Integration of Probabilistic Decision Making into a Junior Year Engineering Design Course

Yin M. Chen, John Sharon, Sven K. Esche & Constantin Chassapis

Department of Mechanical Engineering
Stevens Institute of Technology
Hoboken, NJ, USA

Abstract

Decision making is a very important aspect of the engineering design process. While many real-world decisions are made under conditions of uncertainty and risk, current undergraduate engineering curricula rarely include any principles of decision theory or use probabilistic modeling and computational techniques. For example, while utility theory is a crucial component of the decision making process, it is typically omitted in engineering curricula. Also, probability theory, which establishes the basic mathematical tools needed for the proper assessment of uncertainty and risk, is often not included in a learning-enhancing context such as engineering design. This situation calls for a paradigm shift in design education where practical examples of real design cases are used to illustrate the application of these scientific principles.

This paper describes our latest progress in an NSF-sponsored pilot program that aims to develop, implement and assess approaches based on stochastic modeling and simulation for the engineering design education at Stevens Institute of Technology (SIT). We have constructed a series of design scenarios by which we will implement stochastic methods into Engineering Design VI. This course is taken by mechanical engineering students in the junior year. Previously, this course was based on deterministic approaches for integrated product design, spanning the entire process from product conception to product realization, following the syllabus outlined by Ulrich and Eppinger.[1] This paper discusses how the newly developed lecture materials based on the framework by Hazelrigg[2] have been integrated into the existing course syllabus. Furthermore, it describes the design scenarios together with appropriate MATLAB and MS Excel analysis modules that were developed for student usage in laboratory exercises. The pilot course is currently in progress during the spring semester 2005. Upon its successful completion, student performance will be examined, the approach evaluated and revised if necessary, and implementation into the capstone design sequence in the mechanical engineering department will be planned.

Introduction

Most engineering undergraduates only gain a cursory knowledge of how engineering design works in the real world, outside of the idealistic, fully-defined circumstances typically assumed in educational design exercises. In order to better prepare students for working under real world conditions, design and decision making under uncertainty must be included in the core engineering curriculum.[3,4]

In the past, curricula have been changed by the addition of requirements for classes on probability theory and project planning. However, these types of classes often do not actually apply these concepts in a practice-relevant fashion. So far, the focus of these classes has mostly been in probability theory, without emphasizing engineering applications or decision making on design options.[1] Instead, we will focus on engineering design projects with inclusion of methods that deal with decision making, probability and uncertainty.

Although working with uncertainty is often very difficult even for experienced professionals, it remains an important part of decision making and design, especially for students who go on to become management level engineers. Their decisions can impact the success of their projects, their departments and perhaps even their companies. As a result of their responsibilities, these engineers must not only be able to choose the best option but also to defend their choices. Management curricula have included decision making for quite some time.[5] It is imperative that engineering curricula expand to also include this very important topic. In addition, it provides a common language between the two disciplines. Although no decision making method is infallible, standard approaches and guidelines serve well as a base for making complicated and involved decisions. It should be noted that any decision-making method is only a tool, and the ultimate selection depends on preferences and thus rests with the decision maker. The more familiar the decision maker is with the subject, the better the resultant decision.

As a first step of this project, the decision making process is condensed into a simplified form. This material, along with the software and their guides, are then implemented into the existing syllabus of a junior-level engineering design course.[6] Although the material is not meant to comprehensively cover decision making in all its myriad complexities, it will enable students to solve any problem they may encounter in their undergraduate career and give them a good start for post-graduate work.

Original Course Syllabus[1]

This course had initially been intended to introduce students to product design and development. By the completion of the class, the students will have learned to:

- Identify opportunities, evaluate and prioritize projects
- Complete pre-project planning
- Identify, organize and evaluate customer needs
- Define evaluation metrics
- Collect competitive benchmarking information and set target values
- Generate concepts, develop concept classification trees and concept combination tables, screen and score concepts
- Develop technical product models, develop cost models
- Develop customer surveys, communicate concepts to customers, measure customer responses and interpret results
- Establish product architecture
- Apply industrial design concepts
- Design the product with consideration of manufacturability and assembly
- Estimate manufacturing costs

- Estimate life cycle
- Develop a business plan, build base-case financial model, and prepare final project documentation

The main purpose of the course is to take the students through the entire product cycle from conception to market, which makes it the perfect medium to introduce decision making and uncertainty. In addition to homework assignments, the students are required to complete a comprehensive project throughout the entire semester in which they actually develop a product.

