

The Machine Component Design Manual Project and Other Tools for Teaching Mechanical Design

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Abstract

The difficulties in teaching and learning the design of machine components and the assessment of a students ability to do so are addressed in this paper. Teaching and learning machine design is hindered by the inexperience of students and an instructors' inability to motivate students to learn this sometimes ambiguous topic. Students are often intolerant of the ambiguity that shows up in the iterative nature of design, full of decisions, and conceptualization. The assessment of design ability is complicated by the traditional assessment tool; i.e., the examination, which usually requires a unique solution leaving little room for design decisions. In the following manuscript: the currently most-favored pedagogy for teaching design, project based learning (PBL), is reviewed and discussed; A novel project developed for a machine component design course in an effort to motivate students and provide practical experience is presented; And, several tools useful for the design of machine components and in-class assessment of a students ability to design a machine or machine component are presented.

1 Background

Improving the design sequence in engineering curricula is the object of intense discussions in nearly every engineering department and the topic of focused research in the literature. This is due, at least in part, to the changing skill sets of students entering engineering programs today. Wood and Wood concluded the following:

Instead of a tinkering background with the dissection of machines and use of tools, students are now entering with computer, video games, and other “virtual” experiences. This focus has left a void in the ability to relate engineering principles to real-world devices and applications¹.

And that, these different skill sets (and learning styles) can be addressed by introducing more hands-on experiences into engineering curriculum. These conclusions were the motivation of the current research. That is, it was taken as a premise that moving from a traditional lecture format to a more active learning format provides a better learning experience for the students of today.

The reason that students have a better learning experience with a more active format is summarized by the Kolb model of learning, Figure 1. Learning begins with (concrete) experience. We all associate a new topic with something we already know. So, simulating real-world experiences in the classroom, especially for students with less experience “tinkering”, is an important part of learning design. Also, it is difficult to teach abstract hypothesis and conceptualization in the traditional lecture format. Hands-on experiences can also help develop the conceptualization because it is only the observations made from experiences that hypothesis can be made. So, what is the best way to provide a more active learning experience?

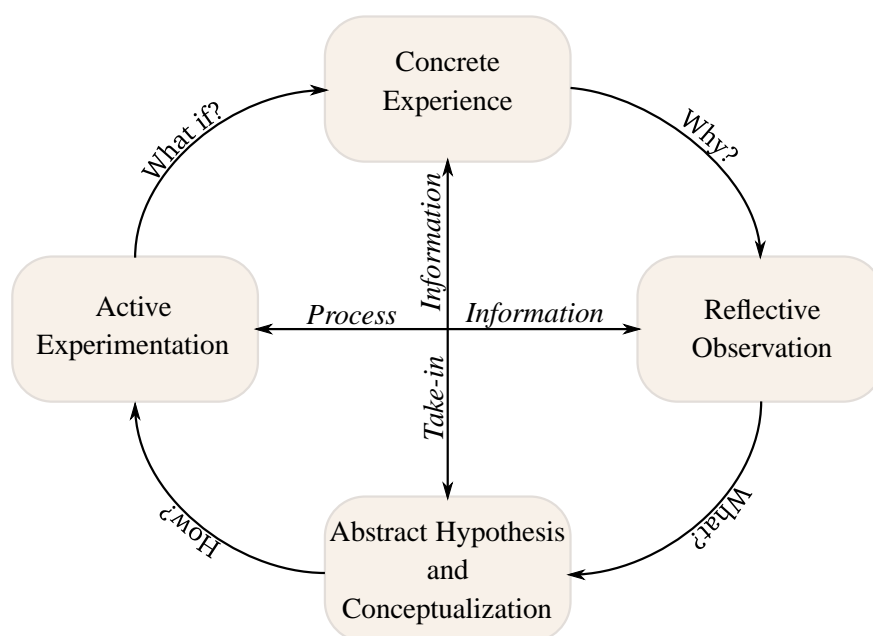


Figure 1: Kolb's model of learning.

Currently, the favored pedagogy for teaching design is project-based learning (PBL)². Dym et al, describes design thinking as an iterative divergent-convergent questioning process and proposes that PBL is the best way to teach students how to design using a systematic questioning process. Projects give students an opportunity to experience the cycle of developing concepts (divergent questioning) and evaluating these concepts to determine the best solution (convergent questioning). The concept of divergent-convergent questioning is also represented in the Kolb Cycle, Figure 1. The questions: *What?* and *What if?* are part of the divergent questioning process. The questions: *Why?* and *How?* are part of the convergent questioning process. Typical examination questions used in a more “traditional” pedagogy require convergent thinking. That is, everyone should get the same answer because the evaluation of the examination requires the question to be verifiable. This leaves little room for asking: “*What* is causing this phenomenon?” or “*What if* this property were different?” Projects help develop the generative, creative, concept type skills needed for the divergent questioning processes.

