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Integration of Design Process, 3D printing, Simulations and Experimental Testing in a Laboratory through Design-Build-Test Cycle

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Abstract
Additive manufacturing (3D printing) has become an integral part of engineering design and lab courses in K-12 and higher education. Low-cost and readily available 3D printers allow integration of design, prototype manufacturing, and testing which is otherwise difficult to incorporate using traditional, subtractive manufacturing methods in courses. To that end, the authors designed a four-week design-build-test (DBT) lab for junior mechanical engineering students. The lab meets the following learning goals; 1) develop proficiency in using a desktop 3D printer, 2) explain the impact of selected 3D print settings on dimensional accuracy and tensile strength of a shape, 3) evaluate the use of simulations in the engineering design process, and 4) use data to improve the design. The entire class of junior mechanical engineering students, approximately 80 students annually, are split into teams of four to five students per team. Collectively, the class investigates the impact of infill density (20, 40, 60, 80, 100 %) and three print orientations on the dimensional accuracy and strength of a printed part under tensile load. Each team uses the data in conjunction with static, structural simulations to redesign the original part without increasing the mass, volume, size, or manufacturing time. The DBT lab sequence concludes with a written report and an oral presentation. The lab provides the students with a DBT sequence while investigating a specific additive manufacturing method. The investigation allows students to apply and learn the engineering design process, the use of simulations in engineering design, experimental tensile testing, quality assurance methods, and sophisticated statistical analyses. The feedback from the students indicates that the DBT lab sequence; a) provides an appropriate level of challenge, b) keeps students engaged, c) enhances learning, and d) equips students with multiple, different tools for a successful DBT cycle, without a significant requirement for lectures.

I. Introduction

Engineering courses that employ experiential learning techniques, wholly or in part, have gained popularity in recent years and are a major focus of engineering pedagogy discussions and research [1]. In an experiential learning environment, students are directly and actively applying the concepts and principles being studied [2]. A course that successfully implements experiential learning techniques can provide the student with a learning environment that is exciting, challenging, and spurs creativity [3].

The Engineering Design, Build, Test (DBT) framework is one type of experiential learning modality and involves iterative hands-on design, prototype manufacturing, and experimentation to meet defined technical and end-user specifications. DBT curricular experiences provide a context for students to practice critical design skills and an opportunity for students to learn deep lessons about the nature of the engineering design process, including project and team management [2, 4].

Additive manufacturing (also referred to as 3D printing) has become an integral part of engineering design and lab courses in K-12 and higher education. Low-cost and readily available 3D printers allow prototype manufacturing and testing which is otherwise difficult to incorporate using traditional, subtractive manufacturing methods in courses. 3D printers have great potential beyond simply serving as a prototyping tool.

The objective of our work is to develop, implement, and assess an experiential learning curricular activity for third-year mechanical engineering students at a four-year university. The authors conducted a four-week DBT project in the required, junior-level, lab course. The desired student learning outcomes were mapped to ABET outcomes 2, 5, and 6, related to applying engineering design, functioning effectively in a team, and conducting experimentation and data analysis, respectively [5].

II. Lab description

The Design-Build-Test (DBT) lab is designed to take place over 4 weeks (one 3-hour session per week), and the goal is to understand some of the subtleties of 3D printing (print orientation, infill, repeatability, strength) and make sure that all students understand how to use the technology. The lab does not have any pre-requisites, however, students enrolled in the course have taken a semester-long, required course in (a) SolidWorks to help with 3D solid modeling, (b) MATLAB to help with graphing and analysis, (c) mechanics and materials to help with using FEA results to predict failures, and (d) analysis and design to help with 3D printing, prior to this lab.

The learning outcomes for the lab are to

(1) Explain variability in the fused deposition method (FDM) and incorporate the understanding towards designing a product or refining the design of a product
(2) Use simulations to predict the impact of changes in a design
(3) Develop proficiency in using a desktop 3D printer (LulzBot series) to fabricate a product to meet desired conditions.
(4) Use statistical methods to test, determine product variability and compare predicted and actual performances of a design.

