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ASSESSING DESIGN PROCESS KNOWLEDGE IN 1ST AND 3RD-YEAR UNDERGRADUATE ENGINEERS USING A TOY DESIGN PROJECT

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Synopsis:

The purpose of this study is to compare the design process knowledge and application across the two student groups by assessing the effectiveness of the teaching methods and identifying their weaknesses.

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Abstract

Universities are using innovative teaching methods that include project-based learning and contextual engineering design. Hence, assessing the effectiveness of those teaching and learning activities is essential for moving forward. Various assessment methods such as surveys, interviews, focus groups, conversational analysis, observation, and design rubrics have been used by researchers to assess student understanding of the engineering design process. The University of Michigan - Dearborn has introduced engineering design thinking in two courses –a first-year introductory engineering course and a junior level manufacturing course— through a toy design project. This study aims to compare the design process knowledge and application across the two student groups by assessing the effectiveness of the teaching methods and identifying their weaknesses. The team was inspired by previous scholarly work to adapt an existing rubric and assess the evidence of design process knowledge as communicated through written reports, oral presentations, PowerPoint slides, and project proposals. This rubric would provide the University of Michigan - Dearborn with a more objective way of assessing students' strengths and difficulties. This work could also provide Engineering/STEM Educators with adaptable guidelines to assess engineering design knowledge as the learner develops.

Keywords: Engineering design; assessment; project-based learning; Toy design;

Introduction

Engineering design is a core competency that engineering students from all disciplines need to acquire (Atman et al., 2007; Dym et al., 2005; Simon, 2019). Currently, there is a consensus that the success of engineering programs must be measured by the effectiveness of students' design solutions to help societal needs. While the engineering science model was historically used to train future engineering (Dym et al., 2005), a shift towards more practice-based learning (PBL) engineering curricula is being implemented. Indeed, to attempt to bridge the gap between engineering theory and practice, while strongly encouraged by ABET engineering accreditation requirements, senior-level industry-sponsored design (capstone) projects were introduced (Dutson et al., 1997). Later on, engineering programs were infused with first-year engineering design courses (cornerstone design) to expose first-year engineering students to the basic elements of the design process (Agogino et al., 1992; Dally and Zhang, 1993; Dym and Little, 1999; Froyd and Ohland, 2005; Gainen and Willemsen, 1995). More recently, the importance of engineering design education gained momentum and accordingly, project-based learning emerged as a solution that provides a continuous real-world engineering design experience between freshmen and senior years.

While practice-based learning has proven to be an effective engineering education approach, quantifying the student's cognition of engineering design concepts is of high importance. Hence, it becomes essential to develop an engineering design assessment methodology to guide educators in adapting the educational strategies to meet curricular learning objectives. Accordingly, to move forward with curriculum development and improvement the following questions should be explored:

How to assess students' acquired design skills and proficiencies at a different level of residency in the engineering program?

What design skills do students demonstrate at the end of their first and third year in an engineering program?

The University of Michigan - Dearborn has introduced engineering design thinking in two courses –a first-year introductory engineering course (cornerstone design) and a junior level manufacturing course— through a toy design project. The purpose of this study is to compare the design process knowledge and application across the two student groups by assessing the effectiveness of the teaching methods and identifying their weaknesses. While inspired by the work of Atman et al., (2007), we assessed the evidence of design process knowledge as communicated through written reports, oral presentations, powerpoint slides, and project proposals.

Background and aims

Educational assessment based on learning objectives is useful in creating better learning experiences. Project-based learning facilitates the understanding of the engineering design processes and enhances collaborative learning. It has also been shown to elevate students' motivation, self-image, and self-efficacy beliefs in engineering design at all levels (Doppelt, 2003; Zhou et al., 2017). With project-based learning, students are expected to work in teams as well as identify design goals, demonstrate critical thinking, generate design ideas, and build prototypes that solve real-world problems. Teachers are also able to identify areas where students experience difficulty. Assessment of the engineering design process knowledge can be done using project-based learning (Guo et al., 2020).

