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Augmenting Design Learning through Computer-Aided Exploration

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Approved by Major Professor(s): Karthik Ramani

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Head of the Departmental Graduate Program Date

AUGMENTING DESIGN LEARNING
THROUGH COMPUTER-AIDED EXPLORATION

A Thesis

Submitted to the Faculty

of

Purdue University

by

Anirudh R. Sriram

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science in Mechanical Engineering

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West Lafayette, Indiana

To my Mother, Father, and Sister.
Thank you.
For everything.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Sriram, Anirudh R. MSME, Purdue University, December 2015. Augmenting Design Learning through Computer-Aided Exploration. Major Professor: Karthik Ramani, School of Mechanical Engineering.

Much of engineering design courses are taught through the use of standard and simplified textbook problems that typically have a “correct” answer. In helping undergraduate students learn engineering design, it is very important that they explore scenarios that are realistic. A majority of the current educational methods and computer-based tools do not bridge the gap between the textbook problems and the real world and also lack affordances for design exploration. Although computational methods such as Finite Element Analysis (FEA) have this potential, they are hard to use and require the users to spend a significant effort in learning to use them. Also, several instructors have identified significant knowledge gaps between theory and practice in concepts related to structural design and strength of materials when the students reach their senior year. To this end, a problem-based, exploration-focused interface to allow for rapid design exploration within engineering design curricula using an easy-to-use, simplified and constrained version of finite elements for stress analysis and exploration has been developed. This interface makes it possible for users to rapidly explore various design options by incorporating a FEA back end for design exploration. The current approach uses constrained design problems for weight minimization that incorporates elements of structural topology optimization but does not automate it. In addition the tool constrains the solution generation process so that users do not get poor results. Instead, the user is provided with control on decision making for changing the shape through material removal while obtaining good solutions. Using this interface, the decision making and methodology of users in the course of the activities that provide a context of control, challenge and reflection is explored. Using questionnaires, video and verbal protocol analysis assessment is integrated in ways that are important and interesting for learning. The interface demonstrates that computational tools that are transformed for learning purposes can scaffold and augment learning processes in new ways.

1. INTRODUCTION

As engineering systems become more complex and their designs driven by computer aided tools, the use of analysis becomes imperative in the design of these systems. For students to succeed in engineering design and practice they must be proficient in several skills. The ability to make design decisions that are grounded in data and analysis is one such very important skill [21, 22]. A proper intuitive understanding of concepts becomes even more important to make such design decisions confidently [1, 23, 3]. For example, a firm grasp of basic engineering concepts such as in Mechanics of Materials is important. Several researchers have expressed their disappointment with students' general lack of understanding and inability to apply these concepts in a real world scenario as well as in subsequent senior level design projects and advanced courses that build on the basic concepts of Mechanics of Materials [73, 35, 49]. This highlights the need to modify existing educational methods to ensure better understanding of the basic concepts of foundations in elementary physics and Mechanics of Materials in order to develop better design practices.

Significant research has been done by educators in this field. For the current work, a Project-Based Learning (PBL) approach[47] has been adopted. PBL focuses on the learner and their engagement in authentic, real-world problems. PBL is a form of situated learning where the underlying theory posits that student understanding of concepts is augmented when their understanding is scaffolded by exploring and working with the concepts. PBL allows for students to form hypotheses, challenge existing understanding of concepts and to explore alternative ideas [34]. Studies using PBL in a similar context such as the one in this paper have been performed before. One such example is Bernstein et al. [5].

In PBL, the inquiry process can be augmented through scaffolding and exploration takes place through authentic, situated inquiry using cognitive tools [7]. Simulations can be considered to be a type of cognitive tool in that they allow students to test hypotheses and explore ‘what-if’ scenarios [76]. Simulations can also vastly enhance learning as they offer an interactive and visual medium for design exploration. Simulation tools like Finite Element Analysis (FEA) have tremendous potential in providing affordances for learning through design exploration because of their wide applicability in solving problems across a range of domains [50].

However, these tools have a steep learning curve and modeling directly using them is a very tedious process [54]. This creates a significant barrier to entry for the novice user. The use of these tools is thus, largely restricted to advanced students and trained analysts performing specialized analysis after a design cycle. This creates a significant gap between professional engineers (experts) and college students (novices) in using these software for analysis. Teaching assistants and instructors who know how to use the tools find it difficult to cater to the individual learning patterns and needs of a large number of students [42]. The steep learning curve for the students and the limitations of scale faced by instructors and teaching assistants becomes a barrier to scaffold the student learning process. Novice engineers who can potentially leverage the powerful exploration capabilities of FEA to improve their understanding of concepts that they learn in the classroom typically don’t do so because of the above reasons.

In order to cater to these gaps in learning, a problem-based, exploration-focused interface to augment student learning of concepts of Mechanics of Materials through a PBL approach was developed. In developing this approach, a “computer-as-a-partner” philosophy was embraced to support the learner. As a part of the application of this interface in the context of students learning of concepts of Mechanics of Materials, an FEA backend was incorporated for exploration of 2-D structural problems. The interface provides affordances for quick exploration of the design space by facilitating rapid iterations and allows students to pose ‘what-if’ questions at the early stages of the design process.

This thesis discusses the exploration-focused interface's potential to support student learning through two studies that explore: (i) student learning of concepts in mechanics of materials, (ii) student design practices, and (iii) usability of the interface.

2. MOTIVATION AND NEED IDENTIFICATION

Engineers must have the ability to both perform analysis and engage in design thinking when making design decisions. In undergraduate engineering education, these skills are often taught in a discrete manner: taught in completely separate classes and often handled by different and completely separate groups of faculty. Students are then forced to reconcile their understanding of these skills through independent application opportunities.

The potential danger in introducing analysis and calculations too early in the design process is that this may lead the designer to get fixated on the current design [39, 77] and not explore other, potentially better design solutions. This is problematic as engineering education endeavors to teach students to be more innovative.

Early introduction of engineering analysis can not only cause fixation; it can lead to knowledge gaps which can lead to misapplication of concepts and lower innovation in design [62, 71] . Students may face challenges when prompted to recall and apply theoretical knowledge learned from their related coursework. Furthermore, students who do not have a strong understanding of how to apply theoretical knowledge to diverse real world contexts, which may differ from what is described in their textbooks, might not explore alternate design solutions given a design task because of their limited knowledge and their inability to form a connection between concepts learned earlier.

To ensure applicability of concepts being learned by students, a change at the 'conceptual level' has to be enabled [79]. Presenting information and knowledge inconsistent with existing mental models and conceptual structures leads to the formation of misconceptions about the concepts being taught. It is therefore necessary to adopt an approach which enables a smooth experience in terms of learning new concepts/addressing knowledge gaps.

In a Project-Based Learning (PBL) approach, software and online applications can facilitate students' learning by helping to ground their understanding of concepts and theories. By taking advantage of the visualization capabilities of simulations, affordances can be provided for design exploration.

Finite Element Analysis (FEA) has wide applicability in solving problems in structural, dynamic, thermal, fluid and electrical engineering problems [74, 61, 42, 45], and the ability to demonstrate a wide variety of concepts effectively, for example, applying FEA to a common truss problem can help the student visualize the bending of truss members and deformation in a way previously not possible. Use of FEA for studying engineering concepts is similar to the inclusion of laboratory experiments in lecture courses, to provide reinforcement of core lecture material more effectively than a textbook [11]. Also, FEA can be used to bridge the gap between traditional learning through textbooks, which typically incorporate standard geometry, and applying those concepts to realistic design problems with complex geometry, where knowledge gained from textbooks alone is not sufficient.

Though powerful with advanced graphics and animation capabilities, these commercial tools do not lend themselves to use in engineering education as they were primarily developed for the industry [50]. The student must, therefore, become familiar with the software or application itself before using it as a medium for exploration. The complexity of a software application that will help students explore more design alternatives may actually serve as a hindrance to the student until they:

(a) Improve their understanding of the needed engineering concepts and/or

(b) Become familiar with the software application.

There is thus, a need for a simplified interface that enables users to take advantage of advanced simulation software for design exploration.

3. BACKGROUND

In this chapter, previous work on addressing knowledge gaps in Mechanics of Materials prevalent among students is first discussed. Following this, approaches that have been taken by researchers to introduce FEA in lower-level engineering classes are discussed.

3.1 Addressing Knowledge Gaps in Mechanics of Materials

Mechanics of Materials has conventionally been viewed as a challenging subject by students[32, 26]. Several researchers have observed that students often miss the overarching connections and interdependencies that exist between various concepts. They also observe that students face difficulties in understanding and applying concepts of Mechanics of Materials to real-world problems[35, 26, 25, 57, 60, 64]. Such observations have motivated extensive research to address these concerns.

Pioneering researchers in this field[2, 18, 40] suggest that the traditional pedagogical methods followed in engineering education do not facilitate effective learning of Mechanics of Materials concepts by the students. To this end, some research has been undertaken to look at introducing different techniques and methods in the classroom to improve students' understanding of concepts of Mechanics of Materials.

