2006-725: APPLICATION OF STANDARD DESIGN TOOLS TO SPECIALTY ENGINEERING DISCIPLINES

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Application of Standard Design Tools to Specialty Engineering Disciplines

Introduction

Example applications of most engineering design tools, such as reliability testing or optimization, are oriented toward the major engineering disciplines and not toward smaller, more unique disciplines. Furthermore, design in a field such as the author's disciple of geological engineering does not generally produce manufactured items, mechanized processes, or high performance activities, which are what many design tools were developed to optimize. For these reasons, a set of design tools and examples was developed that specifically apply to geological engineering. Examples are developed for typical geological engineering problems, shepherding students through the same decision points they will face in this industry. The modifications and motivations to develop these tools may be useful to other specialty engineering disciplines, such as mining, petroleum, geophysical, environmental, metallurgical, nuclear, and materials/ceramics, to name a few.

Tools include general engineering design skills such as problem solving techniques, discipline-specific writing skills, project management techniques, and use of scientific principles to solve typical geological engineering problems. Numerical tools include optimization methods (differentiation, Langrangian multiplier, and linear programming), economic analysis (with examples different from the "machinery purchase and depreciation" models usually given), and statistics. Analytical tools include reliability and failure analysis, fault trees, risk assessment, and maintainability (which, for geological engineering, often focuses on "design for low maintenance"). Design management skills include ethics exercises specific to geological engineering and project management exercises aimed at students who will enter the consulting engineering and construction industries.

Design in Specialty Engineering Disciplines

In any engineering discipline, a contrast may be made between "engineering science" and "engineering design" problems. Engineering science problems typically share the following characteristics:

- "the problem statement is compact and well-posed
- the problem has readily identifiable closure
- the solution is unique and compact
- the problem uses specialized knowledge"[1]

Typical engineering science problems might include calculation of deflection of a loaded steel beam or calculation of current flowing through a given circuit.

In contrast, engineering design problems have more open-ended characteristics:

- "the problem statement is incomplete, ambiguous, and self-contradictory
- the problem does not have a readily identifiable closure
- solutions are neither unique nor compact
- the problem requires integration of knowledge from many fields"[1]

A typical engineering design statement in a traditional discipline (mechanical, in this case) might be, "design a system for lifting and moving loads of up to 5000 pounds in a manufacturing facility. The facility has an unobstructed span of 50 feet. The lifting system should be inexpensive and should satisfy all relevant safety standards."[1]

Specialty engineering disciplines add other characteristics to engineering design problems. In geological engineering, for example:

- the solution is not usually a widget, but may be a procedure, an investigation, a way of detecting something underground, etc.
- the working materials are not visible, are not homogeneous, and are difficult to characterize
- judgment and experience play a greater role
- the level of ambiguity is uncomfortably high

A typical engineering design statement in geological engineering (italicized portion of the problem description below) displays this ambiguity:

> There is interest in a possible new lead ore trend in south-central Missouri. This trend is located in the Mark Twain National Forest, and there has been a strong public reaction to proposed subsurface exploration. In addition, there is some concern that the mining activities will impact Big Spring, near the town of Van Buren and within the Ozark National Scenic Riverways.
>
> Big Spring is fed from the Roubidoux Formation and mining will occur in the Bonneterre and Lamotte Formation at greater depth. The Roubidoux is separated from the mining zones by the St. Francis confining unit.
>
> *You have been asked to assist the Forest Service in developing a testing program to assess the effectiveness of the St. Francis confining unit.* Your work will address the concern that mining will influence either water quality or flow at Big Spring.

Problem Solving Skills

In some sense, problem solving skills are universal: what works in one field, will work in another. The author uses excerpts from the book by Starfield, Smith and Bleloch[2] to give students practice using the heuristics they propose:

- if a question is difficult to answer, start by asking an easier question (and the corollary, if a problem is difficult to solve, start by solving an easier problem)
- use Occam's Razor (embrace the most-straightforward, simplest solution)
- ask what would it take to get the best possible answer
- list assumptions, rank them, decide which are the best to replace with hard data
- cut through the details to get to the bare essentials (Gordian knot)
- imagine yourself inside the problem – what is going on around you?[2]

The authors also introduce a number of universally useful tools:

