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Work in Progress: The Roles of Design and Fabrication in Upper-Division Mechanical Design Courses

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Abstract

This work in progress (WIP) paper focuses on two aspects of upper-division undergraduate mechanical design courses: (1) how the engineering design process is enacted in the course and (2) how fabricating physical artifacts relates to course learning outcomes in design and analysis. In this work, we conduct an extensive review of undergraduate mechanical engineering curricula across several institutions to understand students' design and analysis backgrounds prior to taking upper-division mechanical design courses. We also develop two survey instruments focused on project-based learning within mechanical design courses. The first survey focuses on how the design process is enacted by students during their projects. The second survey examines how students make fabrication decisions to support their project work.

A pilot study using both instruments was performed with undergraduate students who had previously taken an upper-division mechanical design course. Preliminary results from the design survey highlight generally high student engagement with multiple stages of the design process but suggest limited participation in both user-oriented design and analysis. Initial results from the fabrication survey suggest wide variation in the extents to which availability, advising, design decisions, and project management influence fabrication decisions. This decision process should be explored further through qualitative follow-up questions in future work. Additional future work includes (1) refining survey instruments, (2) survey deployment to faculty, machine shop / makerspace staff, and broader student study participants, and (3) examining results disaggregated by different curricular and project contexts.

Introduction

This work in progress (WIP) paper describes preliminary survey instruments, initial results, and future implementation plans for a study of instructor practices and student experiences in upper-division mechanical design courses. For this work, we define upper-division mechanical design courses as courses focused on the analysis, detailed design, and implementation of predominantly mechanical systems, mechanisms, and machine components. These courses generally build on both topics learned in foundational mechanical engineering subjects (e.g., mechanics of materials, dynamics) and earlier exposure to the engineering design process through cornerstone design or introduction to engineering courses.

Several previous works have described implementations of design projects within upper-division mechanical design courses. These projects ideally require applying course material, including detailed design and analysis, alongside a broader understanding of the engineering design process, to support successful design documentation and/or physical implementation. Project topics can include participation in student design competitions, instructor-selected topics, and student-proposed machines. These projects can facilitate learning goals including applying course material to an ill-posed problem [1], [2], connecting multiple course topics [3], [4], preparing students for industry [5], and promoting systems-level thinking [6].

This work in progress focuses on instructor and student perceptions of how the engineering design process is enacted during such projects. We aim to understand how instructors balance analytical skills, creativity, and detailed design in course activities. This work also investigates how students apply prior knowledge of the design process and how their understanding of the design process is further shaped by their experiences in the mechanical design course. We also aim to elucidate where faculty and students hold differing perceptions of what course activities are considered design work and where design concepts might be obfuscated by an activity or class structure. Understanding these perceptions can help faculty reflect on their course design and identify where changes to course activities or framing are needed to meet instructional goals.

Of particular interest in this work are projects that require not only detailed mechanical design and analysis, but fabrication of a mechanical assembly. Fabrication projects are often included in mechanical design courses (e.g., [7], [8], [9]) because they require students to complete a full design process, including a physical implementation. Students apply and contextualize course material, build hands-on mechanical engineering skills, and experience professional practices such as teamwork and project management. This work aims to measure how student experiences align with these goals. We also seek to identify potential disconnects between how a fabrication project is executed and the design and analysis skills taught in the class. For instance, students may employ 3D printing to manufacture project components, but this decision may be driven by cost or availability constraints instead of an analysis-supported design recommendation. Understanding how fabrication decisions for mechanical design projects are made can help instructors develop projects that emphasize and build on the course material. These findings can also help improve project advising from both instructors and machine shop / makerspace staff.

Curricular Context

One goal of this work is to identify how students utilize and build on their understanding of the design process while taking upper-division mechanical design courses. To better characterize students' prior knowledge and experience with the design process, we conducted a curriculum review of published course catalogs. This curriculum review aims to inform survey development that can be applicable to a broad set of institutions. The curriculum review sought to assess (1) what percentage of upper-division mechanical design courses require an explicit prerequisite or corequisite course in design and (2) how that background compares to other core mechanical engineering subjects. The prerequisite chain for all courses was followed as far back as information was available (to courses such as statics and first year math and physics). We additionally flagged programs that included a prior design course in their curriculum but did not designate that course as a specific prerequisite for upper-division mechanical design coursework.