Design process knowledge is difficult to assess due to its nature. Past studies have assessed engineering design knowledge through various means (Wind et al., 2019). Surveys, self-reported questionnaires consisting of close-ended or open-ended questions, interviews, focus groups, tests, observation, self-reflection journals and artifacts, are frequently used assessment techniques to measure learners' knowledge (Olds et al., 2005, Guo et al., 2020). Surveys and interviews capture unobservable data and are used to assess individual knowledge. They can be designed to be process-focused and scored using a rubric. Interviews take a large amount of time and the validity of surveys and interviews depends on the honesty of the participants

Written responses and design-step logs portray the actual knowledge gained by students (Schubert et al., 2012). Essays, videos, design step logs, design reports, final designs, or verbal protocols are valid means of presenting engineering design process knowledge for assessment. The application of design principles, ideas, relevant arguments, assumptions, limitations, methods, and procedures can be fully elaborated on using essay responses, design step logs, videos, or verbal protocols.

The verbal protocol allows participants to think out loud as they perform the design tasks. Data about the thinking process is then gathered and used to investigate design behavior (Atman et al., 2007). Atman et al. (1999) and (2005) utilized verbal protocol to document, describe and compare the student cognition of design processes. For that purpose, first-year and fourth-year students were given an open-ended design problem to solve while verbally recording their work and interaction. The results show that the seniors gathered more information, considered more alternative solutions, transitioned more frequently between design steps, and progressed further into the final steps of the design process producing higher-quality designs.

Other assessment methods include peer evaluation, the use of standardized tests, or judgment of oral presentations by an expert panel. (Campbell & Colbeck, 1998) argues that peer evaluation and the use of standardized tests tend to miss out on the assessment of design process knowledge present in reports, diaries, or design step logs. Nonetheless, the use of self-assessment and peer evaluation strategies showed increased learning outcomes and improved positive attitudes of students (Cifrian et al., 2020).

Design logs, reports, student questionnaire responses, videos, and data obtained from the verbal protocols can be assigned scores using a rubric designed to assess engineering design process knowledge. Rubrics are either analytic or holistic. An analytic scoring rubric is a reliable and more objective way of assessing students' engineering design process knowledge, strengths, and difficulties based on learning objectives. (Bailey & Szabo, 2006) assessed students' design process knowledge by having them critique a proposed process. The major points and elements of design are listed in an analytic scoring rubric. Although the result showed that the analytic rubric was too detailed and should be made simpler, it emphasized the belief that an analytic scoring rubric is a reliable and more objective way of assessing students' engineering design process knowledge, strengths, and difficulties based on learning objectives. A scoring rubric is suitable for assessing students' designs.

Assessment using videos can be used for team performance evaluation. This requires a huge amount of time. (Ambrosio et al., 2021) applied the use of a video pitch. The results showed an understanding of the design challenge and mastery of the engineering design process. Design reports can be used in the assessment of group projects in project-based learning. Assessments based only on final designs are not process-focused. (Bailey & Szabo, 2006) emphasizes the need for any engineering design knowledge assessment strategy to be process-focused. Design reports showcase the design process and are scored using a rating scale.

For engineering design tasks performed on a computer, models capable of automatically assessing students’ engagement are being developed. Additionally, artificial intelligence models are capable of predicting the future performances of students in similar tasks. (Xing et al., 2021) utilized a Bayesian network to assess 111 ninth-grade students’ asked to provide a solution to an engineering design challenge. The model was found to be efficient at predicting students’ performance.

In this study, we compare the design process knowledge and application across two student groups by identifying the design knowledge, skills, and weaknesses present in their written reports, PowerPoint slides, and project proposals using the toy design project.

Methodology

The research team selected two courses that implemented a Toy Design Project in the curriculum. ENGR100 is the Introduction to Engineering and Engineering Design course and is the required first engineering course for incoming students. The purpose of this three-credit course is to provide a general introduction to the engineering profession, engineering design, and programming using MATLAB. The course introduces the design-build-test-learn cycle through lectures, hands-on based laboratory activities, and a team project. The Manufacturing Process I course (IMSE 382) is a four-credit course that introduces the students to the fundamentals and principles of manufacturing processes for engineering materials. The purpose of this four-credit course is to provide the students with an overview of the manufacturing process's advantages, limitations, and their influence on engineering materials' mechanical and microstructural properties. Topics covered include structure and manufacturing properties of metals, casting, heat treatments, bulk deformation processes, sheet metal working processes, processing of polymers and composites, surfaces and coating, powder metallurgy, machining, and joining. Case studies of design for manufacturing and measurement of product quality; economical aspects and cost considerations in manufacturing systems are studied.