- assessment of accuracy / development of error bounds
- sensitivity analysis
- analysis of upper and lower bounds and how to narrow the difference
- importance of symbolic and graphical representations or diagrams
- use of algorithms and lumping of parameters to estimate answers
- calibration to the real world
- presenting trade-off alternatives rather than numbers
- use of stochastic models[2]

Most of the chapter-long example problems in the book might apply to any quantitative discipline, as they deal with volume estimation, thermodynamics, probability and system dynamics. Individual instructors could modify some of the problems to deal specifically with their own fields. For example, one of the book's problems explores estimating how many ping-pong balls would fill a room as a way of forcing students to analyze how they model, gauge accuracy and error, and make assumptions. In geological engineering, a parallel problem asks students to estimate how much limestone a given hill might produce for concrete aggregate. This simple substitution suddenly transforms the problem into something the students can better connect with and reinforces the relevance of their own field of study.

Optimization

Many optimization techniques rely on differential calculus to identify critical maxima and minima as points representing lowest costs, lowest material usage, lowest time or labor commitments, and so on. Methods such as the Lagrangian multiplier or linear programming allow optimization of multiple variables simultaneously or incorporation of multiple constraints. Typical examples given in design texts include equipment operation costs[3], manufacturing costs[3], packaging/shipping[4], construction of complex items with multiple constraints[5], and solutions to sets of equations and boundary conditions whose purpose is not expressed[4].

For geological engineering, the author teaches optimization by differentiation methods using an example of treatment of expansive (swelling) clays. Students are given equations to calculate treatment costs by either lime mixing or by excavation, backfill, and recompaction. Crossover points can be calculated to show the expansive soil layer thickness best treated by each method. Likewise, the Langrangian multiplier method is taught using a discipline-specific model, where students are challenged to optimize the number and length of tieback cables used to stabilize a landslide.

Reliability

Reliability in traditional engineering design often measures failure of mechanical or electrical components. The closest analogs in geological engineering design are instrumentation or mitigation elements, which can be used to convey the ideas of series and parallel networks. For example, Figure 1 shows an example of remote landslide monitoring with a series network, in which failure of any single component would result in system failure. Figure 2 shows an example of debris flow mitigation using a parallel network, where only one component needs to function properly for the system to succeed. Figure 3 is an example of bridge scour mitigation using a series-parallel network, which requires success of at least one component in each of the series.

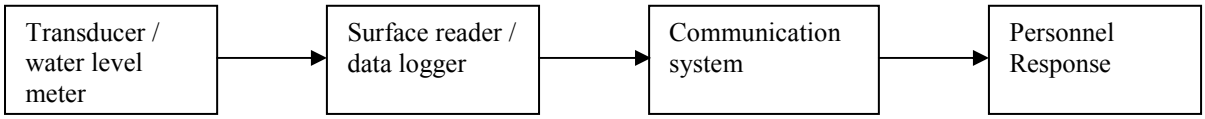


Figure 1. Representation of reliability of remotely measured piezometer to track ground-water levels in a landslide, using a series network.

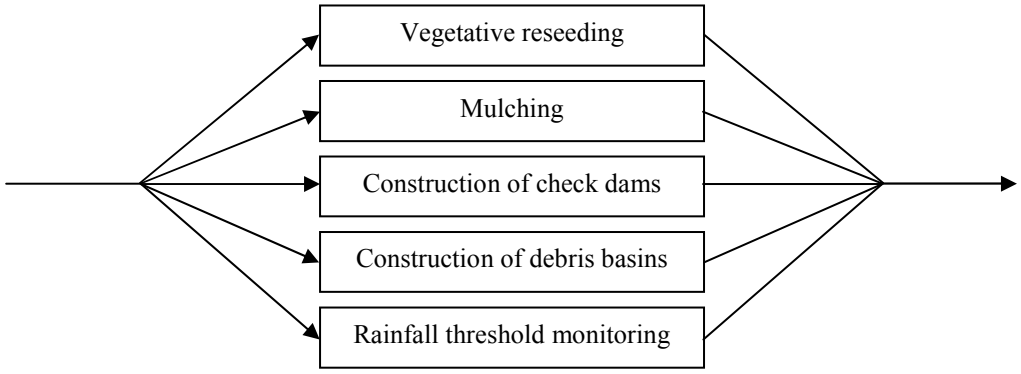


Figure 2. Representation of reliability of debris flow mitigation by a parallel network.