We identified schools for the curriculum review from a national (US) ranking of undergraduate engineering programs [10]. While rankings are not an objective measure of curriculum quality, these lists provide a convenient pool of institutions that have received recognition for their educational experience. Programs were selected in ranking order to include at least 10 schools categorized as each of public doctoral, private doctoral, public non-doctoral, and private non-doctoral. We also included any additional institutions tied with these programs. All schools offered either a B.S. in Mechanical Engineering or a B.S. in Engineering (only if no mechanical degree offered). A total of n = 83 institutions were initially identified. First or second year courses, semester- or year-long capstone project courses, online programs, and graduate courses that undergraduates could take were excluded from the analysis. After applying the exclusion criteria and eliminating curricula that did not include an upper-division mechanical design course, the final sample was n = 74 institutions that each offered at least one required or elective (only if no requirement) upper-division mechanical design course. The most common course titles in the dataset were Machine Design (13 instances), Mechanical Design (12 instances), Design of Machine Elements (6 instances), and Mechanical Engineering Design (5 instances).

Figure 1 shows the percentage of institutions that required a pre- or co-requisite course in each topic, as well as the number of institutions where students would have previous coursework in the engineering design process. Mechanics of materials was the most common prerequisite for upper-division mechanical design coursework, followed by dynamics, then design. Standalone CAD, machine shop, and manufacturing courses were not present in all curricula considered; these topics were also often integrated into an introductory design course. These results emphasize that prior coursework in both engineering analysis fundamentals and the design process are common before upper-division mechanical design courses.

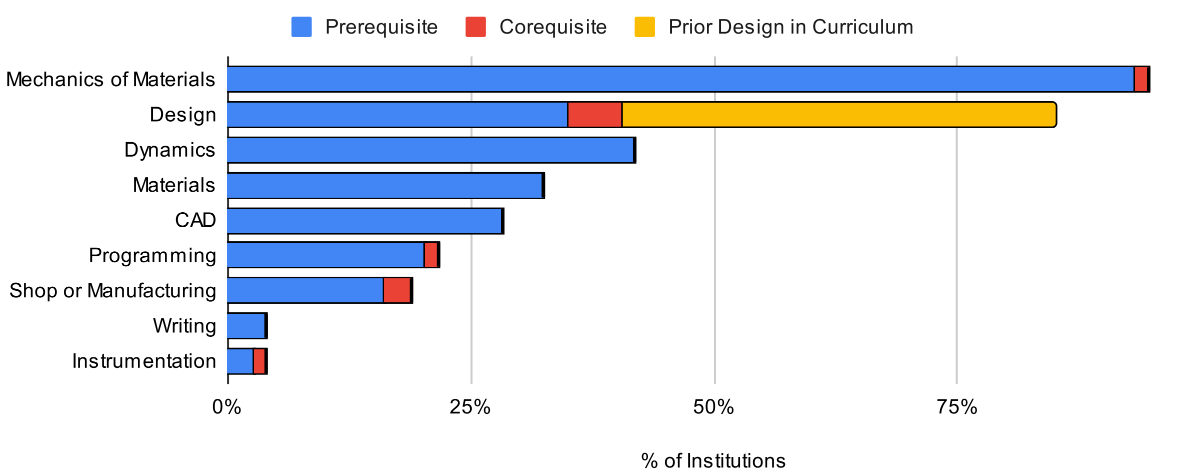

Figure 1. Upper-division mechanical design course requisites. Bars show the proportion of institutions (n=74) requiring a pre-requisite (blue) or co-requisite (red) course in each topic prior to their upper-division mechanical design courses. The yellow region shows institutions where students have taken an additional foundational design course, but the course is not an explicit pre- or co-requisite for upper-division mechanical design coursework.