Project-based learning is primarily used in corner-stone courses (first-year) and in capstone courses (fourth-year). However, some have proposed the PBL pedagogy be dispersed throughout the engineering curriculum²⁻⁴. Jensen, et al.³ used projects and other hands-on activities in machine component design courses to improve “target” lectures which were previously identified as low-motivation or low-interest lectures at the US Air Force Academy (USAF) and the University of Texas at Austin (UTA). The introduction of a two part deconstruction and redesign project in the form of an RC car competition was credited with an approximately 15% increase in scores in several categories of the course assessment. However, the proposed projects significantly reduce the scope of the course as some topics must be removed from the syllabus to accommodate the projects^{1,3}.

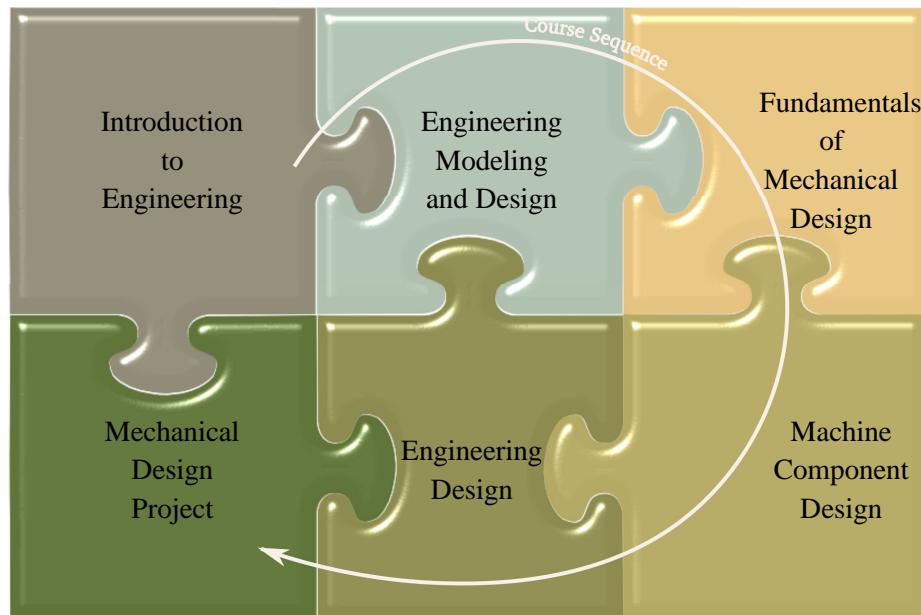


Figure 2: The design curriculum at TECH.

2 Objective

The objective of this work was to improve the design curriculum at Arkansas Tech University (TECH), shown in Figure 2, by utilizing the PBL pedagogy in the (third-year) machine component design course without significantly reducing the topics covered during the course. It is the thesis of this research that it is just as important to cover the topics of the course as to provide hands-on experience through projects. Clearly, if a student does not cover the topic of rolling-element bearings in class they will have little or no knowledge, in the absence of personal experience, to help learn more about selecting the correct rolling-element bearing or even that a rolling-element bearing is needed.

3 The Design Manual Project

The development of a design manual project from the stated objective is summarized in Figure 3. That is, the Design Manual Project was developed as a project for Machine Component Design that meets all educational and topical objectives and provides practical experience and improves student motivation.

The educational objectives are derived from ABET criterion 3 (a-k) and will not be discussed in detail. However, two important program outcomes primarily addressed in the Machine Component Design course are that students graduating from the Mechanical Engineering program should have: (1) an ability to apply principles of engineering ... to model, analyze, design, and realize physical systems, components or processes; and (2) an ability to work professionally in ... mechanical systems.