The original lecture schedule before the described modifications is in Table 1:

Table 1: Original lecture schedule for Engineering Design VI

Lecture	Title
1	Development Process and Organizations
2	Identifying Customer Needs
3	Product Specifications
4	Concept Generation
5	Concept Selection
6	Concept Testing
7	Product Architecture
8	Industrial Design
9	Material Selection / Design for Manufacturing
10	Prototyping
11	Cost Estimation / Product Development Economics

The Decision Making Process

The decision making method starts with identifying the problem to be solved and finding different solution options. These options are then described by their individual characteristics denoted as Evaluation Measures (EM). These characteristics determine the overall decision. For example, if the problem is to purchase an automobile, the EM could be mileage, purchase price, years of warrantee, resale value, number of standardized luxury options, etc.

The crucial part of our approach is the modeling of the EMs by probabilistic variables. Some EMs, such as years of warrantee, are deterministic. Others, however, such as mileage, are probabilistic and should be represented by distributions. For each EM, weights are then chosen according to their relative importance. For example, if the most important aspect of the car is the purchase price, then one would choose a value such as 40% or 0.4. Next, the values of each EM for each option are multiplied by their respective weights resulting in a single number. The decision can then be concluded based solely on quantitative comparison. Finally, the sensitivity of the decision is checked to ensure a robust result.

As we insert this decision making process into the class, the individual concepts are aligned with the corresponding lectures in the current content. Each component of the process, however, will come before the final decision making lecture, which will tie all the parts together. The order of topics will be as discussed in the next section.

Proposed Additional Modules

In the second class lecture, a weighing module will be added to 'organizing customer needs.' It will explain the weighing methods that are available for ranking and prioritizing requirements. These weighing methods fall into two categories, direct and indirect.[7]

All direct methods involve two steps. First, one must order all the EMs from most important to least important. Then, one of the formulae listed in Table 1 is applied, where wt_i is the weight of the i^{th} EM.

Table 2: Formulae for weight calculation

$wt_i = \dfrac{K - r_i + 1}{\sum_{j=1}^{K} K - r_j + 1}$	Rank Order Method: r_i: rank of i^{th} EM K: total number of EMs
$wt_i = \dfrac{(K - r_i + 1)^z}{\sum_{j=1}^{K} (K - r_j + 1)^z}$	Rank Exponent Method: r_i: rank of i^{th} EM K: total number of EMs Z: measure of weight dispersion (Z>0)
$wt_i = \dfrac{1/r_i}{\sum_{j=1}^{K} (1/r_j)}$	Rank Reciprocal Method: r_i: rank of i^{th} EM K: total number of EMs
$wt_i = \left(\dfrac{1}{K}\right)\sum_{j=1}^{K}\left(\dfrac{1}{r_j}\right)$ $wt_1 = \left(1 + \dfrac{1}{2} + \dfrac{1}{3} + \ldots \dfrac{1}{K}\right)/K$ $wt_K = \left(0 + 0 + 0 + \ldots \dfrac{1}{K}\right)/K$	Rank Order Centroid Method: r_i: rank of i^{th} EM K: total number of EMs

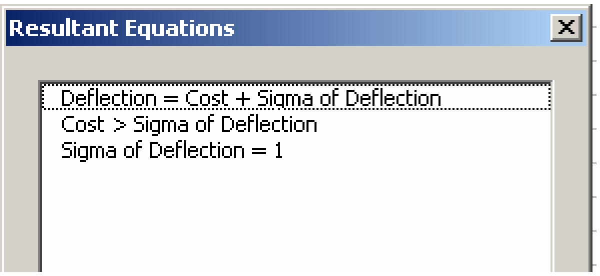
Except for the rank exponent method, these methods require much less information on the subject than the indirect method. Only the order of importance is required. For the rank exponent method, one only needs to choose an additional dispersion factor Z, which determines how much the weights differ from each other. A smaller value of Z will return more similar weights.

