Decription of An Engineering Design Problem

A. *System Requirements or Specifications*

In design problems, the starting point is a list of design requirements or a system's description that the designer should observe when coming up with a solution. In practice, this list is usually prescribed by a customer, or an end user of the product designed to carry out a particular functionality. The customer's "need, want, preference, value, purpose, objectives, and/or goals" motivate design thinkers to create solutions [12, 19]. Often design problem goals set by customer's are not fully attainable, and the designer would have to work with the customer to bridge the gap between "what is required" and "what is attainable," or augment subgoals during the development of the design. However, that is not the case in measured design problems introduced in engineering classes formulated by an engineering instructor where all system requirements are measured and set prior to the design stage.

In ABET requirements, instructors of engineering design courses are further expected to challenge their students to relate their designs to factors that can be of relevance to the real world. Engineering designs bear close impact on community, corporate, and both national and international economies. Engineering design thinkers are introduced to the design disciplines that evaluate the impact(s) of their solutions on contexts like environmental effects; public health; global, cultural, and societal aspects; diversity, equity, and inclusion; welfare and safety; and economic factors.

B. *Design Constraints*

The second step for a design thinker is to identify the engineering constraints for the underlying problem. Constraints usually comprise elements, of technical or non-technical nature, that affect the solution to the design problem, but the designer has little or no control over. Gross et al., 1987, defines the constraints as "the rules, requirements, relations, conventions, and principles that define the context of designing" [22]. Engineering designers need to work their way around in order to optimize their solutions in spite of those constraining factors, or bottlenecks. Engineering design students learn about engineering tradeoffs and hone their cognitive skills in dealing with design bottlenecks [10]. Common non-technical constraints in ECE class projects can include time to complete the assignment; cost, or budget; and manpower, i.e., the number of students working on the assignment. Technical constraints are more specific to the system requirements.

C. *Design Conceptualization and Implementation*

The third step for an engineering design student is to conceptualize the solution of the design problem. In this stage, the designer is a problem solver who turns the user specified requirements into functions or modules that can be implemented while observing the design constraints. There are several methods for problem solving that can be used to conceptualize the design solution like the means-ends analysis; a hierarchical, modular, breakdown of the general objectives decomposed into sub-goals, the subgoals to actions or functions, when all modules are assembled the desired end is achieved. Another problem-solving method is conceptual translations in which a designer would bridge the gap between theory and goals using causal functions that fit into the designs [12]. Several other methods exist in literature.

III. Introduction of Design Modules in Elementary ECE Sophomore-level Courses

The 101 and 202 core-courses in the Electrical and Computer Engineering Department of the school in this study, are sophomore-level book courses with laboratory components. In the elementary circuits course, ECE 101, the students are introduced to analysis of linear circuits and systems. The lectures are heavily analytical in nature, and the lab experiments are structured to instruct the students to follow procedures to implement electrical circuits and obtain measurements of electrical signals. ECE 202 introduces ECE students to embedded systems and microcontrollers interfacing. While students in 202 should experience design problems through programming the microcontrollers, but the current structure of the lectures, exams, and labs will have students implement procedures and not plan, design, or contemplate engineering trade-off problems. Also currently, the students do not produce designs following appropriate instruction and official introduction to elements of the design problem. These instructions are deferred to junior and senior design courses.

The researchers in this study are the instructors of these sophomore courses and have worked to revamp the lectures and lab experiments to include design problems, to allow students to engage design problem-solving early-on in their study of Electrical and Computer Engineering. The lectures for both courses have been renovated to include design questions and to introduce students to elements of the engineering design problem, and how to approach them. Design problems have also been added to lab experiments to allow students to engage design problem solving after they have completed the systematic lab procedures. The revamped courses have been rolled out this spring of 2024, and it is the intent of the researchers to continue to offer the courses until a sizeable sample is obtained. In the following section, the results from the 202 course will be presented for the enrollment number for X02 courses are normally higher during spring semesters, but not the 101.

IV. Preliminary Results of this Study

A. *Assessing Students' Performance in Design Problem Solving*

Two populations of students were tasked to solve the same design problem in a final exam in two offerings of ECE 202. The first population, comprised 45 sophomore students who have not been introduced to elements of the design problem, nor have engaged systematic design problem solving. The other population were 52 students who have been introduced to design problem solving and have methodically engaged the design modules during spring of 2024. Two of the rubrics devised and used for assessing the students performance are given tables I and II, to identify the ability of the engineering student in devising a design solution that considers the system specifications in the problem posed, and considers and workouts the constraints of the problem.

TABLE I. Rubric Used for the Assessment of Satisfaction System Requirements in the Design Solution Proposed

Rubric Scale	Performance on Satisfying System Requirements
Unsatisfactory	Invalid design: the design does not fulfill any of the given system specifications.
Developing	The design does not fulfill one or more major system specifications.
Satisfactory	The design does not fulfill one or more minor system specifications.
Exemplary	The design correctly fulfills all system requirements of the problem.

