AC 2004-298: NOT AS BAD AS IT SEEMS: TEACHING PROBABILITY AND STATISTICS IN CIVIL ENGINEERING

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Session 1793

Not as bad as it seems: Teaching Probability and Statistics in Civil Engineering

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Abstract

Most engineering students dread the day they take probability and statistics. This paper documents a project-based, learn-by-doing approach that provides the vehicle for teaching the analytical skills of probability and statistics. Through this project, students also engage in the engineering design and construction process doing so with realistic engineering constraints. This approach also provides opportunities for discussions related to societal, environmental, and ethical issues. All of this is geared towards the sophomore level and thus allows for realistic design early in the curriculum at the same time it reinforces prior knowledge and introduces new technical content.

The Problem

Probability and statistics are perhaps one of the most commonly found yet least understood topics in most engineering programs. Sure, a large number of students successfully pass their probability and statistics courses. Some even are successful at applying the course information to subsequent courses and eventually in their professional work.

But ask the typical engineer "on the street" to interpret the outcome of the 2001 Major League Baseball World Series. The Arizona Diamondbacks won the contest with a "thrilling and dramatic" bottom-of-the-ninth rally. Little could have been more dramatic except unless there had been two outs instead of one. When informally surveyed, most students in a sophomore-level probability and statistics course found this to be "one of the best world series ever."

When prompted to explain why the Diamondbacks won, few thought critically about the application of variability and uncertainty; even fewer paused to consider basic probabilistic models to shed light on the outcome, perhaps even in a Bayesian manner. Instead, interpretations and explanations of the outcome tended to focus on a team or player being "the better one that day." Most even thought the Diamondbacks would have been clearly the dominant team had they won in four straight games instead of seven. Explanations tended to include everything *but* the notions of variability and uncertainty, especially if the respondent was a fan of the winner.

In Bloom's taxonomy[1] parlance, students were performing at best on the application level when synthesis and evaluation levels would have been preferable. When students were prompted with similar engineering-based scenarios, there were responses were much the same. That is, there was a clear ceiling in the students' mastery of the course material that did not extend beyond the application level.

The Approach
With the goals of moving student performance to the higher levels on Bloom's taxonomy including the valuation level, a hands-on, learn-by-doing, bridge design project was selected. This project replaced many of the traditional textbook problems, even those that used engineering data. The bridge building project documented in *Designing and Building File-Folder Bridges*[2] was modified for a sophomore-level applied probability and statistics course for civil engineering students during the fall semester of the 2001-2002 academic year when the author was teaching at Valparaiso University.

Learning Objectives
By the end of the project, students were expected to be able to:

- **Conduct** experiments, collect and **analyze** data to **develop** empirically-based design models for structural members.
- **Design** a model truss bridge to meet a set of design requirements.
- **Construct** a model truss bridge, consistent with their set of plans and specifications.
- **Analyze** and **Assess** the performance of their model truss bridge.
- **Explain** how construction quality affects the performance of a structure.
- **Explain** the difference between system and component reliability and the implication for design.
- **Discuss** hazard and risk and implications for protecting public safety and welfare.

Project Description
Student teams of three each designed, constructed, tested, and assessed a 1/40 scale truss bridge made of manila folder material. Strength data on tubes and bars made of file-folder material was limited, so students conducted their own physical experimentation and developed their own models representing structural member strength. Geometric criteria were provided as well as probabilistic load criteria. Figure 1 shows one bridge being subjected to the probabilistically simulated load, which for this case was 5 kg.

Figure 1: A successful bridge resisting the probabilistic design load.

As shown in the table below, the project was divided into eight components.

Project Component	Title	Description
A	Member Preparation	Manufacture of Specimens for Strength Testing
B	Member Testing	Strength testing of tubes and bars
C	Data Analysis	Statistical analysis of strength data and development of empirical strength models.
D	Bridge Analysis	System analysis of the strength capacity of the 6-bay Pratt Truss of Learning Activity One[2].
E.1	Preliminary Design	Preliminary selection of truss configuration.
E.2	Preliminary Design	Preliminary selection of member sizes and gusset plates.
F	Final Design	Submission of design drawings and documents.
G	Load Testing	In-service load testing of bridge.
H	Analysis and Assessment	Analysis and assessment of bridge performance.