Several researchers believe that the reason for the general lack of understanding of these concepts and phenomena is due to their abstract nature and subsequent difficulty of visualization. They therefore focus on developing hands-on models which enable active learning of the abstract concepts of Mechanics of Materials learned in the classroom. For example, Karim[44] used simple physical models to demonstrate concepts like simple beam bending, shear stresses and the mechanics of trusses and subsequently discovered that using such models in the classroom was received with a lot of enthusiasm by the students. Similar work has been done in introducing physical models and experiments [43, 56, 63, 68, 55, 69, 52, 81] as well as videos [27, 31] in the classroom to promote learning. However, these methods are not very easy to disseminate and as such, require extensive setup before they can be used repeatedly[40].

Other research has focused on changing how content is delivered to the students in the classroom by using strategies like active learning experiences [40, 38, 4], interactive models[53], visualization methods [75, 6, 14, 12], learning games [60], research on concept inventories [26, 66, 28, 16] and development of better problem-solving approaches [33].

A new emerging trend in addressing knowledge gaps in Mechanics of Materials is the usage of computer programs and software. Steif[73] and others[24, 37, 65, 15, 59] have detailed efforts taken in this direction. FEA programs are one such medium and their applicability in the undergraduate engineering curriculum is discussed next.

3.2 Introducing FEA in the Undergraduate Engineering Curriculum

Several researchers have identified the growing use of CAE (Computer-Aided Engineering) software in the industry and have attempted to get students acquainted with them by introducing them in the undergraduate engineering classes. Steif and Gallagher[74] argue that the use of these software, particularly FEA would be very helpful to improve the learning of fundamental engineering concepts, particularly in Mechanics of Materials. Several efforts have thus been taken over the years to incorporate FEA into the mainstream undergraduate engineering curriculum[17, 48, 70, 51, 9, 41, 67, 11, 61]. The results have been largely positive, demonstrating that the use of FEA programs to aid learning in Mechanics of Materials is very effective. However, one of the recurring challenges in these endeavors is that the commercial programs as such are very difficult to be used by student engineers. There is thus, a need for simplification of these tools in order to enable novice users to leverage the powerful capabilities of the software to improve their understanding of basic concepts in Mechanics of Materials.

In summary, previous researchers have identified some shortcomings in the way concepts of Mechanics of Materials are conventionally taught in the classroom. Several endeavors have been taken through a variety of methods by educators and instructors to address this concern and improve student understanding. One method that has been documented as very effective is the use of FEA as a learning companion for Mechanics of Materials.

The approach adopted in this thesis is a Project-Based Learning (PBL) approach that leverages the capabilities of commercial FEA software to assist in rapid exploration of the problem design space and thereby augment the learning process of the student engineers. FEA is used as a metaphor for exploration. The new interface enables the student to engage in simulation directly without having to learn how to use the FEA software. In the next chapter, the design of this exploration-focused instructional framework and associated interface is discussed.

4. METHODS

In this section, the theory which informed the design of the exploration-focused interface and subsequent studies to evaluate it are briefly introduced and discussed. Two studies were conducted to evaluate the learning impact of the new interface and to explore future implications of using the approach in educational settings.

The steps followed to design activities to address knowledge gaps in student understanding of Mechanics of Materials were as follows:

- *Develop design problems that provide an authentic context to concepts in mechanics of materials:* In particular, the aim was to design problems that were of sufficiently higher complexity than standard textbook problems so as to discourage students from falling back on formula-based problem-solving approaches.

- *Enable discovery learning through student exploration:* It was hypothesized that in approaching the problems from their own perspectives, the students will resolve their learning in this process. Problems that require exploration typically do not have one right answer and a departure from the common text-book problems which have a pre-determined answer will result in a better learning experience for the students (cite Van Joolingen).

- *Analysis of Student Exploration Process:* Thoroughly document and record all facets of the student exploration process (through logs of student work). Analyze these records to make observations and gain insights about students' design rationale. These insights are essential in enabling change at a "conceptual level" [79].

4.1 Design of the Interface

Based on the steep learning curve associated with existing commercial FEA software and the existence of knowledge gaps in students' understanding, an exploration-focused interface that uses an FEA back end with an objective to allow for more opportunities for learning of fundamental principles of Mechanics of Materials through easy design exploration was developed. The interface was designed to meet the following objectives:

- Stimulate an environment for design-analysis exploration, in which questions like 'what-if', 'why', 'what' and 'how' will be more effectively answered through on-the-fly simulation and visualization.
- Incorporate a visual approach to allow better understanding of practical situations through solving problems, where conventional equations do not apply, and also beyond "toy" textbook problems.
- Enable the transition from a passive, teacher-centered model of education to one that is student-centered [78] and emphasizes active-learning [8].
- Enable self-learning in students through critical exploration of engineering concepts.
- Empower the student designers to analyze and explore different concepts for stresses, deformation and failure during the early stages of design, rather than the conventional way of analyzing after detailed design.

The control on meshing and other FEA parameters was removed from the participant and default parameters were set that ensured a reasonably accurate solution without compromising on solving time. The interface was designed to present a constrained design problem that participants solved as part of a user study (more details are provided in later chapters). By constraining the design problem, it was thus ensured that participants did not have to focus on any other aspect of the problem other than the exploration and importantly, ensured that participants did not require any expertise in FEA to solve the design problem.

To maintain the constraints that had been imposed on the design space, only material removal operations were allowed. These operations could be carried out by combining three shape primitives in any manner using Boolean operations. The shape primitives provided to the user were the rectangle, the circle and the rectangle with filleted corners. Rigid constraints on the boundary conditions of the problem were also imposed. Fig. 4.1 shows a screenshot of the exploration-focused interface. The interface has a backend which uses PHP and ANSYS Parametric Design Language (APDL) to mesh the model and run the FEA simulation. After the FEA simulation was run, the equivalent von Mises stress distribution (SEQV) plot would be downloaded to a separate folder where they could be viewed by participants. For future dissemination, the interface was developed to run on a Web browser.

4.2 Selection of an Appropriate Design Problem

Situated learning environments have been shown to support knowledge transfer from more decontextualized theoretical knowledge to more authentic contextual application [13]. The focus for these studies was to provide a simple yet meaningful context for participants as they were learning, to apply mechanical engineering principles to solve design problems. By situating the design task in a context which differs from that presented in traditional textbook problems, the student engineers were given an opportunity to exercise their knowledge transfer ability and gain experience using tools and engaging in practices which may resemble those used by professional engineers.

Structural design optimization (SDO) problems require a combination of intuition and other quantitative and qualitative parameters to be solved [58]. From a geometry point of view, SDO involves the selection of an appropriate geometry for a structural member to satisfy a set of constraints. The design space can be further narrowed

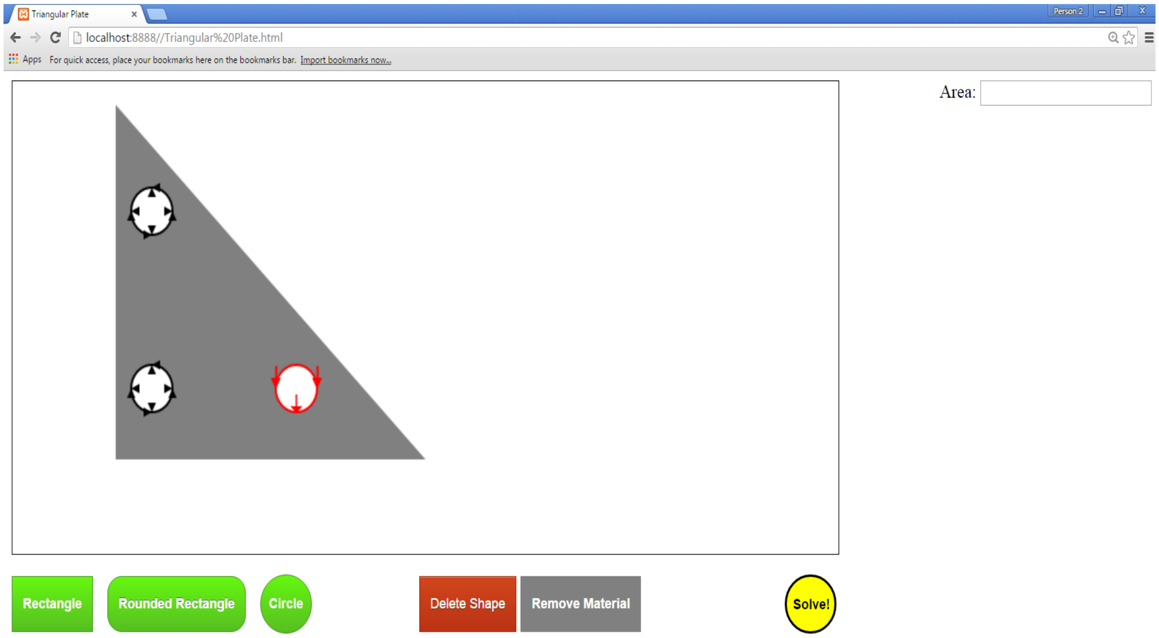


Figure 4.1. Screenshot of the exploration-focused interface. The green buttons are the different shape primitives available for material removal. The Delete Shape button enables the user to delete any of the primitive shapes created and the Remove Material button enables the user to get a visualization of how the member would appear with material removed at the places specified by the user. The Solve button runs the FEA simulation.

by imposing additional constraints on the problem such as maximum stress, strain and volume limits. Constraining the design space in exploration is important because not all learners exhibit proficiency in unconstrained exploration and this can severely restrict their learning in such an environment[10].