Table 1. Toy Design Project and Artifact Summaries

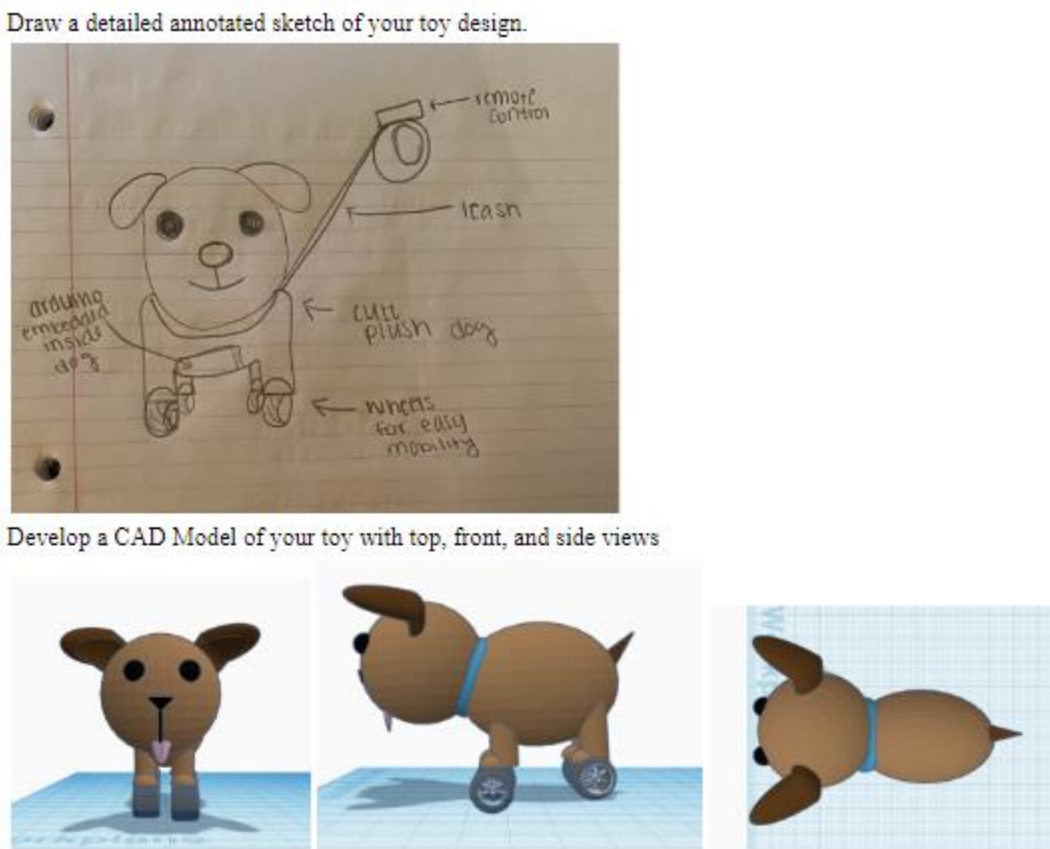
	Course	**Project Summary**	**Artifacts for Assessment**
Toy Design Project	ENGR100	Mid-Semester 2-week long project that reinforces concepts such as programming, prototyping, and design process knowledge	Final Project Report
	IMSE382	Semester-long project that reinforces concepts such as manufacturing and material selection and design process knowledge	Project Proposal Final Report Final Presentation

Students in both courses were expected to work on a team to prepare, present a manufactured product in a way that demonstrates their understanding of either the engineering design process and/or manufacturing process, technology evolution/processing-structure-property-application relationships of materials.