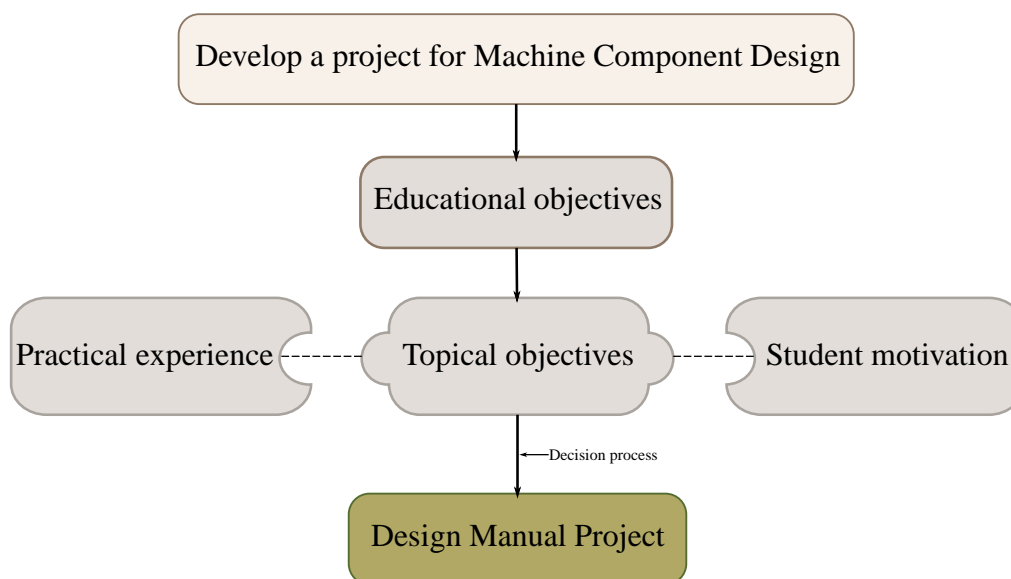


Figure 3: The path from objective to decision.

As stated previously, it is important to cover as many topics as possible in the Machine Component Design course. The topics currently covered in the Machine Component Design course, in addition to the Design Manual Project, are: (1) shafts, shaft components, and shaft supporting elements (rolling and journal bearings); (2) gears; (3) screws and bolted-joint design; (4) welding and other permanent joints; (5) springs; and (6) clutches, brakes, couplings, and flywheels. Topics not covered, but included in the text for the course⁵, are: (1) detailed analysis and design of spur, helical, bevel and worm gears; and (2) chains and belts. The discussion will presently turn to two important questions: (1) *How does the Design Manual Project improve a students ability to design machine components?* and (2) *How does the Design Manual Project improve student motivation?*

Improving design ability

The design skills developed by the Design Manual Project are presented in Figure 4. These skills can be viewed as essential tools that students need to acquire to be good designers. They are tools for their *design toolbox*. The essential tools of a designer, as summarized by Dym, et al.², are:

- ① tolerate ambiguity that shows up in viewing design as inquiry or as an iterative loop of divergent-convergent thinking;
- ② maintain sight of the big picture by including systems thinking and systems design;
- ③ handle uncertainty;
- ④ make decisions;
- ⑤ think as a part of a team in a social process; and
- ⑥ think and communicate in the several languages of design.

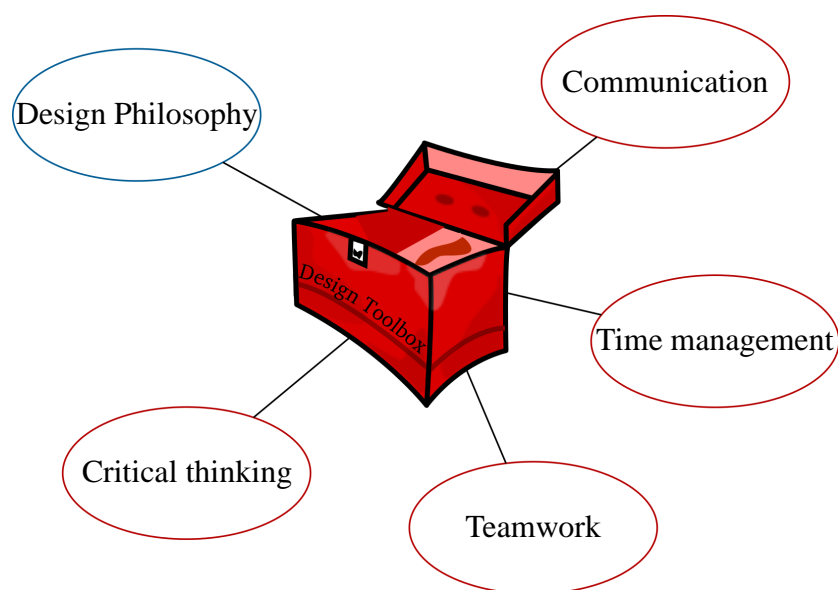


Figure 4: The tools developed by the Design Manual Project.