The DBT lab is executed as a project in which students are tasked to use 3D printing to design a strong carabiner shape for daily use applications. The students are given the following goals:

(1) To understand the effect of infill density and print orientation on the tensile strength of the shape, location of the failure, and dimensional accuracy
(2) To use the outcomes from goal 1 to redesign the shape to make it stronger without increasing mass, cost, size, and manufacturing time while maintaining a minimum internal space to retain "functionality."

The project tests a total of five infill densities: 20, 40, 60, 80, and 100% and three print orientations: horizontal, spine, and vertical (Figure 1). Each team is given a specific combination of orientation and infill to manufacture for the experiments (details shared below). As each team experiments and collects data, they share the outcomes for their specific experimental set (combination of orientation and infill) through a shared spreadsheet. This gives the entire class (~ 15 teams) access to the force at which failure occurred, the location at which failure occurred, and dimensional accuracy for all five infill densities and all three print orientations.

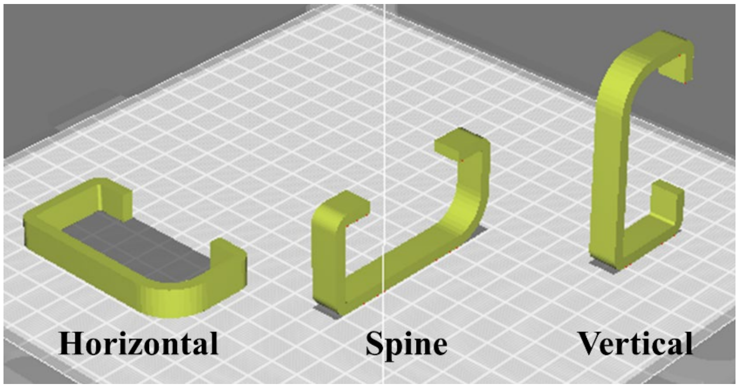


Figure 1 Three print orientations investigated by the class

Weekly Milestones:
At the core of the laboratory is the design of a 3D printed "c-clip." Each day begins with a short 'lecture' that introduces the students to the relevant topics to meet that day's milestones, followed by significant hands-on project time during which students complete that day's milestones. The lab progresses as follows:

Week 1

- Lecture: Introduction to additive manufacturing technology in general, in-depth discussion of fused deposition modeling (FDM), project goals and milestones.
- Activities: In groups, students are given an engineering drawing of a c-clip (Figure 2A). They use SolidWorks to create a 3D solid model from the engineering drawing. They then prepare the model to be 3D printed and initiate their prints with assigned print orientation and infill percentage. Each team is required to print 5-7 clips in different orientations. Finally, groups are asked to use finite element analysis (FEA) to determine force and location at which the failure would occur under tensile loading. Simulated failure is noted as the force at which the maximum stress on the geometry is greater than the yield or ultimate stress of the material used (PLA, in this case). Students use SolidWorks to conduct FEA.

Week 2

- Lecture: Introduction to statistics for quality control and a discussion of dimensional measurement techniques
- Activities: Student groups are first asked to measure various dimensions of the clip and upload them to a shared database (Figure 2B). Using the shared database students develop statistical measures and present their data visually. They then use a tensile tester to break all their clips to determine the maximum load the shape can withstand under pure tension and location of failure (Figure 3A). Experimental failure is noted as the tensile force at which the shape breaks.

Week 3

- Lecture: Before class, the instructor performs an analysis of the data and goes through a discussion with the class (Figure 3B). Topics covered include inference, outliers, and data presentation. The discussion focuses on identifying trends, if any, best practices for using data to make decisions about design and the use of FEA in the engineering design process.
- Activity: Based on the data analysis, students redesign the clip to maximize the strength while remaining smaller and lighter and using less time to build on the printer than the original c-shape. The redesigned shape must also maintain functionality of the clip by maintaining a minimum internal area. They create a solid model of their redesigned part,