The first-year engineering course required students to design a simple motion-oriented toy for a child. They first must identify the need and purpose of the toy. Then gather information and generate possible toy designs. The students then select one design idea, generated sketches, and

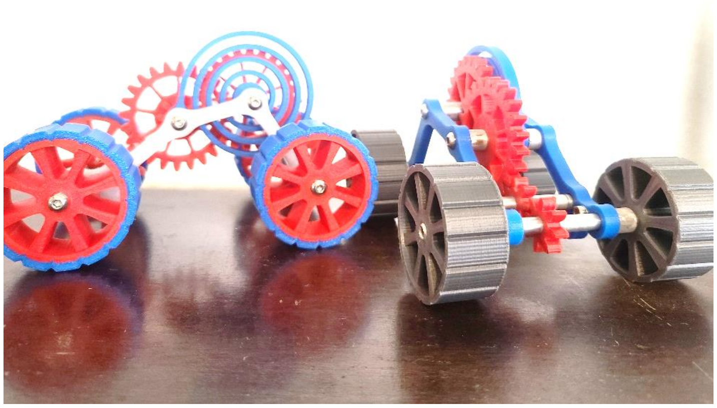
CAD drawings, and build a prototype of their toy. See figure 1 for an example of toy design projects from the ENGR100 course.

Figure 1. First-year students Annotated Sketch and TinkerCad Model



In IMSE 382, Manufacturing Processes I, students are asked to work in groups to design and manufacture a product that stimulates kids' engagement in STEM through educational toys . The students are given a few weeks to conduct research and choose a STEM concept to be demonstrated through a toy design and provide a manufacturing plan through a consultation first between the students and later with the instructor. The students submit a project proposal presenting their research, selection of STEM concept annotated sketches detailing the techniques they intend to use for manufacturing. Accordingly, the students will have to take the appropriate machine shop training. After the semester-long project, the students write a report detailing the design of the selected part, the manufacturing strategy, and a description of the manufacturing experience. The students present their machined products to their colleagues so it can be tested and assessed. For the third-year design course, the students designed and manufactured a pull-back wind-up car. The toy was manufactured using machined metallic rods and 3D printed components. The final prototype is shown in Figure 2.

Figure 2. Final design by third-year students



Rubric

The rubric used in this study was adapted from the design process knowledge research of Atman et al. (2007) in which they identified ten design activities that were organized into three stages. Additionally, evidence of each of the design activities in the students submitted work was scored on a scale from 0-2. The complete rubric is shared in the Appendix A.

After we selected this design process model for assessment, the second and third authors reviewed the design stages and operationalized how these activities should emerge in each of the student artifacts (i.e., final reports, presentations, project proposals) and proposed additional activities that did not fit within the selected model. Then the first author applied the rubric to one artifact and received feedback from the research team. Following that she continued to assess and analyze the remaining artifacts for one student team from each course. There were four artifacts analyzed as shown in Table. 1.

Results and discussion

To answer the research question (What design skill do students demonstrate at the end of the first and third year using the toy design project), we analyzed each level's essay responses based on the adapted scoring rubric. The stages according to the rubric used in the assessment are problem definition, gathering information, generating ideas, modeling, feasibility analysis, evaluation, decision, communication and prototyping, material selection, and collaboration.

A comparison between the two different levels showed that the rating for the third-year students was higher in all stages when compared to the first-year students, as shown by the quality of the prototypes. They were able to gather and specify more details in their written report than the first-year students. The two groups included cost information and the method and process of fabrication.

Our examination of the Toy Design Project demonstrates a wide diversity of design thinking and creative skill among the students. The two student groups exhibited satisfactory idea generation and modeling of their design. However, the first and third-year design reports lacked a clear problem definition. The two student groups clearly understood the goal of the toy design project. The students researched online to gather information that can improve their designs. The third-year students gathered more information than the first-year students. The third-year students developed a working prototype whereas the first-year students came up with a low fidelity prototype.

Finally, communication of ideas in written or oral form is a professional skill that should be developed by engineers. The extent of their communication skills was portrayed in their reports. The two groups of students included working drawings, such as detailed CAD models or sketches for prototyping and material selection. First-year students made use of Tinkercad to prepare their drawings. The third-year students gave a detailed CAD design, material selection, and manufacturing processes in their written report.

Conclusion

Institutions and faculty members work hard to improve the effectiveness of engineering design programs. For the University of Michigan-Dearborn to ensure that the engineering design courses for first-year and third-year better equip the students with the required skills, a rubric was designed to assess students' design process cognition. Findings show that the students in both courses showcased creativity, critical thinking, and analysis. Student's reports showed understanding of the design process and confidence in applying the gained knowledge in solving a problem.

Based on the results of this preliminary study, our rubric was able to assess students' acquired design skills and proficiencies at different levels in the engineering program. We see that although both student levels showed increased knowledge and confidence level upon the completion of a project, both levels did not clearly define the problem for which the toy design project was created. Hence, more focus should be placed on problem definition to enable both levels to imbibe and be able to apply this skill.