Most, if not all, of these skills are addressed by the Design Manual Project. Students will continue to acquire new tools with on-the-job experience including perhaps an increased ability to handle uncertainty or to make estimates—tools which require more hands-on experience.

The primary tool developed by the Design Manual Project is a design philosophy. The number of considerations that need to be made when designing or selecting a machine component is sometimes overwhelming without some sort of plan or design philosophy. For example, while developing the design manual for springs a student must ask themselves: How does one select an extension spring? The answer is by asking the right questions! In writing a manual students generate a sequence of divergent and convergent questions that develop into the process one should follow to select the correct spring. For example, one might first ask the question: *What* material should be used for the spring? Then, they progress to the question: *How* does one determine the correct material for the spring? The student might decide that the choice of material is primarily driven by cost. In doing so, the student might develop a plan for determining the material which includes using the most inexpensive hard drawn wire unless extra strength is needed. This philosophy is somewhat elementary, but it can be developed into a more refined philosophy by further questioning and more experience.

Students also consider and develop tools for communicating their designs effectively utilizing critical thinking skills. They develop their design vocabulary or learn “the language of design”. The project is presented as a design process in itself by requiring careful review and revision semester after semester. Students begin with the manual from the previous semester. They critically review and revise the manual as needed. And, contribute some additional research, an example, or design tool to improve the manual. This reinforces the idea that design is an iterative process with no unique solution; that we simply develop concepts and synthesis metrics to optimize the design subject to certain constraints.

Students also experience the challenges and benefits of working as a team on large projects. They are required to develop effective time management tools and utilize the abilities of all their

team members if they hope to complete the manual by the deadline. These skills are further developed in the next course in the sequence but this project helps students appreciate importance of project management before they actually learn it.

Student motivation

The Design Manual Project motivates students to learn the material of the machine component design course because: (1) they perceive the project as something they might use in practice; and (2) they are competitive.

The design manual is taken from a “real world” scenario in which an engineer is responsible for developing design manuals for a group of engineers or technicians. These types of manuals become standards for entities like the National Aeronautics and Space Administration (NASA), other government agencies, or even private industries. The Design Manual Project is presented as such “real world” situation. So, students tend to accept the practicality of the project.

As much as this educator would like to believe that he has been successful in motivating students by developing the perfect “real world” project, it must also be recognized that often the primary motivation for students is their competitiveness. They want to show that they can do a better job than the previous semester’s group. Competition is often one of the key components of PBL¹. So it is appropriate, perhaps essential, that the Design Manual Project also includes this competitive component.

Features

The Design Manual Project has many of the features of the RC car competition used at the UTA and USAFA. It is not necessarily as “hands-on”; providing the experiences of a tinkering background. But, the Design Manual Project does teach the design process^{5,6} and design thinking² using PBL. PBL is effective because it involves the divergent-convergent questioning process not because it involves hands-on activities. Although, the effect of hands-on projects on student motivation can not be discounted.

The Design Manual Project involves the divergent-convergent questioning process at two levels. First, they are designing the manual. The development of the material for the manual and its presentation is a creative process involving a lot of divergent questions. The process usually starts with the question: What information is important to the reader? Then, the development progresses to: How can I best present this information? Secondly, they are refining their design philosophy concerning a particular machine component as they are writing the design manual.

The Design Manual Project does not effect the ability of an instructor to cover as many topics in the machine component design course as possible. The topics for the design manuals are presented on the first day of class and the students pair up in teams and work on the project independently. The instructor acts as a coach for the teams meeting with teams periodically.

The development of the manual includes research of manufactures’ catalogs. This is a major factor in the motivation of the students to learn. Students see that catalogs often include engineering sections which describe the selection of a component that closely parallels the lecture and course material. Just seeing the catalog material is similar to what they learned in class gives them more confidence that they can design a machine (but that they might have to pay attention in class).

4 Assessment

The object of assessment for the Design Manual Project is the ability to apply principles of engineering . . . to model, analyze, design, and realize physical systems, components or processes. An assessment of how a student feels about his or her ability to design a component in the form of course evaluations is only a partial indication of their actual ability to do so. It is important to test students. However, as Dym, et al. questioned:

Can exam questions in an engineering science course be designed to require students to generate concepts by asking generative design questions and then to reason about them by asking deep reasoning questions before offering solutions? If such exams could be designed, how would their concept generation performance be graded, since concepts are neither true or false?