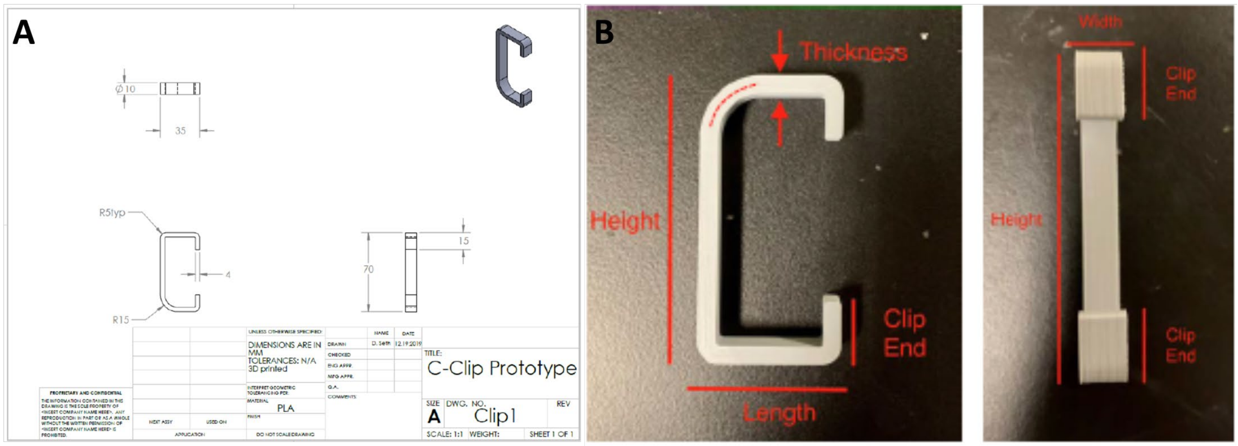


Figure 2. (A) Engineering drawing of the initial c-shape provided to the students. (B) Measurements made on the printed c-shapes to determine the dimensional accuracy of the 3D printers

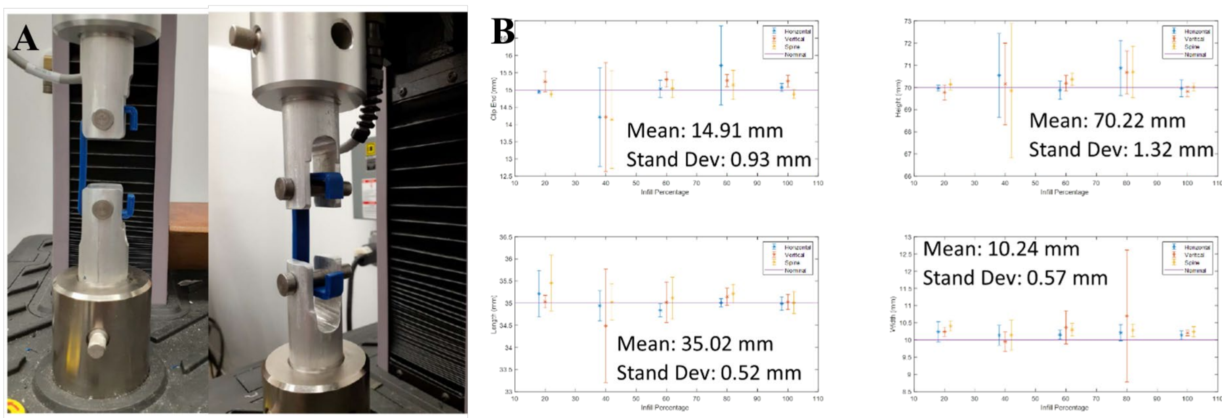


Figure 3. (A) A 3D printed c-shape set up on a tensile testing machine to determine the force and location at which failure occurs. (B) An example of summarized data to illustrate dimensional accuracy as a function of infill percentage and print orientation, created by the instructor

use FEA to validate their redesigned shapes, and print 5-7 samples of their final, revised redesigns. Students reflect on the inaccuracies in FEA and use FEA to investigate the trends in strength as they change the geometric design of the part, rather than using FEA as an accurate predictor of strength.