TABLE II. Rubric Used for the Assessment of Consideration of Design Constraints in Design Problem Solving

Rubric Scale	Performance on Identifying Constraints
Unsatisfactory	No consideration of constraints in the design.
Developing	The design considers and addresses minor constraints but misses major constraints.
Satisfactory	The design considers and addresses major constraints but misses minor constraints.
Exemplary	The design considers most constraints and addresses them correctly.

Fig. 1 shows the results of the assessment of the performance of the two student population on solutions provided to the design problem, with the two populations labelled pre and post, for pre- and post- design modules application, respectively. It is evident that approximately 68.9% of the post- design students have produced designs that were either at exemplary or satisfactory level, while 60% of the pre-design students were able to produce similar designs. Approximately 29% of both populations were capable of producing developing design, were their solutions lacked multiple system requirements and have not taken adequate measures to overcome design constraints. A clear discrepancy were shown in Fig.1 for the percentages of students who performed at unsatisfactory level, for both populations.

The results showed that there is a considerable improvement of how the students approach engineering design problems when trained to solve them as the percentage of students who have approcahed the design problem with exemplary performance is 51.1%. The counter-intuitive results for the "Satisfactory" and "Developing" performances of the two populations can be explained by the simplicity of the design problem used in this evaluation, which posed an easy challenge for the population of students who were not trained on design problem solving. Also, while the course is sophomore-level, the students enrolled in class are all sophomores, some juniors or even senior students with design experiences may be taking the course; a shortcoming the researchers intend to improve in future iterations of the study.

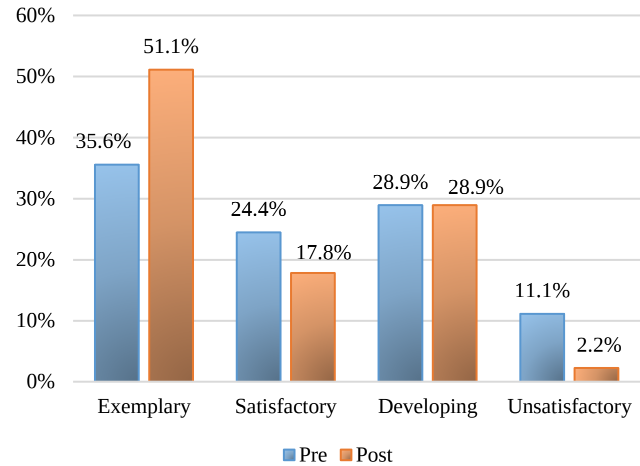

Fig. 1. The evaluation of the students' performance on a design problem for two populations of students, one pre- course revamp to involve design problem solving, and another population post- the introduction to systematic engineering design problem solving.

B. *Students' Satisfaction Surveys*

Students of the population who have encountered design problem solving have been asked to fill out surveys to gage their experience and satisfaction with the design experiences. Most students reacted positively in response to questions about their satisfaction with the design modules; Fig. 2 illustrates. Over 55% of the students preferred working on design problems to regular analytical assignments. About 76% of the students have enjoyed working on design problems, while over 80% have expressed that the design modules have helped them achieve their learning objectives and have influenced their academic growth favorably.

The dissatisfaction, and often backlash, from some students in response to the application of the design module, has been noted by the researchers. Although a minority, this group have expressed their displeasure through instructor administered and OMET feedback surveys. Their main concern was that the students were not used to producing divergent solutions and have found this aspect of design problem solving disorienting in their study. A second concern was the elevation of the degree of difficulty that the design modules have added to the sophomore-level course. While the first concern is inherent in the design problem, the instructors have noted the criticism and will modify the course instruction to better condition the students to divergent solutions. The design modules will also be modified to have a measured difficulty level that pertains better to a sophomore-level course.

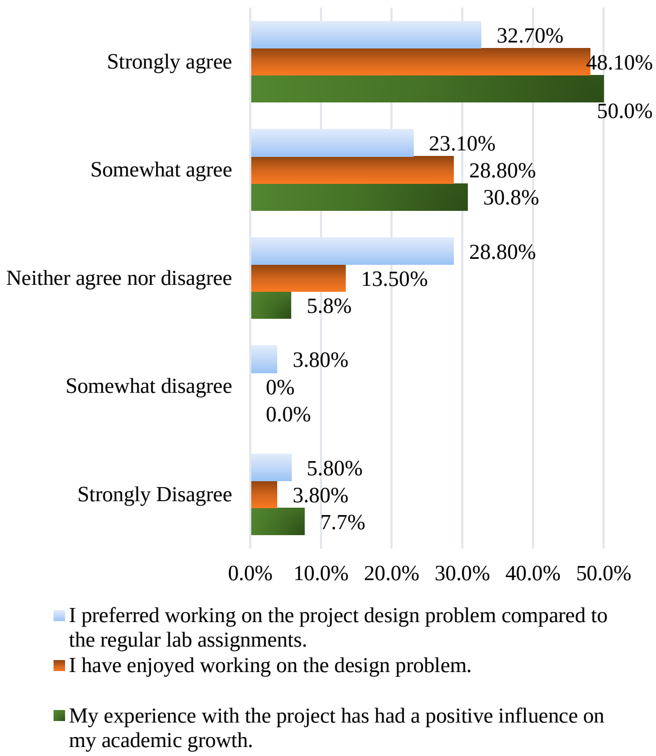

Fig. 2. The results of student surveys revealed the perception of the design modules by the majority of students in the sophomore level classroom.