SDO problems are fairly different from typical textbook problems as they cannot be solved by using equations alone. They require application of discrete concepts and a strong understanding of how these concepts are related to each other. Thus, SDO appears to be an appropriate problem type for design exploration.

4.3 Target Concepts

In order to investigate how the interface could aid students in solving SDO problems, studies were conducted with undergraduate students from Mechanical Engineering.The primary objective of the studies was to investigate how the interface might aid the learning of the following fundamental principles (target concepts) in Mechanics of Materials, the knowledge of which is essential for good mechanical engineering design. The target concepts that are outlined below are guidelines for designing machine components. They are well established in engineering literature and are a part of the mechanical engineering undergraduate curriculum[72, 80]. The target concepts are listed below (P1 to P3). From these principles, corollaries were derived that extended their range of applicability (CP1-CP3.2).

P1-For a member subjected to a general loading configuration, there exist regions of very low stress.

CP1-Remove as much material as possible from the regions of low stress.

P2-For a tensile/compressive loading case, there is an inverse relationship between normal stress and area of cross section.

CP2-Reduce the area of cross section to achieve the maximum allowable stress.

P3-Sudden changes in geometry along the line of tensile/compressive loading result in high stress concentration.

CP3.1-Avoid sharp corners in design.

CP3.2-Increase the radius of curvature of curves along the line of tensile/compressive loading.

Previous research has shown that students tend to learn better when they solve problems that are similar to real-life engineering problems [53]. It was hoped that by incorporating the above concepts in appropriate SDO problems that are similar to engineering problems that are encountered in professional practice, an interesting context for students to explore relationships between concepts learned in the classroom and also critically examine their conceptual understanding could potentially be created. In the next chapter, the studies and their setup are discussed in detail.

5. PILOT STUDY

The pilot study was a preliminary study conducted to evaluate the learning impact of the new interface and to understand its needs, constraints and limitations. Insights and observations gained from the pilot study were used to design a follow-up user study.

For the pilot study, 8 paid participants (all male), aged between 18 and 30 years were recruited. Among them, 1 participant was in the graduate program and the rest (3 juniors, 3 seniors and 1 sophomore) were in the undergraduate program within the School of Mechanical Engineering. The goal of this study was to validate the study setup, design tasks, and approach with a small but diverse population before expanding it to a larger participant pool. Participants for this study were recruited by making announcements of the study and its prerequisites and by signing up volunteers on a first-come, first-serve basis. Since the study aimed to address knowledge gaps existing in Mechanics of Materials concepts, it was ensured that all the participants had already taken a course that taught concepts of Mechanics of Materials. The pilot study was conducted in 3 stages.

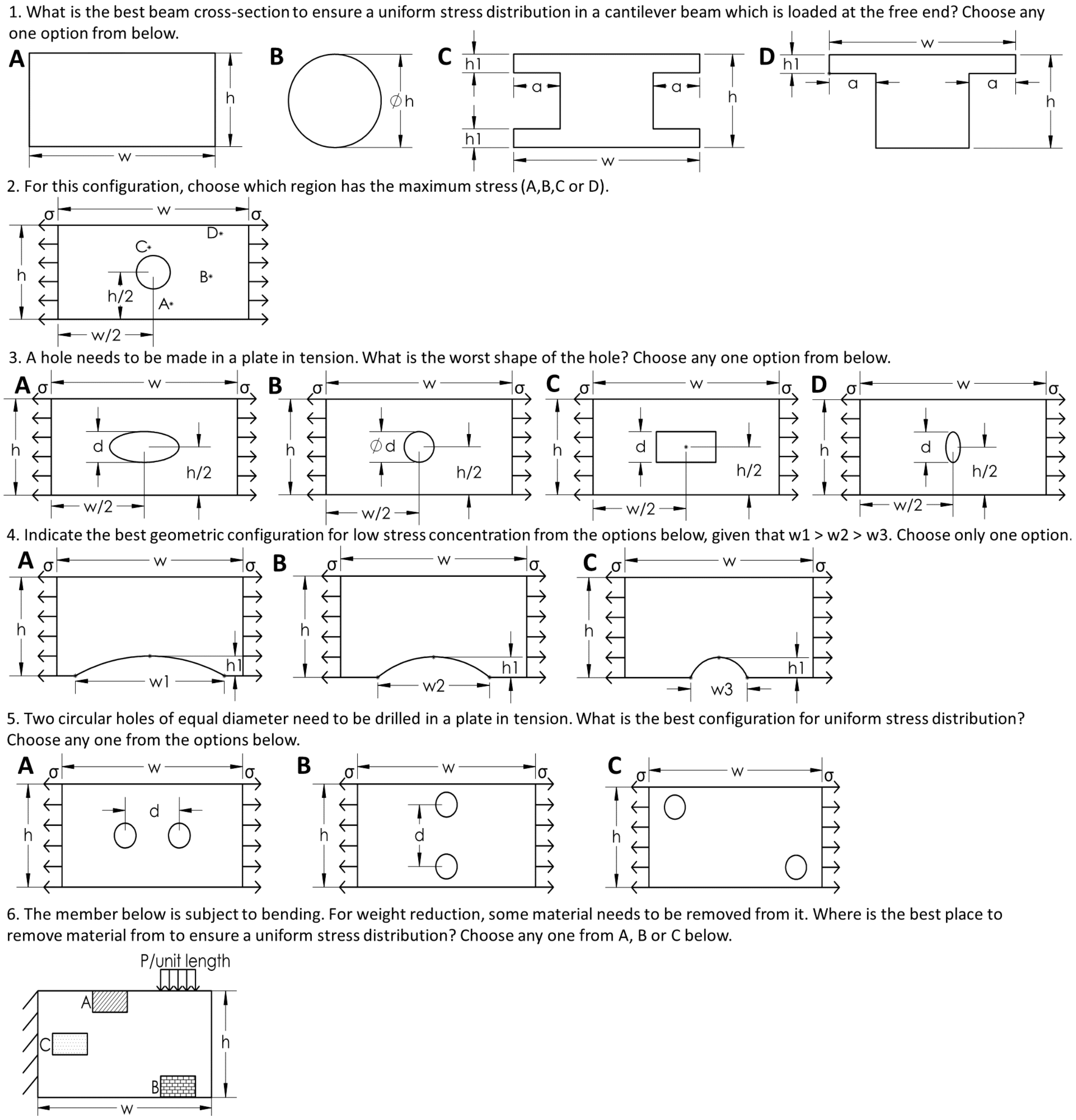
5.1 Stage 1: Pre-Task

Stage 1 of the study consisted of a pre-study survey and a pre-task questionnaire. The pre-study survey was used to get information about the participants' background in mechanical design and FEA. The pre-task questionnaire was framed to evaluate the participants' existing knowledge of the target concepts mentioned in the previous chapter. The questionnaire consisted of 6 multiple choice questions with only one correct answer. The participants were given 15 minutes to answer the questions. The pre-task questionnaire was administered on paper and the participants were given the freedom to make sketches and rough calculations as they desired. To minimize the chances of guesswork and gain a better sense of the participants' conceptual understanding, we asked the participants to mandatorily provide explanations for their answers. Participants were given 15 minutes to work on the pre-task questionnaire. The pre-task questionnaire is shown in Fig. 5.1.

5.2 Stage 2: Design Task

The design task as mentioned before, was a structural design optimization problem which involved the minimization of the total area of the member with a constraint on the maximum stress that could be induced in the member. FEA was used to plot the stress intensity calculated from the Tresca criterion in the member. Before starting the design task, a short tutorial was provided to the participants to train them to interpret the stress plot and to identify the value as well as location of the maximum and minimum stresses in the member.