Week 4

- Lecture: On the last day of the lab, the lecture focuses on highlighting the use of prototyping, simulations and DBT cycle in the broader engineering design or product development process. The instructor shares the broader applications of FDM, and students share their main takeaways from the lab.
- Activity: Students bring 5 – 7 3D printed samples of their redesigns (Figure 4), give a short presentation on their redesign, and determine the force and location of failure using the tensile testing machine.

Figure 4. Some examples of the redesigned shapes created by students in week 3 and 3D printed before week 4's session

Deliverables:

Students complete and submit two short deliverables in the first four weeks, a full technical report in week 10 and an oral presentation in week 13 of the semester. The short deliverables are designed to be included in the full technical report. The first short deliverable is a schematic to show the measurements made for assessing dimensional accuracy as well as a photograph of the failed shape for describing what failure looked like and how the location of failure was measured. The second short deliverable is a graph demonstrating the effect of infill density on the dimensional accuracy, failure force and location of failure (each student submits one graph). The full technical report and presentation are submitted outside the four weeks as a part of the class in which this lab is embedded. The report primarily focuses on the work done in weeks 1 and 2 while the oral presentation focuses on the work done in weeks 3 and 4 (re-designs) (Figure 5).

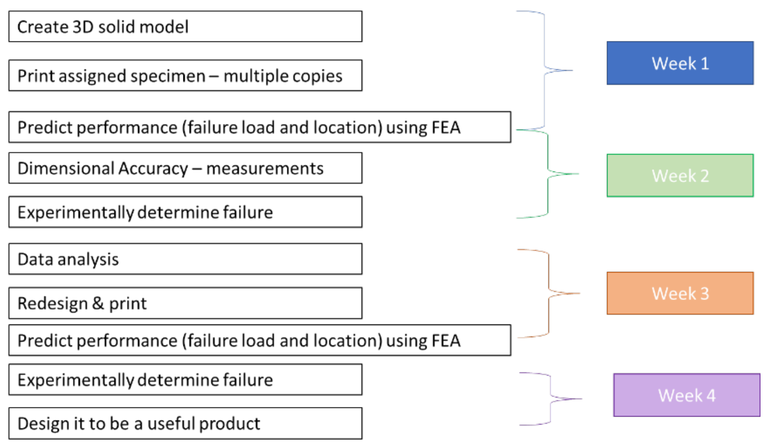


Figure 5. The overall workflow for DBT lab (4 weeks long)

III. Objective and research questions

The objective of the study was to evaluate the efficacy of the lab in integrating design in a laboratory setting. The lab was designed to offer a Design-Build-Test (DBT) cycle that can successfully integrate the design process, simulations, experimental testing, and 3D printing through a 4-week project while providing students an opportunity to be creative through an engaging, open-ended project of appropriate level of challenge.

The assessment of the lab aimed to answer the following research questions:

(1) What resources and tools do students find helpful during the lab?

(2) Which major attributes of the lab are perceived as educational by students?
(3) Which major attributes of the lab posed a challenge for students?
(4) Which major attributes of the lab were engaging for students?

IV. Methods

Sample: The DBT lab was assessed over a period of two years (2019, 2020). The students were enrolled in the required junior-level lab that met once a week in-person. A total of 39 students participated in the voluntary, anonymous study.

Data collection: All students enrolled in the course were requested to complete a voluntary, anonymous survey via email. Google forms was used to administer the survey. A total of 26 questions were included in the survey both years. The list of questions is presented in Table 1. Four primary constructs were measured. We examined resources that the students found ***helpful*** while completing the lab, as well as aspects of the lab that students perceived as ***educational, challenging, and engaging***. To gather information about helpful resources and what students found engaging, a qualitative, open-ended questions were added to the survey (Q1, 17, Table 1). One question asked students rate their overall experience working on the DBT lab (Q26, Table 1). The remaining 23 questions asked students to indicate their level of agreement with a statement on a 5-point scale; strongly disagree, somewhat disagree, neither agree nor disagree, somewhat agree, strongly agree (Q2-16, Q18-25, Table 1).