Design Process Survey Instrument Development

The curriculum review strongly suggests that most students in upper-division mechanical design courses have prior learning of the engineering design process. We developed a survey instrument to understand when and how this familiarity with the design process is leveraged during mechanical design projects. While many survey instruments for the design process already exist (e.g., [11], [12]), we developed a modified survey that includes these elements as well as the detailed design, high-resolution fabrication, and analysis work emphasized in upper-division mechanical design courses. Where relevant, we include items used in previous studies of the design process at our institution for consistency [13]. Table 1 lists the design activities included in the survey, as well as reference definitions for each activity provided to survey participants.

Table 1. Design activities and provided definitions for the design process survey.

Need Recognition [11]: Consulting users, literature, and existing solutions to identify and articulate a design need.
Problem Definition: Define requirements, constraints, objectives, and specifications, determine the project scope, and specify criteria for success. (Modified from [11])
Idea Generation: Develop possible ideas for a solution, brainstorm, and list different alternatives. (Definition from [12])
Conceptual Design: Synthesis, evaluation, and comparison of proposed machines or system concepts. (Definition from [14])
Embodiment Design: In-depth engineering design of individual components and subsystems for the already selected machine or system. (Definition from [14])
Detail Design: Determining configuration, arrangement, dimensional compatibility and completeness, fits and tolerances, standardization, joints and attachment details, fabrication methods, assemblability, and establishing bills of material and purchased parts. (Definition from [14])
Implementation: Creating an instance of a physical machine or product (prototype or final product) for the purpose of testing or final use. (Modified from [11]) • **Low-Resolution Prototyping**: Prototypes produced quickly, inexpensively, and with limited fidelity to evaluate design decisions and identify issues. (Modified from [15]) • **Fabrication and Assembly**: Creating a high-quality instance of a physical machine or product (prototype or final product) for the purpose of testing or final use. (Modified from [11])
Evaluation: Objectively determining suitability of alternatives or proposed solutions by comparing expected or actual performance to evaluation criteria. (Definition from [11]) • **Analysis**: Applying engineering science tools and techniques to determine quantitative information about a design's performance. (Modified from [16]) • **Testing (internal within the team)**: Testing a physical machine or product by the designers to validate performance or identify issues. • **Testing (with users and/or stakeholders)**: Testing a physical machine or product with users, project clients, or advisors for feedback or demonstration.
Seeking Feedback: Solicitation of critical feedback from advisors, colleagues, clients, stakeholders, and users with a goal of improving a design.
Iteration [11]: Revisiting earlier design activities to improve or verify outcomes or respond to new information.
Management and Planning: Development of an overall plan, decomposition of design problem into subtasks, prioritization of tasks, establishment of timetables and milestones. Guidance of course of action during design and in response to changing conditions. Includes management of project schedule, utilization of team members, and the project budget. (Modified from [11])
Documentation: Production of records regarding the design process and design state, including decision history and criteria, project plan and progress, intermediate design states, finished product, and use of product. (Definition from [11])

Student participants are asked to rate the extent to which their team enacted each design activity on a 4-point scale (4: Significantly; 3: Sometimes; 2: A Little; 1: Not at All). Faculty participants will rate how important each activity is to their course learning outcomes on the same scale.

Fabrication Survey Instrument Development

The fabrication survey was developed to assess the factors students prioritize when producing physical artifacts for their mechanical design projects. Survey items were identified from our experiences advising student mechanical design projects and design topics emphasized by other assignments and activities within our upper-division mechanical design course (e.g., material selection). We categorized these factors as either advising (based on the advice of a mentor or instructor), availability, experience (knowledge or prior experience with a fabrication method), detailed design, or management. Table 2 lists the factors that were included in the survey.

Table 2. Fabrication decision factors, their categorization, and definitions of each factor provided to survey respondents.