Participants were required to minimize the total area of a triangular member made of Structural ASTM A-36 Steel in constrained loading such that it satisfied a primary design constraint that involved the maximum allowable stress of the member i.e. the allowable maximum stress intensity from the Tresca criterion was not to exceed 16700 N/cm^2 (derived from typical Factor of Safety guidelines for structural members). The loading condition of the member is illustrated in Fig. 5.2. The study was conducted on a Desktop PC. Participants used the interface for creating two-dimensional geometric models of their design. For conducting FEA on the designs and for meshing, ANSYS 14.0 was used. The stress intensity distribution from the Tresca criterion of the designs created by the participants was displayed on a separate window. Participants were given 30 minutes for the design task. Each participant was closely monitored by a study administrator who asked questions and took down observation notes at regular intervals (after every design iteration) on their design



1. What is the best beam cross-section to ensure a uniform stress distribution in a cantilever beam which is loaded at the free end? Choose any one option from below.

2. For this configuration, choose which region has the maximum stress (A,B,C or D).

3. A hole needs to be made in a plate in tension. What is the worst shape of the hole? Choose any one option from below.

4. Indicate the best geometric configuration for low stress concentration from the options below, given that w1 > w2 > w3. Choose only one option.

5. Two circular holes of equal diameter need to be drilled in a plate in tension. What is the best configuration for uniform stress distribution? Choose any one from the options below.

6. The member below is subject to bending. For weight reduction, some material needs to be removed from it. Where is the best place to remove material from to ensure a uniform stress distribution? Choose any one from A, B or C below.

Figure 5.1. Pre-task questionnaire for the pilot study.

rationale. The study administrator refrained from providing any assistance to the participants except on using the interface.

To measure the outcomes of the user study, a ‘think-aloud’ protocol was implemented wherein participants were asked to vocalize their thoughts, insights and

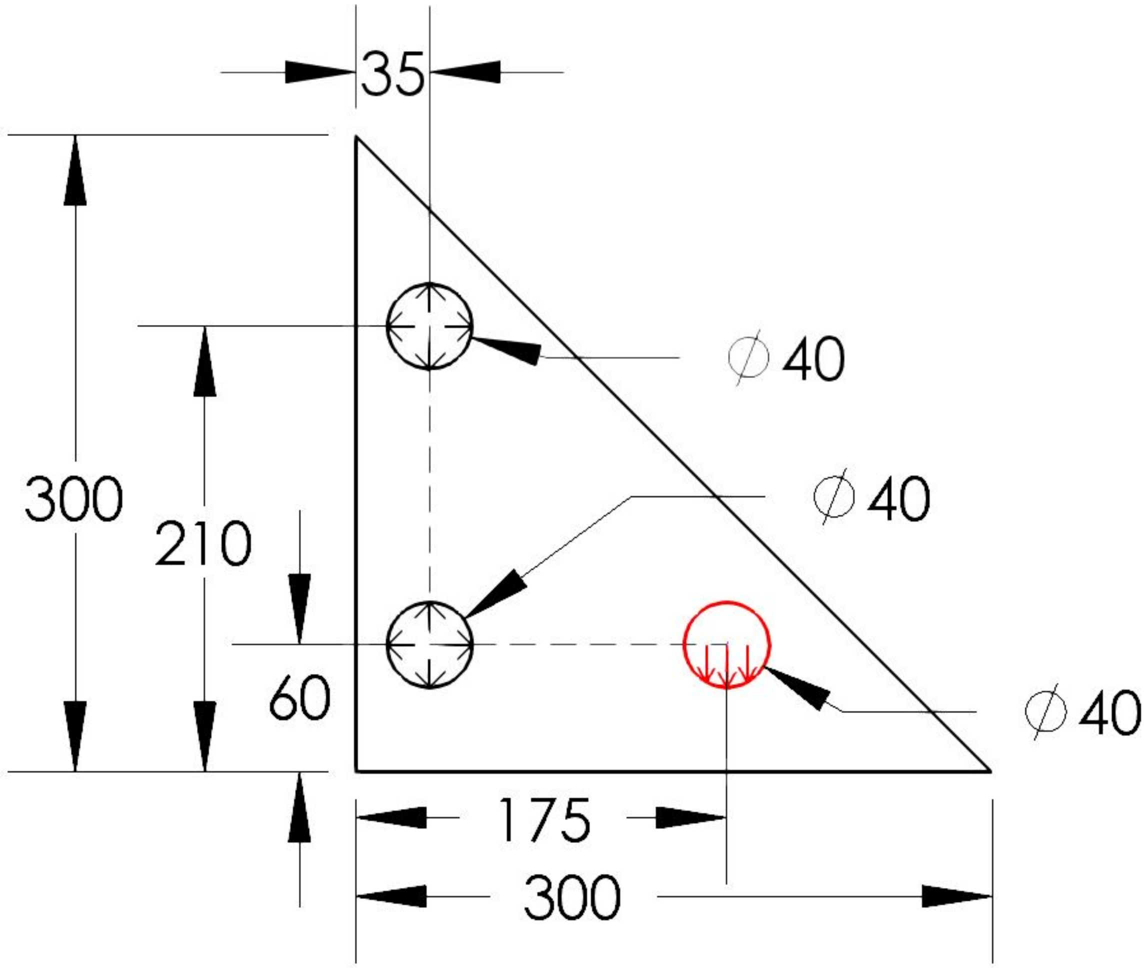


Figure 5.2. Loading condition for the design task for the pilot study.

rationale for generating solutions and for exploring the design space while working on the task. Participants were also probed with questions related to significant observations we made during the user study when they working on the problems as well as when they were finished working on them. Verbal protocol analysis has been used extensively in past studies to analyze cognitive design activity [30, 19, 29].Three recording media were setup to capture this data - audio, video and screen recordings. Along with these, detailed observation notes were also made for every study session. The intent was to conduct a post-hoc analysis for understanding heuristics used to generate solutions and to study if the target concepts we aimed to help the participants learn were successfully assimilated by the participants.

5.3 Stage 3: Post-Task

After the design task, the participants were given the same questionnaire as the pre-task questionnaire in order to directly evaluate the learning impact of using the interface. The participants were also given their responses to the pre-task questionnaire for reference. The participants were asked to indicate whether or not they would like to change their answer or their reasoning. A survey related to possible learning outcomes, comments regarding the study and the task load was then administered. Observations made from the various recordings and notes were cross-checked with the post-task questionnaire results and user comments from the survey to assess the learning impact of the interface.

5.4 Results from the Pilot Study

The learning impact of the interface was evaluated by analyzing the results of the pre and post-task questionnaire and by analyzing the different exploration pathways taken by the participants.

5.4.1 Pre and Post-Task Questionnaire Results

As mentioned before, to evaluate the learning impact of using the interface, the responses and explanations provided by the participants to the questions in the pre and post-task questionnaires were compared. The questions that were used in the questionnaires were selected to expose the knowledge or lack thereof of the target concepts listed previously. Fig. 5.3 shows the observations from the participants' responses. However, it was not possible to draw convincing conclusions about the learning impact of the interface from the pre and post-task questionnaire data because

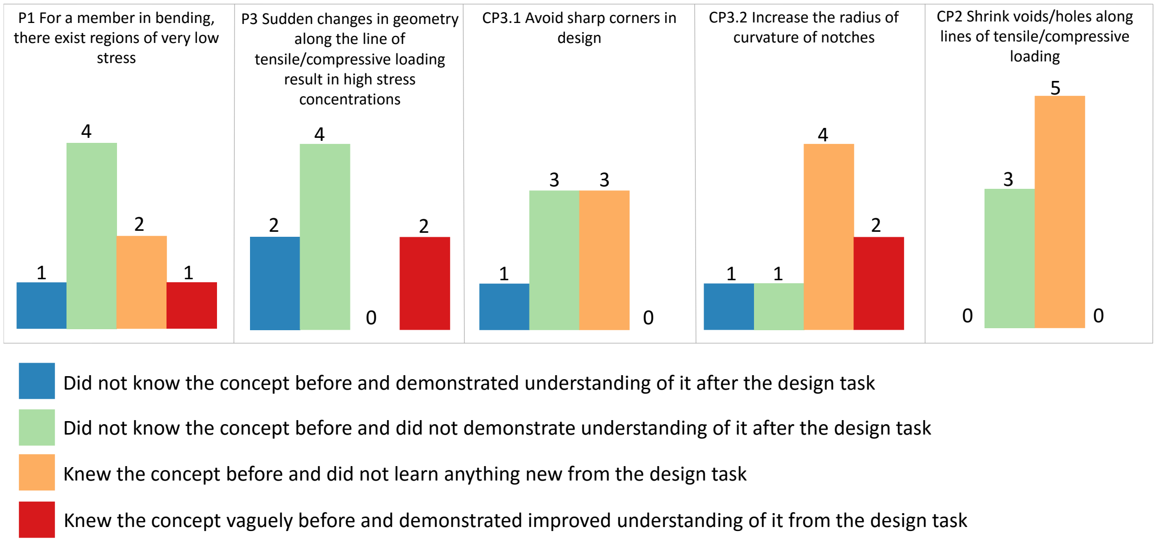


Figure 5.3. Concept-wise learning impact of the interface based on participants' responses to the pre and post-task questionnaires.

of the small size of the participant pool. Therefore, an analysis of the different exploration pathways followed by the participants was done by studying their different iterations.