Design Criteria
The project criteria generally followed that of Ressler[2] of a 60-cm span and 11 cm road-width with the following exclusions and exceptions:

- Each bridge was designed for a random sampling of two simultaneous extreme truck loads, the maximum total mass of which was 6 kg. This was termed a "design level load." The possible extreme truck loads and their odds of occurrence were as follows:

Truck	Truck Mass (kg)	Odds
H15-44	2	1/6
H20-44	2.5	1/2
HS20-44	3.0	1/3

- The minimum factor of safety for each member with respect to its average strength was 2.0.
- To facilitate the design-build nature of this project, each team selected one of 15 configurations.
- The project budget was 10 million (US dollars) composed of an engineering design fee, construction fee, and a materials fee. All but the materials fee were fixed costs

Probabilistic Capacity Estimates
Each team performed capacity estimates for their bridge. Students were strongly encouraged (via grading criteria) to use Monte Carlo simulation to develop their capacity estimates. The statistical properties for the simulation were based upon their experimental work and analyses. Students used a statically determinate failure model, meaning that if one component of the bridge

failed, then the entire bridge collapsed. This failure model is appropriate for the types of bridge configurations available to the students. These analyses required the students think critically about inherent physical and modeling uncertainty and variability, correlation, "parallel" and "series" type systems, and reliability issues. In addition, they had to decide what it meant to report a "single" value for the capacity when simulations provided a histogram of possibilities.

Decision Analysis

In order to drive home the importance of understanding variability and uncertainty when making decisions, each team used their probabilistic capacity estimates to determine what value of load they would be willing to apply to their bridge *beyond* the maximum design level of 6 kg. The teams earned a graduated level of bonus points for applying this "overload" to their bridge. However, if the bridge collapsed during application of this "overload," the students lost bonus points. In essence, each team had to balance their desire for bonus points with confidence in their analyses, which should have included natural and systemic uncertainty and variability.

Project Evaluation

Student Grades

Each team earned grades out of 100 points for each component of the project. Individual student grades were based upon adjustments from the total team grade; the individual adjustment factor was determined from feedback submitted by each team member using a modified version of the Autorating form[3]. Each team's project, of which all teams successfully passed the design level loads and met budgetary criteria,

Educational Evaluation

The students' achievement of the project learning objectives were partially measured during the final exam. Questions were designed to elicit qualitative rather than quantitative responses. This was specifically done to address how the students had progressed beyond the "calculator" level to higher levels on Bloom's taxonomy. Although resources were not available to conduct a high quality "before" and "after" study, responses on this portion of the final exam indicated that at least 50% of the students "got it." That is, students were able to qualitatively address the significance and importance of variability and uncertainty. For instance, they clearly understood that when an engineer designs a dam structure for the effects of a 500-year flood, it doesn't mean that the dam will last exactly 500 years. Rather, they are instead making a decision about the estimated likelihood of failure in a given year.

However, it wasn't clear whether the students could apply their new-found understanding to a new context such as explaining the significance of the outcome of an event such as the world series. Instead, the final exam results suggested that they continue to struggle with the world beyond the "calculations." And, even in the case of "calculations," it seems that the performance was about the same as before. Also what is not clear is whether the instrument devised to measure student performance was adequate.

Primary Learning Benefits of the Project

What *is* clear is that students made significant strides relating the value of the subject matter to the real practice of engineering. Even though the ability to apply statistical and probabilistic techniques may not have changed in a "statistically significant" manner, students integrated the

"Big picture" concepts at a high level of performance. The benefits from their understanding the larger picture of engineering were clearly observed later in their junior-level structural analysis and structural design courses. Many references and connections were drawn to this project that frequently elicited the "ah ha" response we instructors so often desire.

Additional Benefits

The project provided a context for integrating a variety of additional educational directives:

- Design through-out the curriculum and authentic design constraints.
- Roles and responsibilities of participants in the typical engineering project.
- Design-build versus design-bid-build project delivery systems.
- Ethics and professional responsibilities.

Ethics and professional responsibilities was directly included in the project as student teams had to share their data with each other. On more than one occasion, teams had to decide whether to own up to mistakes in their data that they had provided to the entire class, particularly as other teams began to analyze and question the data. The project was also complemented with selected readings from *Rising Tide: The Great Mississippi Flood of 1927 and How it Changed America*[4]. This historical narrative by John Barry discusses in great detail the principal engineers, their projects, and their (un)ethical decisions that influenced both the magnitude and effects of this flood that literally changed the geo-socio-political environment of not only the lower Mississippi region but the country as a whole.

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Biographical Information

SCHMUCKER, D.G. , Dep't. of Engineering at Western Kentucky University. He graduated from Valparaiso University with a B.S.C.E. in 1990 and earned M.S. and Ph.D. degrees from Stanford University in 1991 and 1996, respectively. He has taught courses in mechanics, structural analysis and design, soil mechanics, probability and statistics, and civil engineering materials at Penn State, Valparaiso, and Western Kentucky Universities.