V. Conclusion and Future Work

The introduction of design modules to sophomore-level ECE class clearly has had a favorable impact on ECE students. The students' performance on engineering problem solving was enhanced following the introduction of the elements of the design problem and the systematic solving of design problems. Additionally, the majority of the students have expressed satisfaction with their early introduction to engineering design problems.

There are multiple deficiencies in this preliminary effort that the researchers are determined to overcome. A wide application of design modules in sophomore-level courses is necessary in order to determine effect of developing novice design thinkers. Sufficient data from bigger student populations must be collected, and the academic progress of the student populations will be monitored towards graduation to determine the effect early introduction of design modules in ECE education on the formation of engineers and design thinkers. Furthermore, ANOVA tests comparing the student test scores to previous course offerings, will be carried out to reveal how the design problems have helped students better understand electronics topics and favorably affected their test scores. The comparison of students' solutions to design problems will reveal how the design modules helped foster divergent design thinkers. Students' surveys will reveal how the design modules helped create novice design thinkers, and problem solvers, and if the design modules have helped students grow self-efficacy, confidence and self-worth, through problem solving and producing diverse solutions.

References

[1] R. Razzouk and V. Shute, "What is design thinking and why is it important?," *Review of educational research*, vol. 82, no. 3, pp. 330-348, 2012.

[2] D. Dustegor and M. A. A. Khan, "Fostering higher cognitive skills through design thinking in digital hardware course: A case study," *ICIC Express Letters*, vol. 13, no. 10, pp. 891-898, 2019.

[3] J. M. Carroll, J. C. Thomas, and A. Malhotra, "Presentation and representation in design problem-solving," *British Journal of Psychology*, vol. 71, no. 1, pp. 143-153, 1980.

[4] B. Chandrasekaran, "A framework for design problem-solving," *Research in Engineering Design*, vol. 1, no. 2, pp. 75-86, 1989.

[5] B. Lawson, *How designers think*. Routledge, 2006.

[6] G. Goldschmidt, "Problem representation versus domain of solution in architectural design teaching," *Journal of Architectural and Planning Research*, pp. 204-215, 1989.

[7] S. Kendall, "On design reasoning: lessons from teaching architectural technology," *Design Studies*, vol. 10, no. 2, pp. 89-95, 1989.

[8] M. D. Rychener, "Expert systems for engineering design: problem components, techniques, and prototypes," 1983.

[9] B. Hillier, J. Musgrove, and P. O'Sullivan, "Knowledge and design," *Environmental design: research and practice*, vol. 2, pp. 3-1, 1972.

[10] A. Malhotra, J. C. Thomas, J. M. Carroll, and L. A. Miller, "Cognitive processes in design," *International journal of man-machine studies*, vol. 12, no. 2, pp. 119-140, 1980.

[11] L. J. Ball, J. S. B. Evans, and I. Dennis, "Cognitive processes in engineering design: A longitudinal study," *Ergonomics*, vol. 37, no. 11, pp. 1753-1786, 1994.

[12] G. F. Smith and G. J. Browne, "Conceptual foundations of design problem solving," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 23, no. 5, pp. 1209-1219, 1993.

[13] K. J. Chua, "A comparative study on first-time and experienced project-based learning students in an engineering design module," *European Journal of Engineering Education*, vol. 39, no. 5, pp. 556-572, 2014.

[14] S. Rodriguez, E. Doran, and P. Hengesteg, "Intersections of design thinking and perceptions of success for electrical, computer, and software engineering students," in *2019 ASEE Annual Conference*, 2019.

[15] F. E. Moreno and M. R. Díaz, "Learning electrical circuits for the development of critical thinking," in *Journal of Physics: Conference Series*, 2021, vol. 2073, no. 1: IOP Publishing, p. 012001.

[16] J. S. Halonen, "Demystifying critical thinking," *Teaching of psychology*, vol. 22, no. 1, pp. 75-81, 1995.

[17] J. D. Ericson, "Mapping the relationship between critical thinking and design thinking," *Journal of the Knowledge Economy*, vol. 13, no. 1, pp. 406-429, 2022.

[18] C. Savich, "Improving Critical Thinking Skills in History," *Online Submission*, 2008.

[19] L. B. Archer, "The Structure of the Design Process, Design Methods in Architecture," *Broadbent, Gefforey*, 1969.

[20] D. C. Brown and B. Chandrasekaran, *Design problem solving: knowledge structures and control strategies*. Morgan Kaufmann, 2014.

[21] B. Chandrasekaran, "Design problem solving: A task analysis," *AI magazine*, vol. 11, no. 4, pp. 59-59, 1990.

[22] M. Gross, S. Ervin, J. Anderson, and A. Fleisher, "Designing with constraints," in *Principles of computer-aided design: computability of design*, 1987, pp. 53-83.