Data analysis: The collected data from both years was screened for identifiers and if any found were deleted. The anonymous data was then analyzed using statistical methods to identify differences and trends.

1. The qualitative responses were coded using emergent coding technique [6] where each open-ended response was mapped to a prominent code which related to a specific attribute of the DBT lab. Q1 and 17 asked students to share what they found most and least helpful and engaging. Therefore, the responses were coded into two themes: "most" and "least". Within each theme, the attribute shared by the student in their responses was used as the code. For example, if a student responded "…breaking the clips was fun" then, in the theme named "most" this response was coded as "tensile testing". If a subject responded "…waiting for 3D prints to be ready was not fun", in the theme named "least" this response was coded as "3D printing". A total of seven codes were identified for Q1 and Q17 in each category. Once coded, percentages were calculated to mathematically observe which attributes of the lab were more prominent than others in each theme.

2. The quantitative data within each category (Table 1) was first tested for statistically significant differences using the Friedman's ANOVA test. This test is used to detect statistically significant differences in multiple discrete measurements made from the same subject. Then, Dunn's test was applied to detect between which two groups the significant differences lied. SPSS was used to conduct the tests with 95% confidence interval.

3. The descriptive statistical analysis of the numerical, discrete data involved computing the median and the interquartile range (IQR) for each question.

Table 1. Summary of questions included on the survey

Category	#	Question
Helpful resources/tools	1	Share what you found the most and least helpful in completing the lab
		Indicate how strongly you agree with the following statements related to aspects of the DBT lab:
	2	Finite element analysis was helpful, in general, in completing the lab
	3	Design process was helpful in completing the lab
	4	Experimental tensile testing was helpful
Educational		Indicate how strongly you agree with the following statements related to aspects of the DBT lab:
	5	The DBT lab was educational. I feel like I learned a lot
	6	The carabiner project was educational.
	7	3D printing was educational. I learned a lot about this manufacturing process
	8	The design process was educational. I learned a lot about the process.
	9	Finite element analysis was educational. I learned how to use the software
	10	Experimental tensile testing was educational.
Challenge		Indicate how strongly you agree with the following statements related to aspects of the DBT lab:
	11	The DBT lab was challenging
	12	The carabiner was a challenging project to design, build and test
	13	3D printing was challenging
	14	The design process was challenging
	15	Finite element analysis was challenging
	16	Experimental tensile testing was challenging
Engagement	17	Share what you found the most and least fun/engaging in the lab
		Indicate how strongly you agree with the following statements related to aspects of the DBT lab:
	18	The DBT lab was fun
	19	The carabiner was fun to design, build and test
	20	3D printing was fun
	21	The design process was fun. I enjoyed learning about it
	22	Finite element analysis was fun
	23	Experimental tensile testing was fun.
	24	I felt like I was engaged in the lab activities and tasks
	25	I had fun
General/Overall	26	How would you rate your overall experience working on the DBT lab

V. Results

Overall, the results showed that the DBT lab and selected project provided an optimal balance between learning, challenge, and engagement, and successfully integrated the design process, simulations, 3D printing and experimental testing through a project. On a scale of 1 – 5, with 5 being the higher score, students reported a median of 4 (IQR = 0.5) for their overall experience in the lab (Q26, Table 1, Figure 6). The remainder of this section details the results related to four main categories: helpful resources, educational value, level of challenge and level of engagement. The results summarize how student rated the overall DBT lab and five attributes of the lab (the project, 3D printing, design process, FEA, experimental tensile testing) in each of the four categories.