5.4.2 Exploration Analysis

To further evaluate the learning impact of using the interface, the exploratory paths taken by every participant was studied by analyzing their different iterations. Based on inferences drawn from the think-aloud data and the observations during the study, the design rationale of the different participants was summarized and common themes were derived based on the explorations. Some common themes that were observed from the explorations of the participants are as follows:

- Most of the participants (7 out of 8) relied on an intuitive understanding of how stress is distributed in the member to make a preliminary decision on where to remove material from. In all cases, participants steered clear of the regions of where the loading and constraining occur. The common reasoning they came up with for this is that stress is most likely to manifest itself in regions where there is a direct force being applied.

- Some of the participants (3 out of 8) were aware that sharp corners act as stress risers and therefore used only the circle and the filleted rectangle to remove material. Two of the other participants were aware that sharp corners are ‘bad’ for structural design but were not able to provide a solid reasoning for why they thought it was so.
- A majority of the participants (5 out of 8) exceeded the allowable maximum stress value during the course of their exploration and were able to draw insights on how excessive material removal in certain regions leads to very high stresses being induced in the member.

In addition to the common themes that were observed above, a few themes that were unique to individual participants were also observed.

- Only one participant did an initial solve to determine the stress distribution in the member before proceeding to remove any material. However, this participant did not interpret the stress plot as expected but proceeded to remove material in a random fashion. This participant also had not used FEA before. This was an interesting observation as it motivates the investigation of how students form mental models about engineering analysis results.
- One participant used the approach of removing material in regions as far away from the point of highest stress as possible as opposed to the usual approach followed by other participants of removing as much material as possible from regions of low stress only. This is different in that the participant did not recognize that regions of low stress can sometimes occur in regions moderately far away from the load.

These observations from the pilot study provided a solid platform to ground future studies upon.

5.5 Takeaways from the Pilot Study

The interface was successful in some cases in helping participants to demonstrate correct understanding of some of the target concepts. Learning as a result of using the interface has been of three forms:

1. Participants did not know a certain concept to begin with and demonstrated a correct understanding of it after using the interface.
2. Participants knew a certain concept vaguely (not a complete understanding) to begin with and had their mental model validated after using the interface.
3. Participants were already familiar with a certain concept and were able to solidify their understanding after using the interface.

Conducting a similar study with a larger participant pool and more problems to explore would be very helpful to deeply evaluate the learning impact of the interface. Further, by means of the iteration analysis for every participant, valuable insights into the rationale followed by the participants were obtained and inferences about how they interpreted the results of the FE Analysis with respect to the design task and made design decisions were also drawn.

Also, the exploratory nature of the design task augmented the learning experienced by the students. In the 30 minutes that were provided for the design task, the minimum number of iterations was 5 and the maximum was 24. Data from the Task Load Index and the Usability Scale administered at the end of the study indicated that the participants felt that the interface was easy to use and enabled them to conveniently accommodate the changes that they were asked incorporate during the task.

After the study, participants had the following comments on using the interface and about the study:

- *"I was able to learn from the study that there can be parts in a design that sort of act as zero-force members and carry no stress at all-sharp corners are incredibly bad for max stress in most cases"*
- *"I was able to understand how material removal affects stress distributions in the presence of discontinuities in areas"*
- *"The task helped me learn about where I could remove material - ME323 does not really teach me that, it just tells me where the stress concentration will occur"*

ME323 is an undergraduate course in Mechanics of Materials at Purdue University. It was also observed during the analysis of the participants' design activity that the design problem that was given in the design task featured a combination of different discrete phenomena and concepts in Mechanics of Materials which may have made it difficult for the participants to apply individual concepts as they were solving the problem. Hence, for the follow-up study, the design problem from the pilot study was broken into two sub-problems.

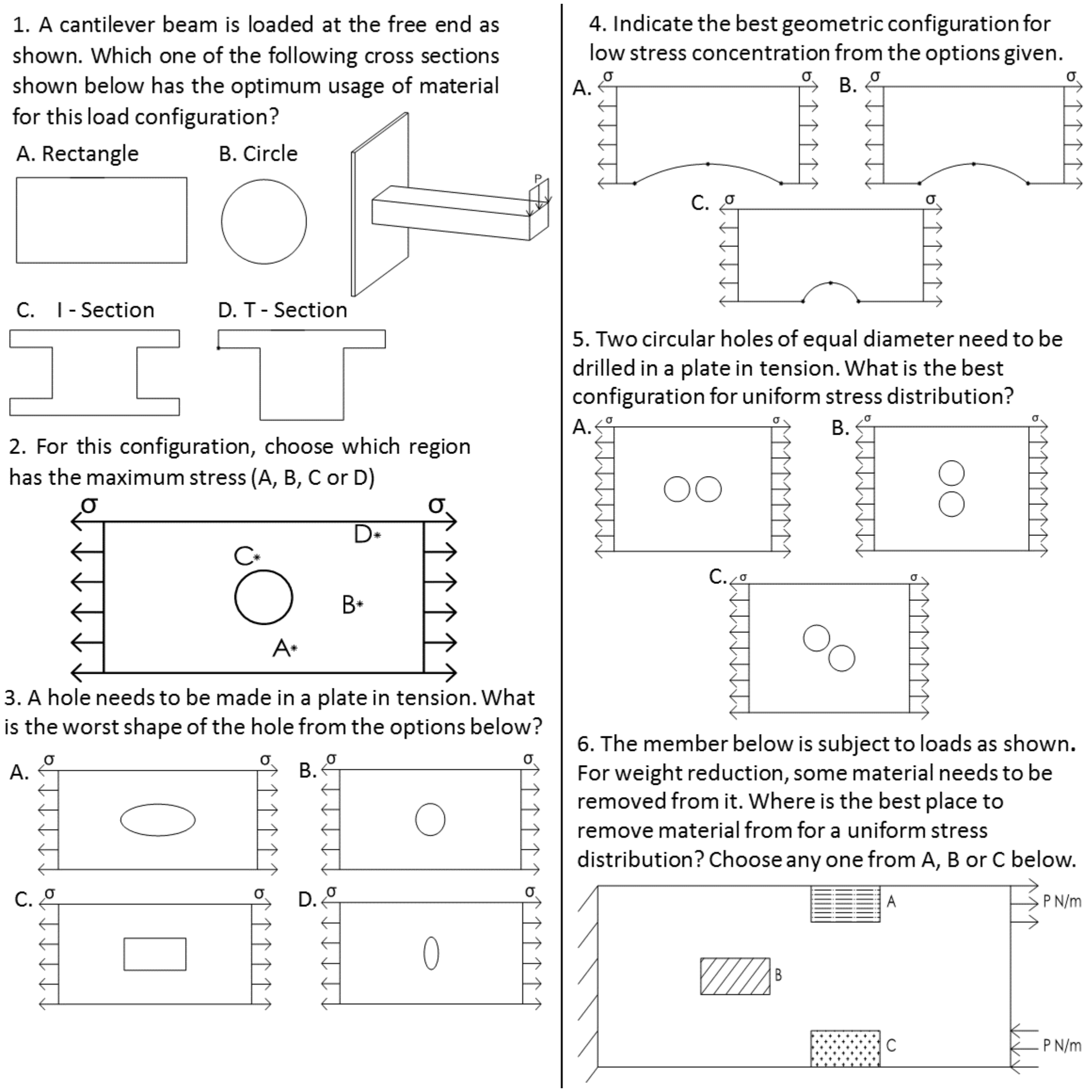
6. FOLLOW-UP STUDY

The follow-up study was conducted exclusively with undergraduate students from the School of Mechanical Engineering. For this study, 10 paid participants (8 male, 2 female), aged between 18 and 25 years were recruited through announcements of the study. To ensure a common baseline, it was required that all participants had completed a course on Mechanics of Materials to participate in the study.

6.1 Study Setup

The study consisted of a pre-study survey, a pre-task questionnaire, three design tasks, a post-task questionnaire and a post-study survey. The pre-study survey was used to get information about the participants' background in mechanical design and FEA. Just like in the pilot study, the pre and post-task questionnaires were administered before and after the design tasks. A web-based post-study survey was administered immediately after the study to receive feedback related to the usability of the interface and the study setup.

The study was conducted on a Desktop PC. Participants used the interface to manipulate the geometry of the member provided for the design task and to create two-dimensional geometric models of their designs. ANSYS 14.0 was used to mesh the model and for FEA. The equivalent von Mises stress plots were downloaded to a separate folder. The participants were given 10 minutes for each design task. The pre and post-task questionnaires are included in Fig. 6.1. The remaining setup for this study was the same as that of the pilot study.



1. A cantilever beam is loaded at the free end as shown. Which one of the following cross sections shown below has the optimum usage of material for this load configuration?