Category	Factors
Advising	**Advice from the Shop / Makerspace**: advice from a shop / makerspace instructor, proctor, or assistant, either informally or in an official capacity
	Advice from an Instructor or TA: advice from a course instructor or teaching assistant, either informally or in an official capacity
Availability	**Machine Availability**: were the tools and machines needed for the fabrication method present and accessible?
	Training Availability: how easily available was training as an operator to use a desired fabrication method?
	Material Availability: how easily available were materials compatible with the desired fabrication method? (separate from material selection to meet design considerations)
	Tooling / Peripheral Availability: was compatible tooling or peripheral equipment available?
	Hours of Access: was the desired fabrication method available at needed hours?
Experience	**Personal Comfort Level**: your comfort using a chosen fabrication method
	Safety: knowledge of safety practices and perceived safety as a user while using the fabrication method (this category does not include the safety of the completed part or machine)
Detailed Design	**Material Selection**: ability to manufacture using a desired material
	Part Geometry or Features: ability to manufacture desired geometric features (e.g. precise holes, overhangs, axisymmetry)
	Tolerancing: ability to manufacture at a desired level of precision
Management	**Cost**: amount of project budget spent to manufacture using a chosen method, may also include costs not paid directly by the team (e.g. availability of scrap stock or general consumables)
	Lead Time / Time Required to Purchase: how long it would take to receive a component if purchased or manufactured externally
	Logistics: factors inside and outside the control of the team such as shipping delays, illness, and machine down-time.
	Time Required to Manufacture: time you would need to spend either actively fabricating a part or waiting for a part to be completed
Other factors not listed?	

Students are asked to rate how important each factor is to the project fabrication decisions they make on the same 4-point scale (4: Significantly; 3: Sometimes; 2: A Little; 1: Not at All) as the design survey. Faculty participants will be asked to rate how important each factor is to their course learning outcomes, as well as how frequently they observe students consider each factor. This instrument (minus the advising category) will also be used to survey what factors arise most frequently for machine shop and makerspace staff advising students on their projects.

Pilot Study

The design process and fabrication surveys were piloted with a convenience sample of volunteer student participants (n = 7). Participants were recruited from two residential undergraduate engineering colleges (Harvey Mudd College and Olin College of Engineering) who had taken an upper-division mechanical design course within the past two academic years. Both courses included a student-proposed, team-based final design project with similar scope and assignment structure. Students were asked to focus on this project for their responses. Students at both institutions had taken an introductory design course and a mechanics of materials course in prior terms. Both campuses had fully equipped machine shops (e.g., mill, lathe, CNC, welding, waterjet cutter) and rapid prototyping capabilities (e.g. 3D printing, laser cutting) for project fabrication. Given the similarity in project format, prior coursework, and fabrication capabilities, home campus was not recorded during preliminary data collection.

We hypothesized that most design activity would be in stages of the design process heavily emphasized by the course (**Embodiment Design**, **Detail Design**, **Analysis**, **Internal Testing**, and **Fabrication and Assembly**). We also expected nontrivial work on front-end design tasks (e.g., **Problem Definition**, **Idea Generation**, and **Low-Resolution Prototyping**). These tasks are generally necessary to reach more detailed design stages. For the fabrication survey, we hypothesized that the detail design factors emphasized by the course (**Material Selection**, **Geometry or Features**, and **Tolerancing**) would strongly affect fabrication decisions. We also predicted that **Cost** and **Personal Comfort** would drive many decisions. We expected that students would be budget conscious and choose familiar techniques in cases where multiple options would work. We did not expect **Availability** of all varieties to be a significant factor given the accessible shop culture and wide range of capabilities at both pilot campuses.

Figure 2 shows survey responses for each design activity. Results suggest a focus on **Idea Generation**, **Detail Design**, and **Fabrication and Assembly**, with most students rating these activities as “4: Significantly” and no students rating these activities lower than “3: Sometimes.” Responses also showed broad use of a variety of design activities, with most activities scoring at least “3: Sometimes” or higher on average. The widest range in activity extent was for **Need Recognition** and **Low-Resolution Prototyping**. Notably, design evaluation was mostly through **Testing (internally)**, and no students reported **Analysis** or **Testing (with Users/Stakeholders)** as their team’s highest frequency activities.