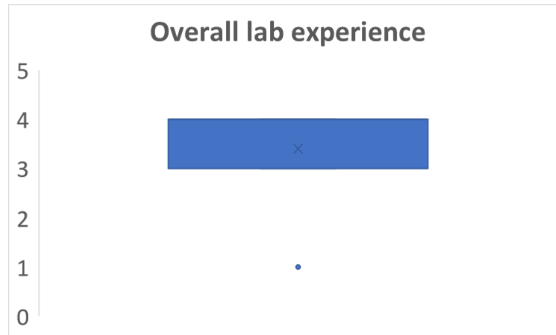


Figure 6 Median response for students' overall feedback on the DBT lab

1. **Helpful resources:** Through the quantitative questions (Q2,3,4), students found FEA, design process and experimental tensile testing useful to complete the DBT lab. Out of the three, students found FEA to be the most useful following by design process and material testing. There were statistically significant differences between the median response to FEA and design process as well as FEA and experimental tensile testing. There was no statistically significant difference in the median response to design process and experimental tensile testing. The responses to the qualitative question (Q1) showed that 75% of the students found SolidWorks/CAD most helpful in completing the lab. Following that 60% students found the design process helpful, 55% students found FEA helpful, 25% students found 3D printing helpful, 15% students found material testing helpful and 5% students found the instructors/TAs as the most helpful resource. 20% of students found FEA to be **least** helpful, followed by 5% students who found the design process and material testing to be least helpful. The low numbers in the "least" theme was an indication of a good use of resources for students to complete the lab.

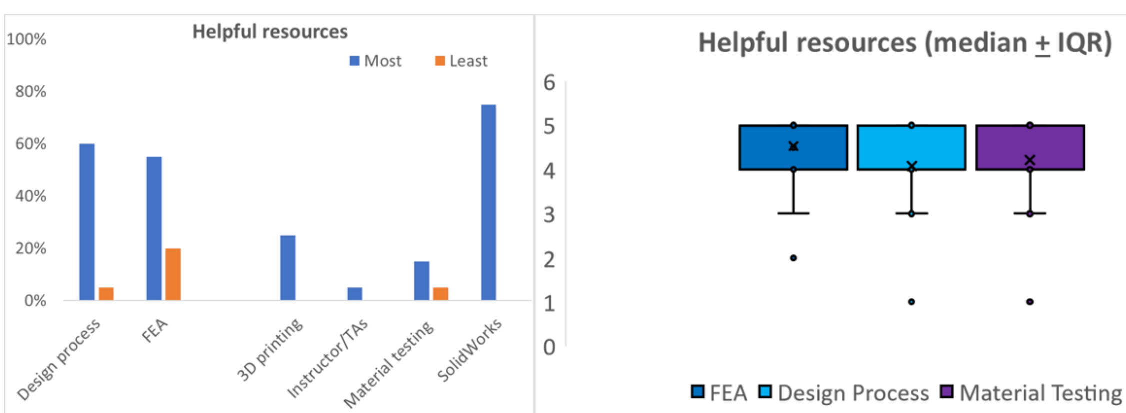
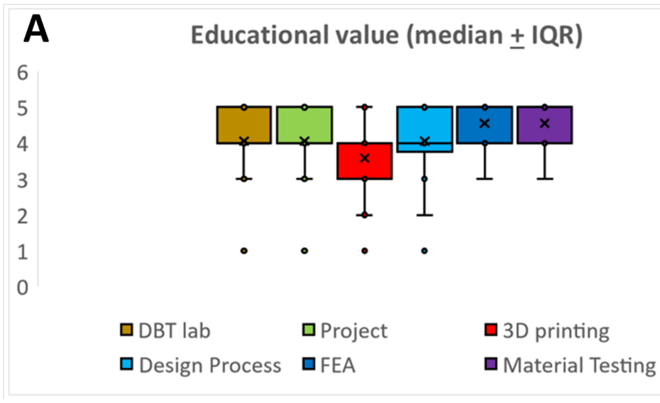


Figure 7. Summary of students' response to attributes they found helpful in completing the DBT lab.

2. **Educational attributes of the lab:** Through the quantitative questions (Q5-10), students found FEA and experimental tensile testing to be the most educational attributes of the lab. There was no statistically significant difference between the median for the above two attributes. Next, students found the design process, overall DBT lab and the project to be educational. There was no statistically significant difference between the median for design process, DBT lab and the project. The students found 3D printing as the least educational attribute of the project. There was statistically significant difference between the median for 3D printing and the median for all other attributes. Figure 8A illustrates the computed medians and the associated interquartile range (IQR) and figure 8B illustrates which pairs had statistically significantly different medians (S = significant, NS = not significant).