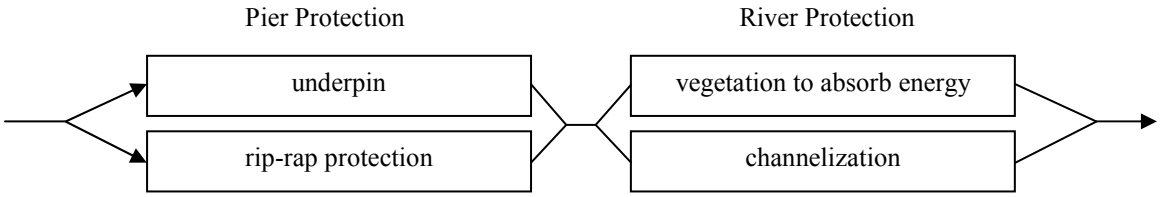
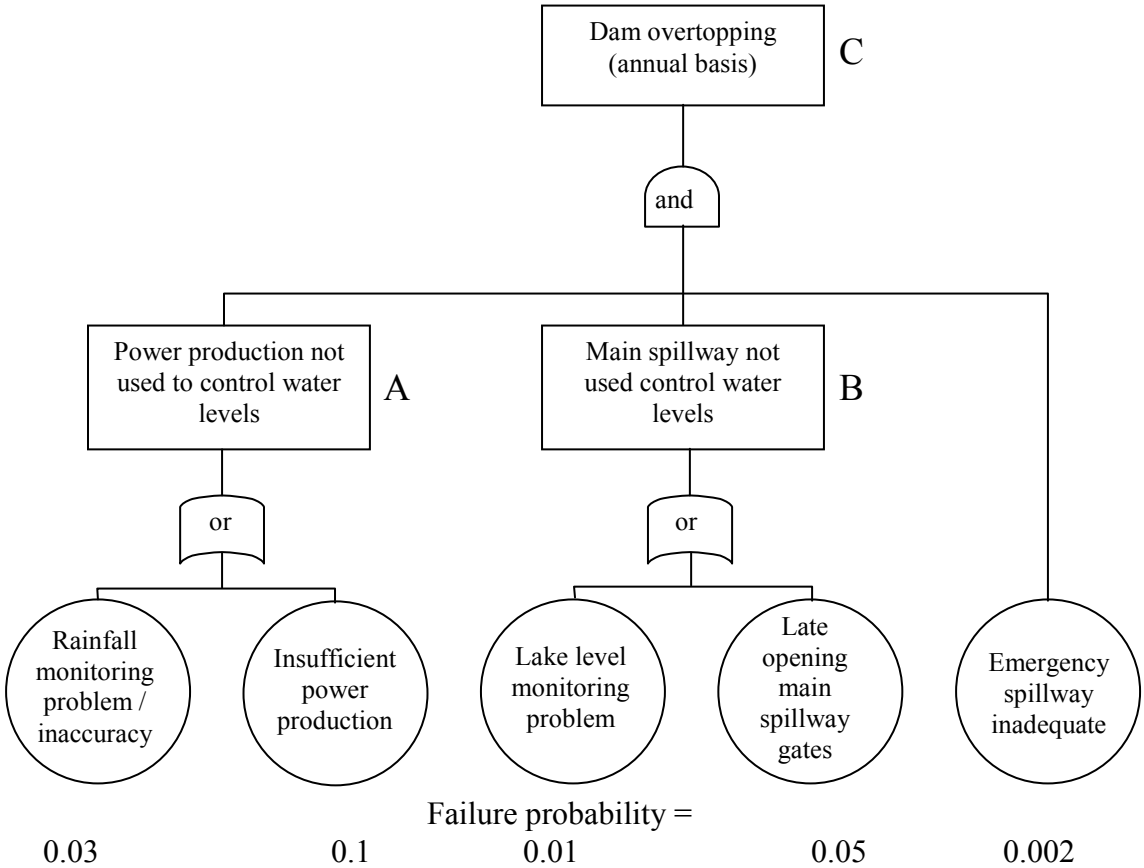


Figure 3. Representation of reliability of bridge scour mitigation by a series-parallel network.

Reliability evaluation by fault trees is shown in Figure 4, where the chance of overtopping of a dam can be calculated.



<u>Failure at A</u>
$F_A = 1-(1-0.03)(1-0.1)$
$= 0.127$

<u>Failure at B</u>
$F_B = 1-(1-0.01)(1-0.05)$
$= 0.0595$

<u>Failure at C</u>
$F_C = (0.127)(0.0595)(0.002)$
$= 15 \times 10e\text{-}6$

Figure 4. Representation of reliability against overtopping of a dam using a fault tree.