So, how do we evaluate a students design ability? The answer is: The same way any other design is evaluated. In the market. The instructor plays the role of the customer and the consumer. He sets some constraints or objectives for the product, acting as the president of a company, and the designer or design teams set out to win the contract. Then he evaluates the designs with the consumer in mind: Which design would the consumer buy? This approach can be somewhat subjective, but as long as the teams know what the consumer (the subject) wants, it is fair. In the classroom is it often prudent to develop a factor of merit (f.o.m.) to evaluate the designs and provide the f.o.m. to the teams with the problem statement.

Perhaps the best way to assess a students ability to design a machine is a competitive project like the RC car used at the UTA and USAFA. However, in the machine component design course it is sufficient to assess the students design abilities at the machine component level on an exam. Then, the final assessment of the design abilities of students can be left to the senior design project (capstone-course).

An example exam question:

- ① Design a support for a 5000 *lb* static load suspended from a $1/2 - 13$ UNC bolt between two rollers that are 12 *in* apart. The design should be light weight, economical, and safe. For the purposes of design assessment use a factor of merit equal to $5 \times \text{cost} + 4 \times \text{weight}$. Do not include the cost of the bolt, but include in your design provisions to support the load by the bolt.

This may seem like a problem with a unique solution but it is clear from the number of solutions such a problem generates that different conceptualization processes exist. Further decision making processes may be introduced by stating that the load is dropped from a height of 6 *in*. Most students will include the impact loading, but not every student will consider placing the structure on an elastic foundation or including a dampener to reduce the effect of the impact load. The lesson is quickly learned in the competition setting.

Assessment tools

Assessment of design abilities by examination is hindered by the time allotted for examinations. One solution is to give take-home test, but the likelihood of cheating often renders the results in-

consequential. Instead one can develop design tools to help with the design process. (See the following section.) These design tools, usually computer programs or spreadsheets, can be developed by students or provided by the instructor and used on the exam to reduce the time needed to complete the exam. This essentially removes analysis from the examination so that assessment can focus on the design ability of the student. However, other questions on the exam can address the analysis if required. These design tools are discussed in the following section.

5 Design tools

Computer programs and spreadsheets are developed by students or provided by the instructor so that the design process can be experienced. By developing design questions which feature optimization of one or a few of the design parameters students must make decisions regarding their value and evaluate and reconsider their decision in an iterative process. Because they must repeat several calculations; the design tools make the process easier to complete within the allotted time.

To date MATLAB[®] has been used to develop programs⁷ for: (1) specifying the shaft layout of a rotating shaft; (2) calculating the critical speed of shafts; (3) the selection of rolling-element bearings; and (4) the design of bolted connections. Spreadsheets are used for the design of springs subject to static and dynamic loading. By way of example consider the MATLAB code presented in Figure 5.

This very simple program calculates a catalog rating load that is then used to determine the correct bearing (or a number of acceptable bearings) for a particular application. The unknown temperature factor f_T and speed factor f_V depend on the bearing selected. Therefore, the student must guess them or take them as one at first. Then, they calculate the catalog rating load, select a bearing from the TIMKEN catalog, determine the application factors f_T and f_V , and recalculate the rating load to be sure the selected bearing is still acceptable after the real application factors have been applied.

The process is even more complicated if a set of tapered roller bearings are used. Then, the equivalent radial load for each bearing depends on the tapered roller bearing used and the orientation of the bearings (direct vs. indirect mounting). The MATLAB code presented in Figure 6 is used to calculate the equivalent radial loads and the trust loads on each of two tapered roller bearings mounted in a single-row-mounting configuration. Then, these equivalent radial loads are used in a call to the code of Figure 5 to calculate the catalog rating load. This process can be quite divergent as a poor selection of bearing can actually increase the required catalog rating load depending primarily on the radial-to-axial dynamic load rating factor K . A low K at one bearing induces a large axial load on the other bearing requiring it to be a (needlessly) larger bearing. Clearly, such a poor choice warrants a penalty because the larger bearing would in general cost more.