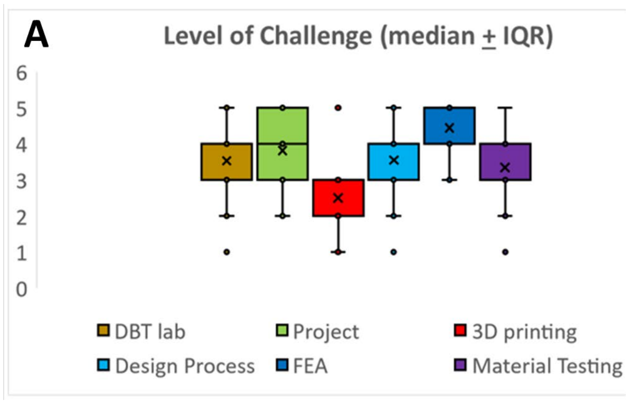
B

EDUCATIONAL	DBT lab	Project	3D printing	Design process	FEA	Tensile testing
DBT lab		NS	S	NS	S	S
Project			S	NS	S	S
3D printing				S	S	S
Design process					S	S
FEA						NS
Tensile testing						

Figure 8. Summary of students' responses related to which attributes they found educational

3. **Level of challenge:** Through the quantitative questions (Q11-16), students found FEA to be the most challenging and 3D printing and experimental tensile testing to be the least challenging part of the lab. The medians for FEA and 3D printing were statistically significantly different from the medians for all other attributes. Although the computed median values for 3D printing and experimental tensile testing were the same, the distribution showed a statistically significant difference. The overall distribution showed that students perceived the experimental tensile testing more challenging than 3D printing. The students perceived the overall DBT lab, the project, and the design process to be similarly challenging (median = 4) and there were no statistically significant differences between the medians for DBT lab, project, and design process. Figure 9A illustrates the computed medians and the associated interquartile range (IQR) and figure 9B illustrates which pairs had statistically significantly different medians.

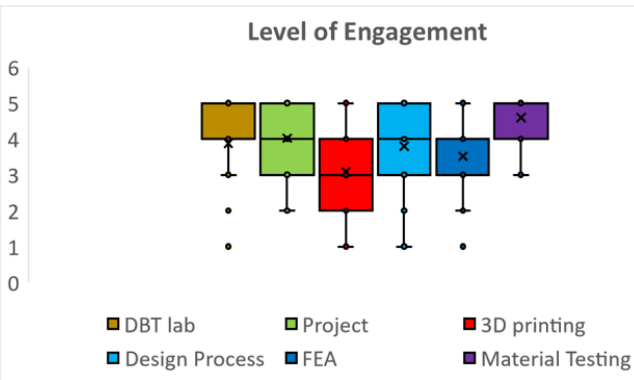
4. **Level of engagement:** Through the quantitative questions (Q18-24), students found experimental tensile testing to be the most engaging and 3D printing to be the least engaging (Figure 10). The medians for experimental tensile testing and 3D printing were statistically significantly different. Further, the median for experimental tensile testing was statistically significant. larger than the median for all other attributes. The computed median values for DBT lab, project, design process and FEA were the same (median = 4) and there was no statistically significant difference between these medians. Two additional quantitative questions were used to measure engagement further. There was no statistically significant



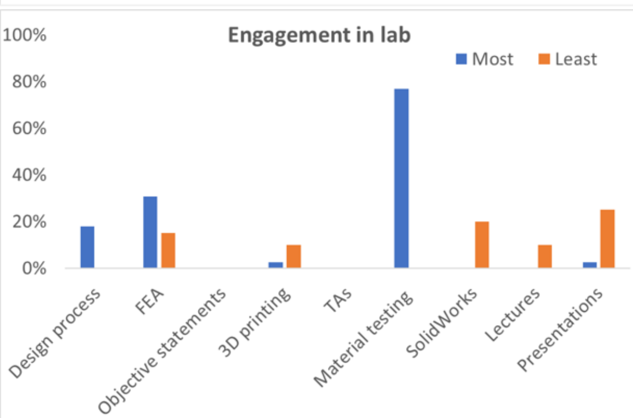
B

CHALLENGING	DBT lab	Project	3D printing	Design process	FEA	Material testing
DBT lab		NS	S	NS	S	NS
Project			S	NS	S	S
3D printing				S	S	S
Design process					S	NS
FEA						S
Material testing						