All four methods have been programmed into MS Excel macros, and it only takes seconds to run any or all of them to choose the best weights for a particular situation.

The indirect method or ‘balance beam approach’ is more complex. The first step, however, is the same as in the direct methods:

- The objectives or EMs are ranked in order from most important to least important.
- A series of questions is posed beginning with “Is the importance of the first objective (a) greater, (b) less than, or (c) equal to the importance of the second and third objectives combined?”
- If answer is “less than”, then the third objective is dropped and replaced by the fourth objective. (If “greater than” then the fourth objective is added to the second and third.)
- The results of these questions are recorded as a set of equations that are in the forms of equalities and inequalities (see Figure 1). In the end, a series of equations that define the weights for all of the objectives is established.
- The least valued objective is given a weight of 1, and a weight is assigned to the second least valued objective. This process is repeated using the developed equations as guides for the range of each objective.
- To get the final weights, the results are normalized into values between 0 and 1.

This method is also implemented in an Excel macro.[8] The program queries the user for each of the comparisons and displays all the compiled answers as a system of equations (see Figure 1).



```
Deflection = Cost + Sigma of Deflection
Cost > Sigma of Deflection
Sigma of Deflection = 1
```

Figure 1: MS Excel macro results for indirect weight elicitation

In the third lecture, a module on defining target tolerances will be added to the ‘setting target values’ part. This module explains what ‘less than,’ ‘equal to’ and ‘greater than’ mean in terms of probability distributions and product output with regard to means and standard deviations. In addition, this module will demonstrate how to express these ideas precisely in terms of mathematic formulae.

For example, in order to explain a requirement that ‘90% of widgets must be less than or equal to X’, Figure 2 shows the graphical representation of the required segment in relation to the whole distribution.

It is clearly visible that 90% is about 1.7 standard deviations from the mean. This and many other examples are explained in the section. These ideas must be made abundantly clear to the students so that they may fully utilize what they know about probability in terms of product realization.

The third lecture will also contain two additional sections. One will explain the measuring of metrics, and the second will explain different probability distributions, along with an introduction to how MATLAB and the Monte Carlo method can be used to model them.

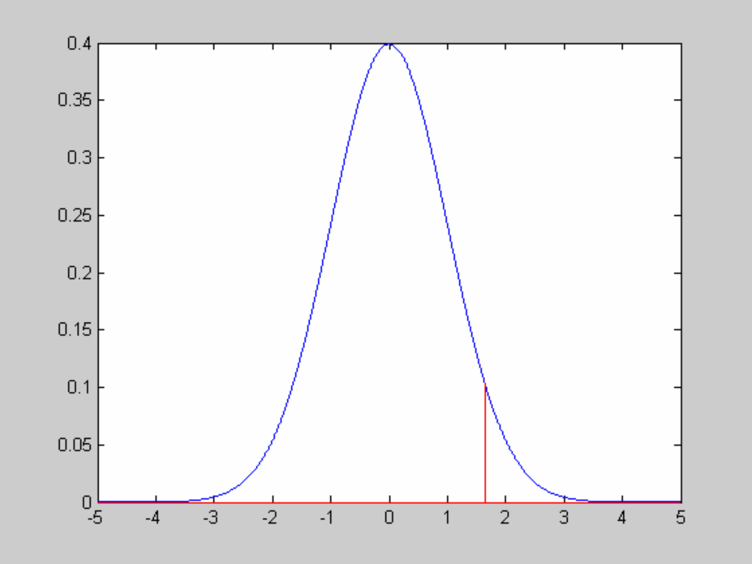


Figure 2: Standard normal distribution with vertical line indicating the 90% mark

The section on metrics first explains that an EM is a category or quality by which an alternative is evaluated. Then it explains how a value scale is set up for an EM along with the difference between linear and exponential value scales.

First, it is important to establish whether the EM is of the 'higher is better' sort or of the 'lower is better' sort. Then, upper and lower limits must be set for the measuring scale. After the limits are set, the scale should be normalized to facilitate computation when combining many different EMs.