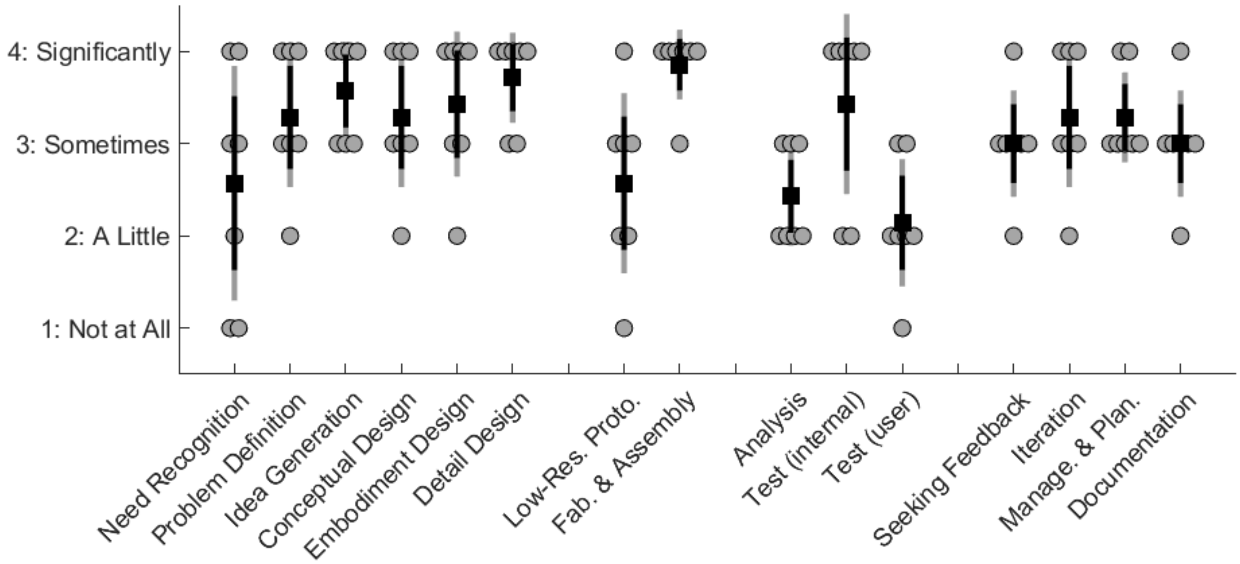

Figure 2. Design process pilot survey responses. All responses refer to activities enacted during the final project. For all categories, gray circles show individual response values, black squares show the mean, the solid black lines show a 95% confidence interval on the mean, and gray lines show +/- one standard deviation.

Given limited normality in the pilot survey data, two-sided Wilcoxon rank sum tests (Matlab function *ranksum*) were used to identify statistically significant differences in the reported design activity extents ($\alpha = 0.05$). Table 3 lists statistically significant pairings ($p < 0.05$).

Table 3. Statistically significant ($p < 0.05$) differences in design activity extent.

Greater Extent	**Lesser Extent**	**p-value**
Problem Definition	Evaluation: Testing (with users/stakeholders)	0.0338
Idea Generation	Evaluation: Analysis	0.0117
Idea Generation	Evaluation: Testing (with users/stakeholders)	0.0058
Conceptual Design	Evaluation: Testing (with users/stakeholders)	0.0338
Embodiment Design	Evaluation: Analysis	0.0466
Embodiment Design	Evaluation: Testing (with users/stakeholders)	0.0221
Detail Design	Implementation: Low-Resolution Prototyping	0.0396
Detail Design	Evaluation: Analysis	0.0058
Detail Design	Evaluation: Testing (with users/stakeholders)	0.0035
Implementation: Fabrication & Assembly	Implementation: Low-Resolution Prototyping	0.0169
Implementation: Fabrication & Assembly	Evaluation: Analysis	0.0023
Implementation: Fabrication & Assembly	Evaluation: Testing (with users/stakeholders)	0.0017
Implementation: Fabrication & Assembly	Seeking Feedback	0.0251
Implementation: Fabrication & Assembly	Documentation	0.0251
Evaluation: Testing (internal to the team)	Evaluation: Testing (with users/stakeholders)	0.0350
Iteration	Evaluation: Testing (with users/stakeholders)	0.0338
Management & Planning	Evaluation: Analysis	0.0326
Management & Planning	Evaluation: Testing (with users/stakeholders)	0.0122