Figure 9. Summary of students' responses related to which attributes they found challenging



FUN/ENGAGEMENT	DBT lab	Project	3D printing	Design process	FEA	Material testing
DBT lab		NS	S	NS	NS	S
Project			S	NS	NS	S
3D printing				S	NS	S
Design process					NS	S
FEA						S
Material testing						



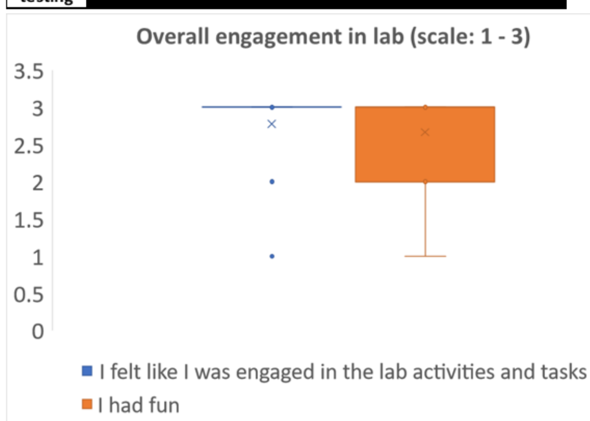


Figure 10. Summary of students' response to attributes they found engaging and their overall feedback on engagement in the DBT lab

difference between the medians for Q24 and Q25. The scale for these two questions was from 1 to 3, with 3 being the highest agreement level and the median values for Q24 and 25 was computed to be 3, indicating that students felt engaged during the lab and had fun. The responses to the qualitative question (Q18) showed that 77% of the students found experimental material testing to be the most engaging part of the project, followed by 31% and 18% students who found FEA and design process to be the most engaging part of the project respectively. 3% of students found 3D printing and presentations to be the most engaging part of the lab. On the other hand, 25% of students found presentations to be the least engaging part of the lab. 20% students found SolidWorks and 15% found FEA to be the least engaging part of the lab. Finally, 10% of students found lectures and 3D printing to be least engaging part of the lab. The lower numbers in the "least" theme was an indication of active engagement and enjoyment for students while complete the lab (Figure 10).

VI. Discussion and Conclusion

Overall, the lab provides a balance between creativity and challenge, and a combination of useful technical resources to execute the DBT cycle within four weeks. The students found the various elements of the lab helpful, educational, challenging and engaging. 3D printing was scored as the least engaging or educational component of the lab; this can be attributed to students' prior familiarity with the machine and the process. By the second semester of the junior year, which is when the lab is offered, students have used 3D printing in at least 3 courses. Additionally, an argument can be made that the process of 3D printing a part is not as hands-on and engaging as setting up a physical piece on the tensile testing machine and watching it break. Once a 3D solid file is imported to the 3D printer as a g-code, the manufacturing of it is quite hands-off and this could be viewed as less engaging by the students. The use of new tools like FEA and tensile testing machine did not deter the students from engaging with the tools, even though FEA was scored to be the most challenging aspect about the lab. FEA allows students to alter geometries of their designs and observe the impact of geometric changes on the strength of the shape. Students found this aspect engaging and useful. This can be attributed to the successful integration of FEA in the DBT lab, as opposed to a course where the simulation work was not integrated with a broader project. Lastly, it was interesting to note that there were no statistically significant differences between students' response to DBT lab, the project and design process in either of the three categories: educational, challenging and engaging. In other words, students, as an aggregate, found the overall DBT lab, the specific carabiner clip-inspired project, and the design process educational, challenging and engaging at similar levels. This can further hint towards a successful integration of the design process with the lab through the project.

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