2. For this configuration, choose which region has the maximum stress (A, B, C or D)

3. A hole needs to be made in a plate in tension. What is the worst shape of the hole from the options below?

4. Indicate the best geometric configuration for low stress concentration from the options given.

5. Two circular holes of equal diameter need to be drilled in a plate in tension. What is the best configuration for uniform stress distribution?

6. The member below is subject to loads as shown. For weight reduction, some material needs to be removed from it. Where is the best place to remove material from for a uniform stress distribution? Choose any one from A, B or C below.

Figure 6.1. Pre and post-task questionnaire for the follow-up study.

6.2 Design Tasks

It was observed from participant behavior and feedback from the pilot study that the design task we provided featured a combination of several phenomena which may have confused participants who did not have a very strong knowledge of the fundamentals. Therefore, for the second phase of the study, it was decided to break up the design task into two sub-tasks which were relatively simpler. The rationale for this was that breaking up a complicated design problem into simpler problems would help participants internalize the relatively simpler concepts and then use this knowledge to better visualize the connections between the concepts and thus, apply them in a design task. Therefore, this study had 3 design tasks - the two sub-tasks to begin with and the task from the pilot study as the final design task. The design tasks are shown in Fig. 6.2. The goal for the design tasks was to minimize the area of the given members such that they satisfied a primary design constraint that involved the maximum allowable stress of the member. The members were made of ASTM A-30 Structural Steel. The allowable equivalent von Mises stress was not to exceed 16700 N/cm2 (derived from typical Factor of Safety guidelines for structural members).

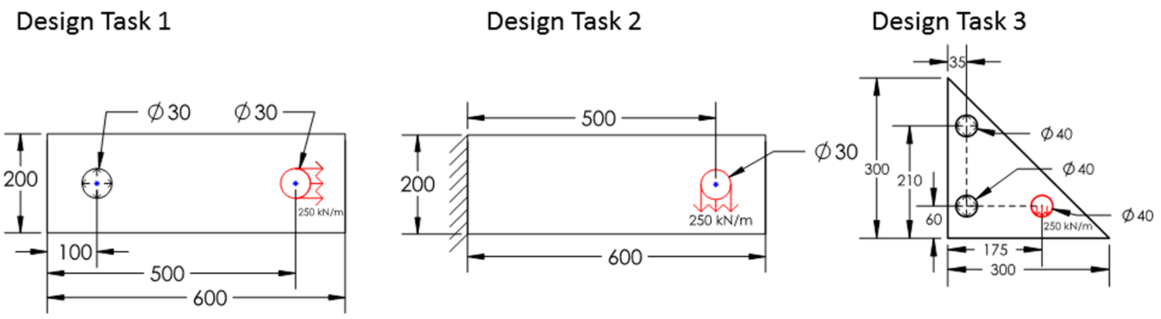


Figure 6.2. Design tasks for the follow-up study.

Participants were allowed to iteratively improve their designs through material removal operations. The area of the member at every step was also displayed to the participants. At the end of every iteration (marked by running the FEA simulation), a plot with the equivalent von Mises stress distribution (SEQV) was downloaded in a separate folder. Participants were instructed to use these plots to guide their exploration.

The results from the questionnaires, surveys and design tasks are discussed in the following section.

6.3 Results from the Follow-up Study

The results from the questionnaires, surveys and design tasks are discussed in the following section.

The first step in the analysis was to evaluate the participants' responses to the pre-task questionnaire. As discussed earlier, the selection of the questions in the pre and post-task questionnaires were in such a manner such that they tested conceptual understanding of the target concepts in Mechanics of Materials. The pre-task questionnaire was therefore a good starting point to understand participants' background knowledge and therefore understand how the mental models of the participants with respect to the concepts changed after participating in the study.

As mentioned before, participants who had previously completed a course in Mechanics of Materials as well as other courses which taught concepts of mechanical design were only recruited. Further, from the pre-study survey, it was found that 2 out of the 10 participants had previous experience in working with FEA through projects and/or coursework. It was therefore expected that all our participants had some fundamental knowledge about mechanical engineering design and stress analysis. However, from an analysis of the responses provided for the pre-task questionnaire, it was observed that only 1 out of the 10 participants got all of the answers and explanations right. This was a matter of concern as it showed that participants did not have a firm grasp of the fundamental concepts of stress and strain associated with concepts P1, P2 and P3.

The next step was to evaluate participants' responses to the post-task questionnaire. This step was done to track any changes in participants' conceptual understanding and mental models with respect to the target concepts after working on the design tasks using our interface. Based on the performance on both questionnaires, it was possible to classify all 10 participants into 6 distinct categories. A concept-wise classification of all participants is shown in Fig. 6.3.

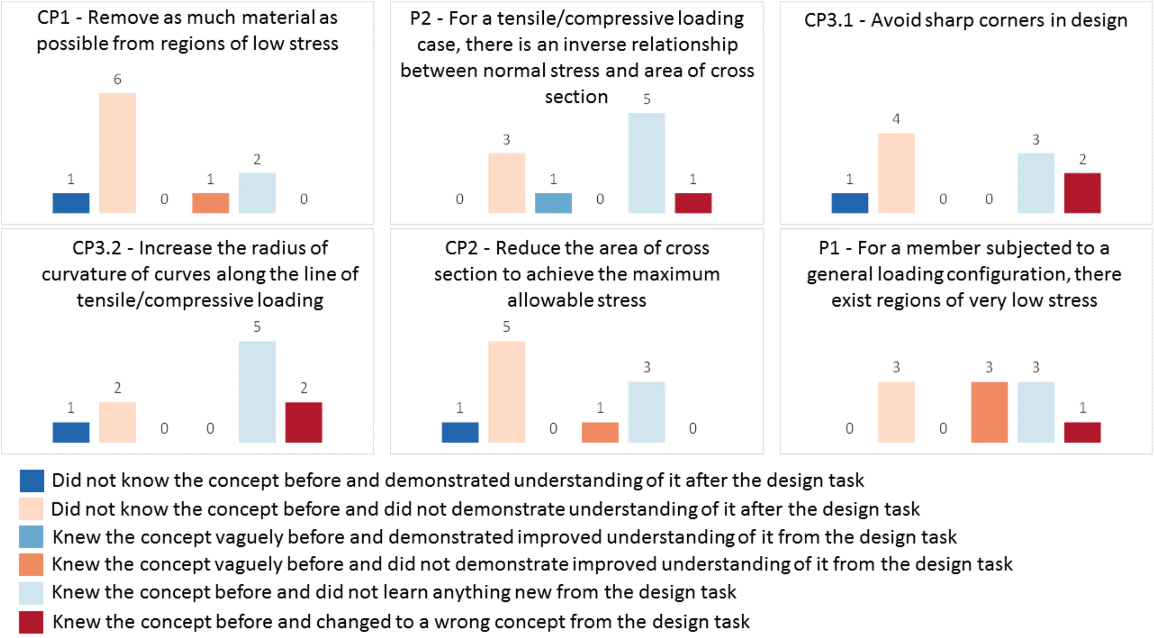


Figure 6.3. Summary of results from analysis of the data from the pre and post-task questionnaires. Each bar chart represents participants' conceptual understanding of that particular concept. The height of each bar represents the number of students corresponding to each category.

From the data summarized in Fig. 6.3, it can be seen that in some cases, after working on the design tasks using the interface, participants demonstrated understanding of concepts they did not know *a priori*. In some cases, participants were able to validate existing knowledge and conceptual understanding as well as dispel false intuitions and mental models after working on the design tasks using our interface. In some cases, participants have also been able to form better mental models of concepts we could see they knew only vaguely before based on their explanations in the pre-task questionnaire. This change is very important as a vague conceptual understanding can have more adverse effects than not knowing a concept at all [62].

Finally, in a few cases, it was observed that participants who seemingly came in with a good understanding of the concepts before the study displayed a lack of understanding of them after. Two inferences can be drawn about the participants in this category from this observation:

(a) The participants did not have a strong mental model of the concepts to begin with. Even though they answered the question correctly with the right explanation in the pre-task questionnaire, this change to a wrong answer and explanation in the post-task questionnaire suggests that the concept was not very well understood.

(b) The participants encountered some artifacts in the course of their exploration over the design tasks that facilitated a change in conceptual understanding. In an unguided exploratory setting like the one in this study, this phenomenon has been commonly observed [46].

It is hypothesized that this phenomenon (in which a participant changed a right answer in pre-task questionnaire to a wrong answer in the post-task questionnaire) associated with unguided exploration can be minimized in future studies through scaffolding. Scaffolding provides clear points where an instructor can intervene to encourage concept learning without intentionally directing the students to the answer desired by the instructor [36]. Participants' exploration pathways were analyzed next and insights into how the changes observed and summarized in Fig. 6.3 took place were drawn.

6.3.1 Exploration Analysis

While the data from the questionnaires provided insights into participants' mental models before and after engaging in the study tasks, it was not sufficient to draw conclusions about how changes in participants' mental models came about. To further investigate changes in participants' mental models participants' individual processes as they worked on the design tasks to draw these conclusions were analyzed. The data from the screen, video and audio recordings as well as data from the transcript of the think-aloud protocol and the study administrator's notes were used for this analysis.