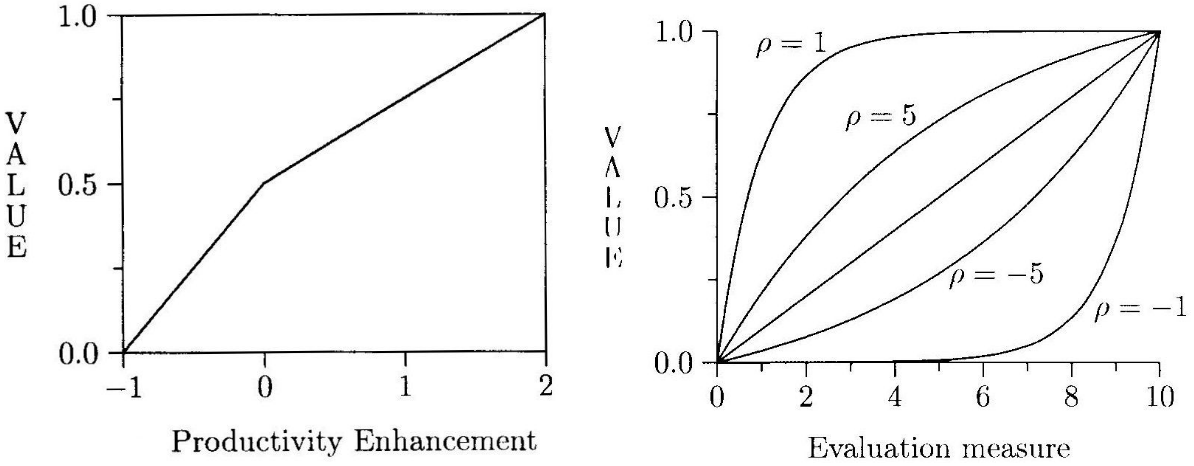


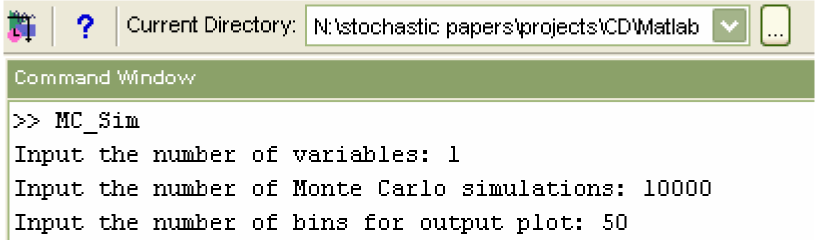
Figure 3: Value scales (left: piecewise linear, right: exponential)

The two types of value scales are shown in Figure 3. The left is an example of a piecewise linear scale, and the right is that of an exponential scale. As its name states, the piecewise linear scale is linear in sections, i.e. each section represents a linear growth in value. In other words, as the measure grows, the value increases at the same ratio. For the exponential scale, the following formula is used, where ρ represents the degree of digression from the linear:

$$v(x) = \begin{cases} \dfrac{1 - \exp\left[-(x - \text{Low})/\rho\right]}{1 - \exp\left[-(\text{High} - \text{Low})/\rho\right]}, & \rho \neq \text{Infinity} \\ \dfrac{x - \text{Low}}{\text{High} - \text{Low}}, & \text{otherwise} \end{cases}$$

The bigger the absolute value of ρ is, the closer the scale is to being linear. The negative and positive quality of ρ lets one choose where the greatest value increase occurs.

In the probability section, the students are introduced to common distributions, including the normal, Poisson, gamma, exponential and Weibull distributions. They are also taught to use the Monte Carlo method to model distributions by a large number of samples. This not only accurately portrays a distribution but also mimics the behavior of production processes and machines. Finally, the students are shown how to create models on their own using MATLAB (see Figure 4).



```
>> MC_Sim
Input the number of variables: 1
Input the number of Monte Carlo simulations: 10000
Input the number of bins for output plot: 50
```

Figure 4: MATLAB shell created for Monte Carlo simulations

In the fifth lecture, a decision making section will be added to the ‘screen and score concepts’ part. This section introduces the concepts of deterministic and probabilistic EMs, applying weights to making the final decision, and finally testing the sensitivity of the weight parameters.