In the pilot responses **Analysis** and **Testing (with Users/Stakeholders)** were conducted to a lesser extent than many other design activities, including **Idea Generation**, **Embodiment Design**, **Detail Design**, **Fabrication and Assembly**, and **Management and Planning**. The role of **Analysis** opposes our hypothesis. One possibility is that analysis performed to inform design decisions was categorized as **Embodiment Design** or **Detail Design** instead of **Evaluation: Analysis**. A more concerning possibility is that the project structure de-emphasizes analysis. Multiple analysis roles should be clearly presented in subsequent versions of the design process survey to clarify this concern. The extent of testing with users or stakeholders likely varies based on the project topic and should be explored with qualitative follow-up questions in future work.

The role of **Low-Resolution Prototyping** is also contrary to our expectations. **Low-Resolution Prototyping** was reported to a lesser extent than both **Detail Design** and higher-resolution **Fabrication and Assembly**. This finding shows one area where upper-division mechanical design projects can differ in focus from earlier introductory design coursework, which often emphasizes inexpensive and quick prototypes. **Low-Resolution Prototyping** may also be reported less when preliminary design validation is performed in CAD instead of through physical prototypes. Subsequent surveys should ask students to elaborate on how they validated their designs prior to any high-resolution fabrication and assembly.

Pilot fabrication survey responses are shown in Figure 3. All the detail design factors (**Material Selection**, **Geometry or Features**, and **Tolerancing**) averaged at least "3: Sometimes" in their importance to fabrication decisions, as did **Machine Availability** and **Cost**. Pilot results also show a notably wide range in how often students considered **Availability** of all varieties, **Personal Comfort** using a desired fabrication method, and **Safety** in their decisions. The findings for **Availability** and **Personal Comfort** suggest that our hypotheses were too generalized. These factors are important to examine with additional context in future work.

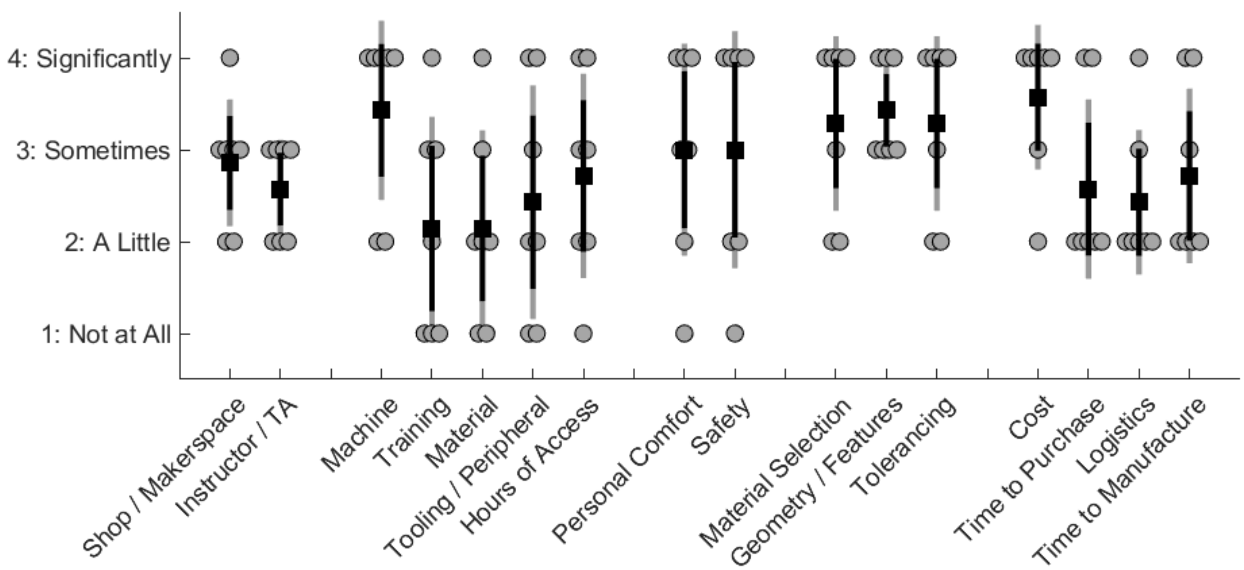

Figure 3. Fabrication decision factor pilot survey responses. All responses considered course final project work. For all categories, gray circles show individual response values, black squares show the mean, the solid black lines show a 95% confidence interval on the mean, and gray lines show +/- one standard deviation.