The first step in this analysis was to study how the participants achieved the objective of the design tasks i.e. to study how participants minimized the area of the provided members. The data from the stress plots generated by the participants during the design tasks was used for this step. To get a holistic overview of how each participant proceeded with the design tasks,the normalized area of the member and normalized maximum stress in each iteration were plotted on a 2-sided bar chart. With such a representation, trends in the exploration process could be observed. It could be seen how participants started over in their explorations or changed their exploration strategy by looking at this representation of the data and also at the various recordings (audio, video and screen) that were captured during the design task. From this analysis, points of interest (from an analysis point of view) were identified based on trends in the participants' processes. For example, when a trend of decreasing area was noticed across iterations and a sudden increase in the area was noticed in the subsequent iteration, it was able to be deduced that the participant had changed the exploration strategy at that point and therefore, that point was classified as a point of interest. From the analysis of these points of interest, the process how changes in conceptual understanding and mental models took place could be identified and analyzed. Fig. 6.4 represents the participant iteration data for two participants.

From the analysis of the participant recordings and design rationale, it was observed that in a lot of instances, participants were able to form new connections between concepts, dispel false intuitions and incorrect mental models as well as improve conceptual understanding. Through exploration, participants were able to critically revisit previously learnt concepts and to also make sense of unexpected results.

The next step in the analysis was to compare the top and less advanced performers in the design tasks. This was done to identify the characteristics of the problem

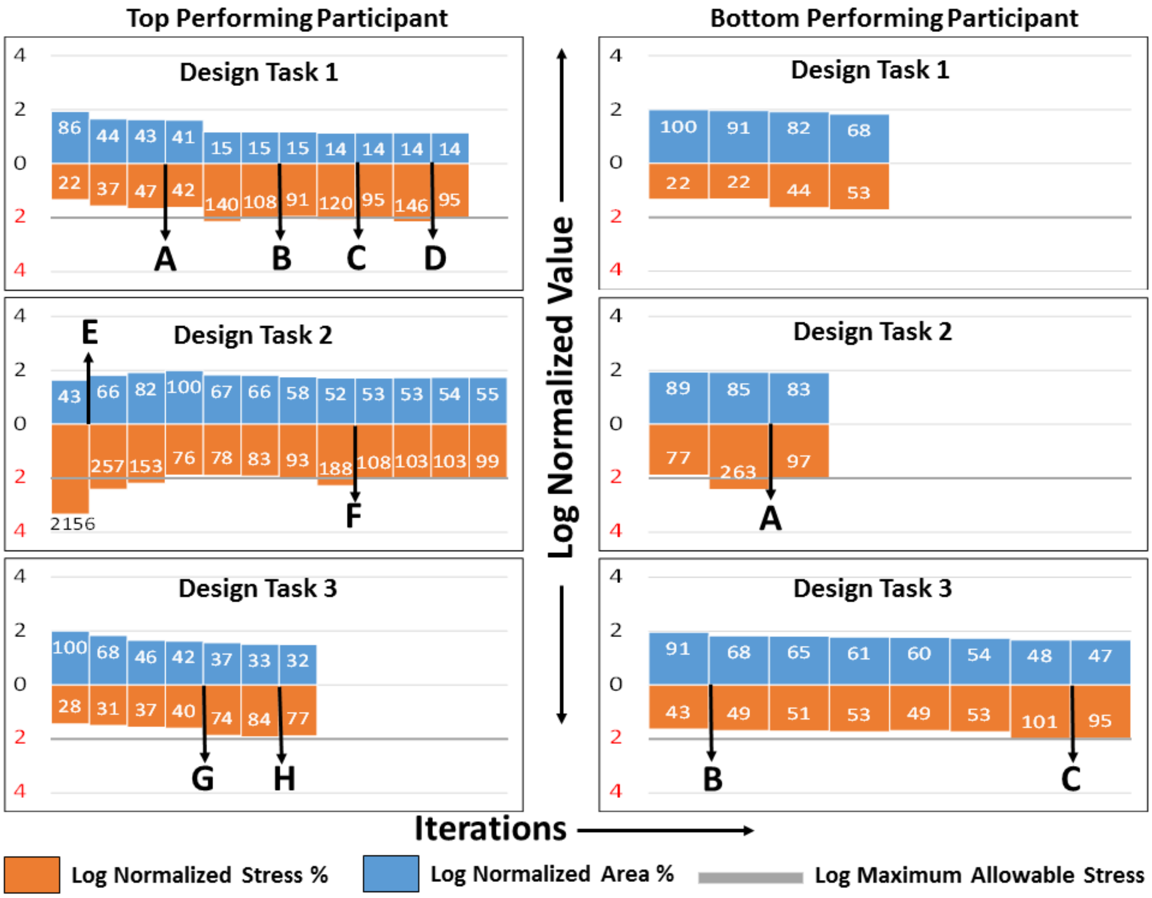


Figure 6.4. Iteration analysis for one participant each from top and bottom performance categories. Here, each column represents a design iteration. The positive Y-Axis represents the logarithm of the final area normalized against the initial area corresponding to that Design Task. The negative Y-Axis represents the logarithm of the maximum von Mises Stress value normalized against the maximum allowable stress value (16700 N/cm^2). The numbers in white represent the normalized percentage values for area and stress. Points marked A, B, C etc. indicate points of interest.

solving approaches adopted by both categories of participants. Participants were first categorized based on their successful performance across the three design tasks. By this categorization, 2 sets of 3 participants who were consistently in the top and bottom halves were obtained. It was observed that participants who performed more design iterations over the course of the design tasks performed better in terms of having lower final areas (For DT1, Pearson r(10) = -0.45, for DT2, Pearson r(10) = -0.61, and for DT3, Pearson r(10) = -0.28). This shows that the participants who leveraged the exploration capabilities of the interface were able to arrive at a better solution which validates the hypothesis that an exploratory assignment of this nature would be an effective approach to support student learning of Mechanics of Materials concepts. It was also observed that there was a significant correlation between the number of failed iterations and final area which allowed us to make the conclusion that participants who explore the design space more broadly and are more liberal in their exploration strategy tend to arrive at better solutions (For DT1, Pearson r(10) = -0.48, for DT2, Pearson r(10) = -0.55, and for DT3, Pearson r(10) = -0.28). Table 6.1.

is a summary of the observed trends. It is expected that the results will be more statistically significant with a larger testing population. Next, the participants' perception of the study and the interface is summarized.

Table 6.1. Summary of participant trends for both groups.

Group	Average no. of iterations	Average no. of times exceeded maximum allowable stress	Average final area % (Design Task 1)	Average final area % (Design Task 2)	Average final area % (Design Task 3)
Top performers	35.3	13.3	17.3	58.3	32
Bottom performers	18.7	4.3	66.3	79.3	49

6.3.2 Participants' Perception of the Study and Interface

The post-study survey after the study, enabled the collection of data about the participants' experience using the interface and in participating in the study. It was noted that there were only 2 instances where participants were not able to complete the design task on time (i.e., within the 10 minutes that they were allotted). Participants reported that the interface helped them to effectively visualize abstract concepts that they learned in class. One participant mentioned that: *"The interface allowed me to simulate different situations very quickly - removes a lot of the complexity from using ANSYS - you need not set so many parameters or create a CAD model in this interface."*

When participants were asked about the helpfulness of the interface and design task to learn new insights or concepts, they commented:

- *"The study validated my previous understanding of concepts - this reinforcement is particularly important because it can also help me identify wrong misconceptions"*
- *"I initially had a mental picture of how stresses would manifest in the design tasks but when I looked at the FEA plots, I was able to see that I did not quite have the right idea"*
- *"I was able to look at material usage in a different way, and thinking of unnecessary waste that can be removed - makes me more aware of structural optimization, whereas before classes only just taught how to analyze simple structures and doesn't challenge one to reduce cost and material waste in a design"*

These comments illustrate the ability of the interface and the exploratory approach to help students improve their conceptual understanding and correct previous misconceptions. Fig. 6.5 summarizes participants' feedback of the study as reported in the post-study survey.