The concept of the "bathtub" curve in reliability (that is, the failure rate of a product is highest both early and late in its cycle, with a reliable "useful life" period in between) is demonstrated by a curve showing failure rates of natural dams created by landslides (Figure 5). In this case, the first part of the bathtub curve is shown: most failure of natural landslide dams occur within about six months to a year. After this time, the failure rate is fairly low, until some unidentified future time (not shown on the graph) when the dams are destroyed by silting and

overtopping, by overtopping from rare, large flood events, or by additional landslide movement caused by large-scale triggering events.

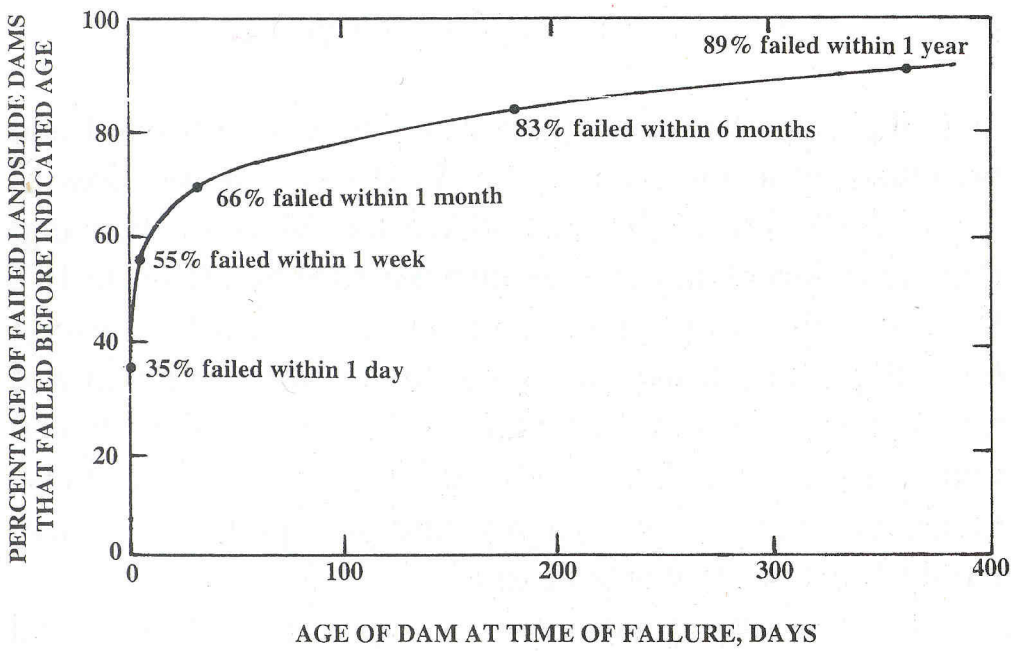


Figure 5. Failure rate of natural landslide dams, based on 187 case studies of failed dams (from reference 6). Note that this curve represents the first half of a bathtub-shaped hazard rate curve.

Maintainability

Dhillon[3] defines maintainability as "a characteristic that reflects the accuracy, safety, cost effectiveness, ease, and time required to perform any needed maintenance tasks."[3] The connotation is that the goal is to keep equipment and machinery in good working order. Although geological engineering does not typically deal with constantly-running machinery, many of the elements of maintainability design are valuable elements in geological engineering design. Table 1 summarizes examples of these elements.

Economic Analysis

Most geological engineers work for engineering consulting firms, which have few tangible assets that are readily evaluated by engineering economic analysis. Other engineering disciplines may have similar business settings: most of the assets are in personnel and client bases and not in capital investments. Examples demonstrating the value of economic analysis may still be developed, and a few in the field of geological engineering are listed below:

- your company is considering buying a $200,000 drilling rig. For 2% inflation and 5% annual depreciation, what will be the rig's value if you hope to sell the

company in 5 years? How much annual business does the rig need to generate to pay for itself in that time period?