In addition, the first-year students demonstrated idea generation, modeling, communication, and prototyping. The third-year students demonstrated information gathering, idea generation, modeling, feasibility analysis, evaluation decision making, communication, and prototyping. The third-year students were able to gather more information and presented a better model of their design than the first-year students. They also selected better materials for their prototype as is seen in the images. These results align with our research question and justify the use of the adapted rubric in assessing the engineering design process.

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APPENDIX

Design Stage	0	1	2
Problem Definition Defining what the problem really is ● Identifying criteria and constraints; saying what they imply for the solution ● Summarizing elaborating, reframing the problem	No mention of needs assessment or design criteria.	Mentions that a needs assessment should be done OR that design criteria should be established	Mentions that user needs should be collected and that these drive the definition of design criteria.
Gathering Information Searching for and collecting information (i.e., facts, data) needed to solve the problem ● Asking/seeking for information	No mention of information that was not provided in the problem statement(s) or no mention of needing more information	Mentions/makes reference to needed information beyond what was provided	Provides information about the problem that was not provided in the original project description
Generating Ideas Thinking of up potential solutions (or parts of solutions) to the problem ● Coming up with an idea/set of ideas for a solution	No mention of alternative ideas that were generated	Some mention of the activity of idea generation and/or acknowledges it is important	States that multiple ideas were generated (brainstorming), provides evidence of multiple ideas, work indicates that idea generation is an important and/or a valuable activity.
Modeling Detailing how to build the solution (or parts of the solution) to the problem. Applies to initial concepts and final design ● Estimating the costs, calculations, measure ● Fitting the solution element(s) in the larger design ● Considers material properties needed to build solution	No mention of how the solution could/would be built.	Some evidence of detailing how the solution will be built but with minimal details	Provides strong evidence of modeling that includes details such as costs, materials, measurements, and process
Feasibility Analysis (maybe a weaker area for both) Assessing and passing judgment on a possible or planned solution to the problem (parts of the problem) ● How well this solution will work	No mention/evidence of feasibility analysis	SImple statement that the solution will work or will function as designed. No discussion or evidence that it	Provides evidence that the solution meets problem definition, criteria, constraints, and is functional

● Examining how well the solution will meet problem definition, criteria, constraints ● Testing -		meets problem definition, criteria, constraints	
Evaluation Comparing and contrasting two (or more) solutions to the problem within a specific set of dimensions (i.e., strength, costs) ● Specifying tradeoffs among alternative solutions ● Applying a tool/scheme for comparing and contrasting potential solutions	No mention of the decision-making process or evidence of comparison between solution dimensions	Some evidence Evidence that decision-making on design criteria/user needs has because a solution is presented but the evidence is lacking.	Explains how decision-making on design criteria/user needs occured. Or provides evidence that decision-making on design criteria/user needs was done and mentions specific technique strategies, such as a screening or scoring Matrix
Decision Selecting one idea or solution to the problem (or parts of the problem) from among those considered. ● Selecting the type of material, process, design element to use from among alternatives ● Eliminating options	No evidence that the student/ team considered alternatives	Some evidence that material properties, processes, design aspects were considered but lacks details	Explains the process used to make decisions throughout the project. Provide evidence that decisions were made between alternatives.
Communication/Prototyping Communicating elements of the design in writing (sketches, diagrams, lists, reports), or with oral reports to contractors and the community,	No mention of building prototype or sketching or final design. No mention of testing.	Includes evidence of communication, the prototype is well thought out and includes annotation to describe functions	.provides extensive evidence of a functional prototype, well-developed sketches and other forms of communication
Other Activities that did not align with adapted design stages ● **T**esting ● Collaboration	No evidence of testing the final or later stage solutions	Evidence of testing is limited to a statement that testing was performed.	Explains how the built designs were tested to determine if they meet established design criteria/user needs

Summary

Score for each of the Design Activities

0 - no mention/ evidence of the design activity. Or mere naming of the design activity with no explanation

1 - if there is evidence of that the design activity was completed but no elaboration

2 - evidence goes beyond the description of the design activity and elaborates on specific strategies or techniques used to complete the design stage