Given the wide range in prioritization of many factors, there were fewer significant comparisons than in the design process survey results. Table 4 lists significant comparisons. **Machine Availability** was considered in fabrication decisions to a greater extent than **Training Availability**. This finding may reflect relatively accessible shop training procedures at the pilot study institutions, but that demand for some tools still exceeded capacity. **Part Geometry or Features** had more of an influence on fabrication decisions than **Advice from an Instructor or TA**, **Material Availability**, or **Logistics**. The **Logistics** factor captures incidental realities of academic project work such as machine downtime, losing a part order, or team member illness. Students that did not encounter any incidental issues likely scored this factor as less important.

Table 4. Statistically significant ($p < 0.05$) differences in fabrication decision factor importance.

Greater Extent	**Lesser Extent**	**p-value**
Machine Availability	Training Availability	0.0396
Part Geometry or Features	Advice from an Instructor or TA	0.0408
Part Geometry or Features	Material Availability	0.0350
Part Geometry or Features	Logistics	0.0175
Cost	Advice from an Instructor or TA	0.0175
Cost	Training Availability	0.0361
Cost	Material Availability	0.0361

Cost was a significant driver of fabrication decisions when compared to **Advice from an Instructor or TA**, **Training Availability**, and **Material Availability**, partly aligning with our hypothesis. While managing a project budget is a necessary and realistic professional skill to cultivate, this factor should be explored further in follow-on work since it also presents a potential tension with detailed design. For instance, a student may perform the analysis to recommend a specific component or material, only to find that this approach is infeasible for the project budget. Design and analysis projects without a fabrication element are one approach to this limitation. Projects with component kits (e.g., [17], [18]) present another approach to constraining costs which might otherwise dominate fabrication decisions. Cost decisions may also factor into the wide range of reported low-resolution prototying extents seen in the pilot design survey responses. Teams may utilize low-resolution prototypes to inexpensively validate designs, or they may limit early prototypes to save resources for their final assemblies.

Future Work

The next stages of this work include survey instrument refinement, expanded student data collection, and surveying faculty and fabrication staff participants. Prior to further data collection, the design process survey should be refined to provide greater clarity on analysis roles and frequency and additional context on project topics and scope. Adding open-ended reflection questions to the fabrication survey may provide additional insight into the wide range of selection considerations seen in the fabrication survey pilot data. Follow-up questions should focus on why a factor was or was not important, what the students were designing and building, and the fabrication facility and budget resources available for the project.

Expanded single institution student data collection will occur in the upcoming academic year during the authors' next offering of their upper-division mechanical design course. Longer-term data collection will include faculty, machine shop and makerspace staff, and students from more institutions. The pilot study finding that machine shop and makerspace staff advising was as, if not more, important as faculty and TA advising when making project fabrication decisions emphasizes the need to include their perspective in this work. This expansion will include courses with different project implementations (e.g., instructor or student proposed topics, projects with and without a fabrication element). These data will enable comparisons by curriculum (e.g., with and without prior design coursework) and project structure.

Conclusions

This work in progress paper seeks to characterize how students in upper-division mechanical design courses implement the design process and how hands-on fabrication projects align with course learning outcomes in detail design. The curriculum review conducted in this work shows that students in upper-division mechanical design courses generally have prior knowledge and experience with the engineering design process, even when an earlier design course is not a prerequisite for the class. Our pilot results using a design process survey instrument show broad coverage of the design process during student projects, with more emphasis on idea generation, detail design, fabrication, and project management compared to evaluation through analysis and user testing. A pilot study on factors affecting students' fabrication decisions during mechanical design projects shows that while detailed design is a nontrivial factor, a wide range of additional considerations are seen across responses. Survey refinement and additional data from faculty, instructional staff, and engineering students are needed to further understand the roles of design and fabrication in upper-division mechanical design courses.

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