Students work homework assignments using the code(s) and develop a design philosophy for bearings. That is, they consider what type of bearing to use by asking the questions: What types of loads are there?; Are axial loads present?; Which type of bearing is better suited for these loads?; How big does the bore diameter of the bearing need to be?; What is the diameter of the shaft where the bearing will be placed?; Will there be room for a housing for oil, or will grease be used?; etc. Generating and answering these questions is the diverging-converging process of design. It is very important to give students the opportunity to generate these questions. So, the problem statement on the exam must be carefully considered, but incomplete enough to make decisions concerning


```

1 function C10=timkenratload(af,P,LD,RD,a3,a)
2 % C10=timkenratload(af,P,LD,RD,a3,a)
3 %
4 % a program to calculate the catalog (timken) rating load
5 %
6 % * * * * * D A T A   C A R D * * * * *
7 % I N P U T -----
8 % af:      application factor
9 % P:      dynamic equivalent radial load
10 % LD:     desired life in rev
11 % RD:     desired reliability
12 % a3:     =fT*fV - operating condition factor
13 % *      fT: temperature factor
14 % *      fV: speed factor
15 % a:      =3 - for ball bearings & 10./3 - for roller bearings
16 % O U T P U T -----
17 % C10:     timken catalog rating load
18 % * * * * *
19
20 C10=af*P*(LD/4.48/a3/(1-RD)^(2/3)/90e6)^(1./a);

```

Figure 5: A MATLAB code for finding the catalog rating load of a TIMKEN bearing.

important questions that must be asked. For example, it may not be immediately obvious that axial loads are applied. An exam could include specifying the bearings on a particular shaft of a two stage gear train with helical gears. Students must consider the axial loads generated by the meshing of helical gears and include that consideration in their bearing selection. A cylindrical roller bearing would not be appropriate for this application and students should be penalized for such a selection.

```

1 function [FaA,FaB,PA,PB]=timkensrm(m,Fae,FrA,FrB,KA,KB)
2 % [FaA,FaB,PA,PB]=timkensrm(m,Fae,FrA,FrB,KA,KB)
3 %
4 % a program to calculate the dynamic equivalent radial load
5 % for single-row mounting on p A33 of timken catalog
6 %
7 % * * * * * D A T A   C A R D * * * * *
8 % I N P U T -----
9 % m:      m=1 if direct mounted m=-1 if indirect mounting
10 % Fae:    externally applied axial load
11 % FrA:    (resultant) radial load at A
12 % FrB:    (resultant) radial load at B
13 % KA: Radial-to-Axial Dynamic Load Rating Factor (bearing A)
14 % KB: Radial-to-Axial Dynamic Load Rating Factor (bearing B)
15 % O U T P U T -----
16 % FaA:    trust load at bearing A
17 % FaB:    trust load at bearing B
18 % PA: dynamic equivalent radial load at A
19 % PB: dynamic equivalent radial load at B
20 % * * * * *
21
22 lhs=0.47*FrA/KA;
23 rhs=0.47*FrB/KB-m*Fae;
24
25 if (lhs<rhs)
26     FaB=0.47*FrB/KB;
27     FaA=FaB-m*Fae;
28     PA=0.4*FrA+KA*FaA;
29     PB=FrB;
30     if PA<FrA
31         PA=FrA;
32     end
33 else
34     FaA=0.47*FrA/KA;
35     FaB=FaA+m*Fae;
36     PA=FrA;
37     PB=0.4*FrB+KB*FaB;
38     if PB<FrB
39         PB=FrB;
40     end
41 end

```

Figure 6: A MATLAB code for finding the equivalent radial loads and thrust loads for a single-row-mounted set of TIMKEN tapered roller bearings.

6 Conclusions

The Design Manual Project provides students with the essential components of the PBL pedagogy. That is, students “experience design as active participants”² and they experience the divergent-convergent questioning process of design. Assessment of similar projects, e.g. the RC car competition, have proven effective in improving student motivation and a students comfort level in designing machine components. Positive student comments and reviews suggest that the Design Manual Project achieves similar results. However, as to the object of the assessment for this research, i.e. the ability to apply principles of engineering ...to model, analyze, design, and realize physical systems, components or processes, no quantifiable assessment data is available at this point. Possible assessment plans include collecting data from the capstone course, program exit interviews, and alumni surveys.

Assessment of design ability by exam evaluation is possible if computational design tools are used. And, it is possible to grade the design process by designing the exam so that important questions must be generated to achieve an acceptable design or by requiring optimization of the design, e.g. lowest possible cost.

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