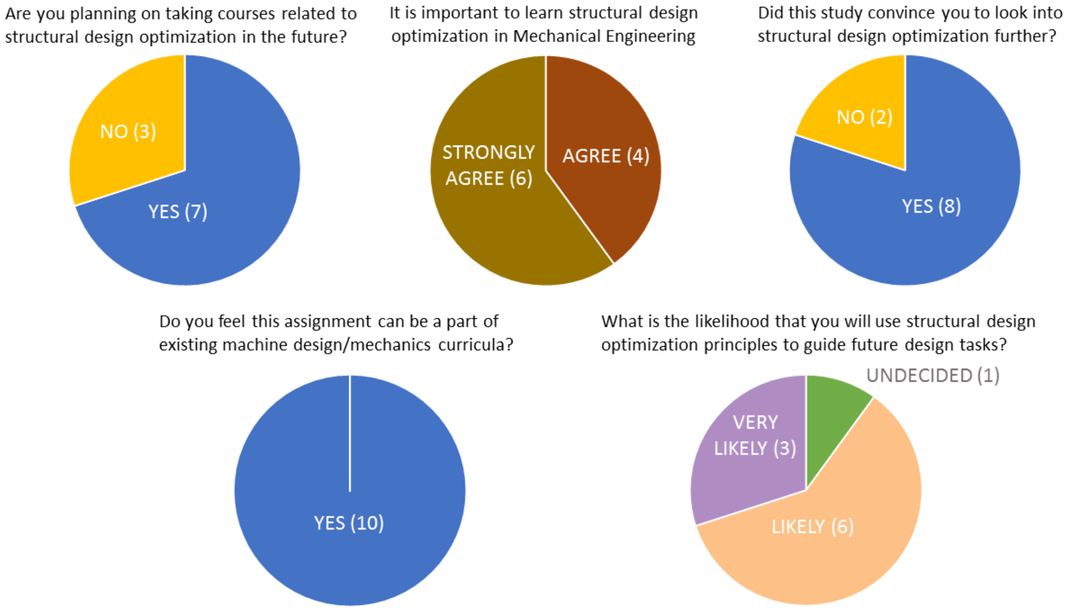


Figure 6.5. Participant responses to questions related to the future use of this interface and study setup in Mechanical Engineering curricula. As seen from the pie charts, participant feedback was largely positive which indicates the usefulness of continuing and expanding the exploration-based study into mainstream engineering curricula.

7. SUMMARY AND CONCLUSIONS

This thesis has detailed the implementation of an exploration-focused instructional framework and associated interface that incorporates an FEA backend to augment student learning of concepts of Mechanics of Materials through exploration via rapid design iterations. Two studies were conducted to test the effectiveness of the approach and interface in aiding students to learn concepts of Mechanics of Materials. Initially a pilot study was conducted and a follow-up study was designed based on results and insights drawn from the pilot study. Results from the follow-up study show that the interface and study setup are beneficial for participants to improve their knowledge of Mechanics of Materials principles. It is also seen that the study helped participants identify incorrect mental models of concepts in Mechanics of Materials and rectify them through exploration.

Based on observations made from the analysis of participants' design activity and usage of the interface, a list of guidelines for designing similar studies and activities related to improving student understanding and addressing knowledge gaps in Mechanics of Materials is presented below:

1. *Guide participants away from 'wrong' pathways of exploration through increased scaffolding:* Scaffolding provides clear points where an instructor can intervene to encourage concept learning without intentionally directing the students to the answer desired by the instructor [36]. It is strongly believed that having the instructor intervene at strategic junctures to encourage students to rethink their exploration strategy would greatly aid the learning process. It would also prevent any negative effects that may arise due to unconstrained exploration such as the formation of new misconceptions due to the occurrence of artifacts during exploration.

2. *Lengthen the duration for the design activity:* It is hypothesized that spreading out future design activities over a longer period of time would help resolve some issues that arise due to time constraints. Also, based on observations from Chapter 6, we can conclude that the participants who perform more design iterations tend to arrive at better final solutions. It is believed that having participants perform a minimum number of iterations would greatly improve their conceptual understanding as there is a higher probability that more preconceived notions would be uncovered and critically examined.

3. *Introduce a competitive element:* During the pilot study, a running leaderboard of the Top 3 final areas for the design task was maintained to encourage healthy competition among participants. It was observed that a few participants proceeded to work further on the design task due to the competitive element that was introduced. However, the leaderboard was removed in the follow-up study owing to the short duration of the individual design tasks. It is believed that fostering a spirit of healthy competition would motivate participants to perform better by exploring more ideas.

4. *Promote collaborative problem-solving:* It is strongly believed that promoting communication between peers while working on similar activities would help reinforce existing concepts while accelerating the discovery of new concepts.

7.1 Limitations and Future Work

The user studies were limited to small participant pools of 8 and 10 as the primary objective of the studies was to make detailed observations of participant behavior and design activity. With these observations, a clear idea of how many participants perceive the interface and the studies was obtained, but other feedback may have been obtained with additional participants.This knowledge will be used to design future assignments and studies to be administered in an academic setting. However, some researchers suggest that a test population of 5-7 participants can be sufficient for testing the usability of new software [20].

Another limitation of this study was the lack of follow-up procedures to check if students have retained what they have learned as a result of participating in the study. This issue will be addressed in the future by conducting longitudinal studies in a classroom setting.

Results from the study show that the interface and associated exploratory design task were beneficial for students to discover new concepts and correct previous misconceptions through rapid exploration of the design space. Feedback received from the participants after participating in the study showed that they welcomed the idea of expanding the use of the interface to a classroom setting. The immediate future work is therefore to incorporate this interface as a teaching aid in courses related to Mechanics of Materials. It is also planned to create a publishing platform which would enable instructors to publish in-class assignments and design problems using this interface.

This interface and study setup is envisioned to lead to an environment that facilitates the integration of engineering analysis and engineering design by allowing users to explore different design options in the early stages of design before any detailed designs are made. To this end, a problem-based instructional framework is proposed below. The instructional model that is suggested in the instructional framework consists of a series of steps that are listed below and are illustrated in Fig. 7.1. These steps are designed to be aligned with specific areas of the theories underlying PBL [34].

- *Problem Identification:* In any field related to engineering design, the instructor should identify problematic areas as observed from student performance and feedback. Understand the shortcomings of the current approach in solving these problems.

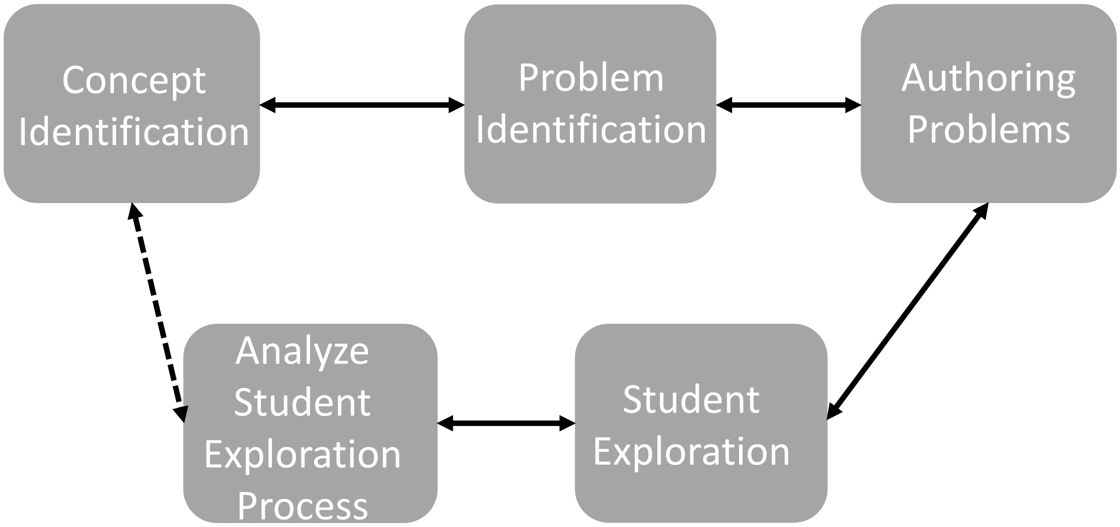


Figure 7.1. Steps in the exploration-focused instructional framework.

- *Concept Identification:* Identify the key concepts in the problem areas identified in the previous step. In particular, identify problem-solving strategies employed by learners to learn these concepts.

- *Authoring Problems:* Develop problems that require application of the identified concepts and which pose situations that are authentic and much more complex than typical textbook problems and also lend themselves to multiple solution pathways. Situating problems in a context which are more authentic and similar to those encountered in professional practice has been shown by previous research [53] to be very effective in aiding student learning. In the future, this work can lead to a meta-language which enables instructors to author their own problems.

- *Student Exploration:* In approaching the problems from their own perspectives, the students will resolve their learning in this process. Problems that require exploration typically do not have one right answer and a departure from the usual trend of solving problems which have a pre-determined answer will result in a better learning experience.

- *Analysis of Student Exploration Process:* Thoroughly document and record all facets of the student exploration process (through logs of student work). Analyze these records to make observations and gain insights about students' design rationale. These insights are essential in enabling change at a "conceptual level" [79].

Since interface was developed on a Web browser, it is planned to expand the capabilities of the interface and expand it to the greater academic community through MOOCs (Massively Open Online Courses) and Web-based modules for online exploration.

Finally, to extend this work and to make it more accessible, the focus will be on developing and disseminating a more intuitive application using a natural user interface (NUI) based software platform.

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