- your client is a mining company who must post a reclamation bond of $3M to be used at the end of the mine's life in 30 years. How much money should they invest today in the bond market (i = 2.7%) or in an index stock fund (i = 9%)?
- a new office computer system will cost $25,000 and you expect to spend $2500 per year on maintenance and software updates. Is this a better deal than a 10-year lease with an up-front cost of $50,000? Than a 10-year lease at $6000 per year?
- compare two alternatives for stabilizing a landslide for a 50-year project life: drains (15-year life, $75,000 initial cost, $2500/year maintenance) or a tieback wall (50-year life, $200,000 initial cost, $200/year maintenance). How would your analysis change if the drains had a life of only 5 years before they had to be replaced?

Table 1 – Examples of Maintainability in Geological Engineering

Maintainability Element	**Description**	**Examples in Geological Engineering Design**
Accessibility	Ease with which a component can be reached for inspection, repair, etc.	• design mudflow catchment basins so that equipment can easily enter and exit to excavate accumulated material • design ground instrumentation devices so that they are not buried by later construction
Modularization	Product designed in separate units that are easily removed and replaced	• rockfall fences are built as individual, connected panels that can easily be replaced when damaged
Standardization	Limit the variety of parts and use readily-available parts if at all possible	• plan for large slurry wall construction should specify common construction equipment wherever possible • most-damaged and frequently replaced components of rockfall fences are available at hardware stores
Interchangeability	Similar parts should be used across different projects	• design rockfall fences using the same components as other fences owned by the client
Safety	Protect maintenance personnel, build in fail-safe elements and inspection processes	• even though they only need cleanout every five years, horizontal landslide drains should be cleaned on an annual maintenance schedule, because that is the frequency that most agencies can maintain reliably

Ethics

In their careers, most engineers will not face "space shuttle O-ring" type ethics issues very often. However, on practically a daily basis they will have to make ethical decisions associated with billing hours and expenses, client and employer relations, issues of advocacy, and general professionalism. Santi[7] gives a detailed set of examples and exercises to:

1. "reinforce the concept that engineers are frequently involved in judgmental decisions with no clear right or wrong answer,
2. encourage students to think through the judgmental and ethical decisions they will face before they have to deal with them in the working world, and
3. help them reach a consensus about the underlying principles which guide each ethical decision."[7]

The reader is referred to this paper for ideas from which exercises may be developed to reflect one's own experience and to emulate the expected ethical issues for a specific engineering discipline.

Risk Assessment

Risk assessment answers the question, "How likely is it that something can go wrong and impact something of value?" Risk calculations are valuable tools for decision-making, as they allow quantitative relative comparison of various "what-if" scenarios. In geological engineering, risk assessment is very important for the analysis of geologic hazards, such as rockfall, debris flow, earthquakes, flooding, exposure to contaminated soil or ground water, or environmental impacts from large operations such as surface mines.

Discipline-specific risk assessment problems will typically deal with risk of human health, environmental damage, or other "disaster-scale" occurrences. Risk calculations can also be used to judge almost any worst-case scenario, such as economic downturn, extreme competition, or loss of market share, for example.

Risk assessment can also be handled in a more qualitative sense, as shown in Figure 6. This sort of flowchart approach teaches students systematic, transparent, and repeatable methods of making complex decisions.

Statistics

In the author's experience, engineers usually learn statistics as it relates to a variety of normally distributed data sets. Textbooks present a wide range of fields in the example and homework problems, but the student will find only a few problems in his or her specific field. It is unlikely that a student in geological engineering will encounter any examples at all within that field. Once in the workplace, geological engineers face statistical questions that their coursework did not prepare them to answer:

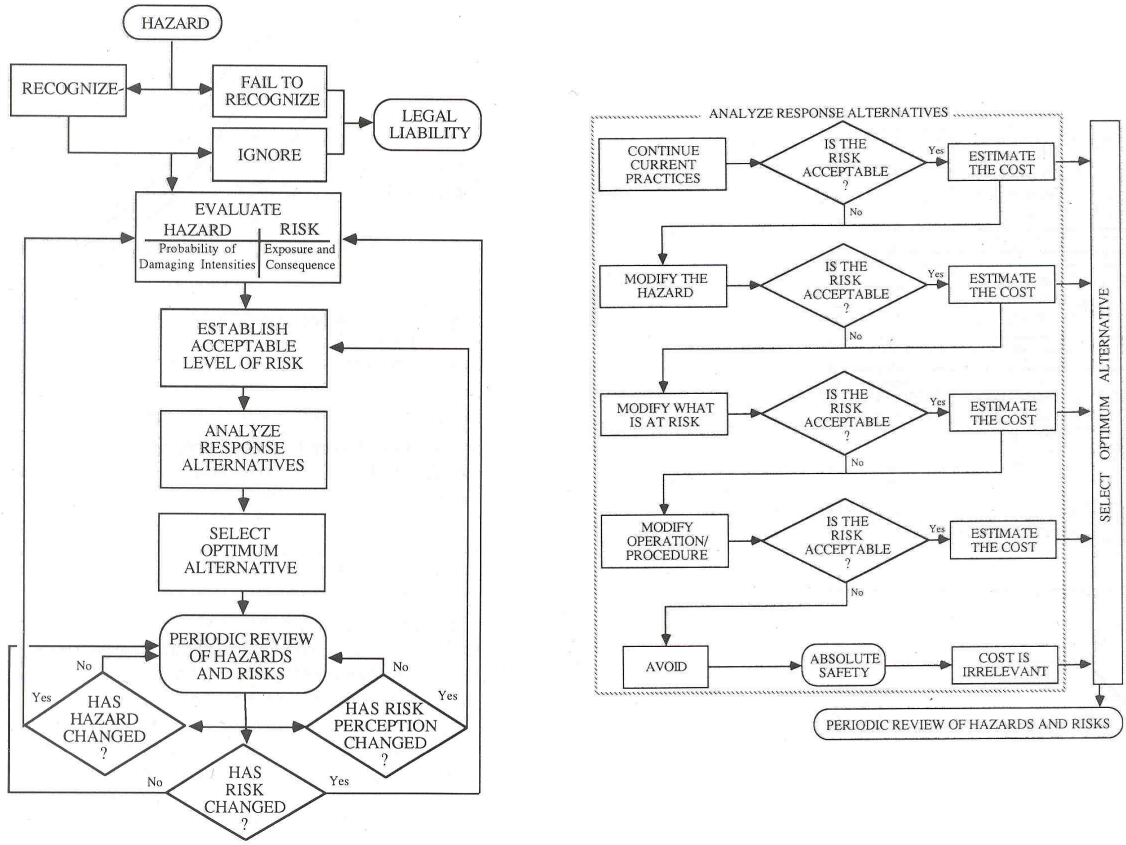


Figure 6. Example qualititative decision-making process using risk assessment principles (from reference 8). Left diagram represents the process for geohazard risk assessment, and the right diagram represents possible responses. This approach could be easily modified to address risk assessment in other fields.

- is the data really normally distributed? If not, how do I handle even simple questions regarding the central tendency ("How much gold is present, given that I have only a few test values of gold concentration, and the mean value is not representative?")?
- does an extreme value really fit in the data set? How do I determine outliers?
- are two data sets equal (Does the arsenic concentration on-site differ significantly from background levels?)
- How do I express my confidence limits, especially for small, non-normally distributed data sets?

These tools can be delivered to students in only one or two compact lectures, provided the instructor has carefully selected the data sets to use for example calculations. Such an exercise has the additional advantage that it teaches students to critically evaluate data and data collection plans, giving them a healthy skepticism for reliance on single data points or mean values. This discipline-specific ability to handle data is a crucial component of engineering design.

Conclusions

Instruction in engineering design can provide content delivery in addition to practice working through the design process. This content will provide the most positive impact on students if it is discipline-specific, using real-world examples that they will encounter in their careers. In some fields, such as geological engineering, students have not traditionally benefited from design tools that have been developed and proven over many years in the larger engineering disciplines.

Various techniques presented in this paper were used in five sections of an undergraduate geological engineering design class during the period 1996-2000 (n=93) and a graduate advanced geological engineering design class in 2005 (n=6). For the undergraduates, the ethics exercises were the highest rated of any class activities (on average, ethics exercises were rated between 3.1 and 3.7 on a 4 point scale). Likewise, focused, discipline-specific statistics instruction was well received (rated 2.9-3.8). Several problem-solving exercises were completed each year: some were well regarded and some were not (rated 2.5-3.8). An introduction to risk assessment techniques was incorporated into design projects for three of the five years (n=63). Students recognized the usefulness of this design tool (rated 3.3, 3.0, and 3.0).

Based on a survey of graduate design class, who were taught all of the tools introduced in this paper, they most appreciated the instruction on problem solving, risk assessment, and discipline-specific ethics, but needed more examples to fully grasp the importance of a few of the other tools (namely reliability and maintainability) in their field.

Bibiography

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