Although the focus of discussion is more on probabilistic calculations, deterministic EMs should not be overlooked. Deterministic EMs are useful for things that are easily quantified such as the number of wheels on a car. They are often very important to the overall decision. Probabilistic EMs are also important. This is where the students can use the knowledge from the previous lectures to model their calculations of the value scores. They will learn to extract the means and other important values from each distribution and evaluate options on the merits of the spread instead of a single number. After all the value scores or grades are calculated, they can be combined with the weights to obtain the final grades for each option using the following formula:

$$FinalGrade = \sum Weight_i * Grade_i$$

After the final grades are calculated, the process goes on to the sensitivity analysis. It tells the user how much the weights affected the decision and how a small change may change the outcome. This process involves changing the weight of a single EM (i.e. one at a time) from zero to one while keeping the proportions of all the other weights the same. The results are then graphed. The user can then look at the area around the originally chosen point to see whether any drastic fluctuations are nearby or whether there is anything else that could provide an unrealistic or unreasonable result. If the decision passes the sensitivity tests, then it can be deemed reasonable and defendable.

It should also be noted that the entire decision making process is programmed into Excel macros, which are made easily accessible to the students. The flow diagrams of these and all aforementioned macros can be found in our previous paper.[6]

Finally, an example will be introduced and developed through every stage of the production conception process. Furthermore, every new topic will be illustrated with this and a few other simple examples. The example chosen was that of a bicycle wheel as discussed by Henri Gavin in his paper: ‘Bicycle Wheel Spoke Patterns and Spoke Fatigue’[9] (see Figure 5).

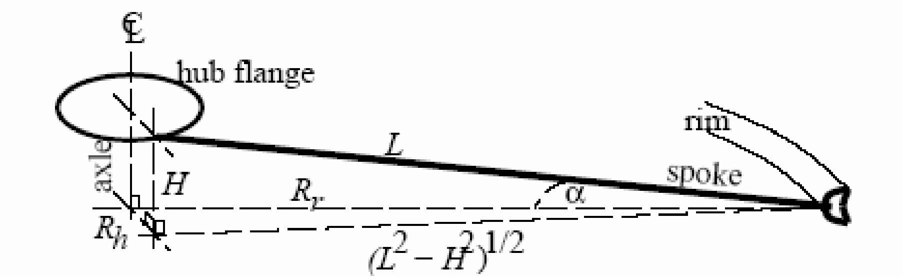


Figure 5: Schematic of a single spoke of a bicycle wheel with hub and section of rim

Finally, the resultant lecture schedule is summarized in Table 3 (all lecture numbers with letter suffixes are new insertions).

Assessment surveys will be distributed to the students at the start and end of the course to gauge the students’ understanding of the material and their ability to apply knowledge from their probability classes in engineering design. The results of these surveys will be available at the beginning of summer 2005.

Conclusion

This paper describes a decision making process that will be presented to students in a pilot program aiming to develop, implement and assess approaches based on stochastic modeling and simulation in engineering design education. Along with these lectures, various software modules, tutorials and practical examples were created. The described approach will allow the students to make design decisions systematically and enable them to solve complicated, multi-attribute decision problems involving tolerances and uncertainty. By including this material into the undergraduate mechanical engineering curriculum, students will gain a new structured way of approaching an engineering design problem. Although they will only be introduced to a limited version of the decision making process, the students will nonetheless be able to solve any engineering design decision problem within the scope of undergraduate engineering.

Table 3: Finalized lecture schedule

Lecture	Title
1	Development Process and Organizations
2	Identifying Customer Needs
2a	Weighing Methods
3	Product Specifications
3a	Defining Target Tolerances
3b	Measuring Metrics
3c	Probability Distributions and Monte Carlo Modeling
4	Concept Generation
5	Concept Selection
5a	Decision Making
6	Concept Testing
7	Product Architecture
8	Industrial Design
9	Material Selection / Design for Manufacturing
10	Prototyping
11	Cost Estimation / Product Development Economics

Acknowledgement

This project is sponsored by the National Science Foundation under grant number 0234016. This support is gratefully acknowledged.

Bibliography

1. Ulrich, K. T. & Eppinger, S. D., *Product Design and Development*, 3rd Ed., McGraw-Hill, 2004.
2. Hazelrigg, G. A., *Systems Engineering: An Approach to Information Based Design*, 1996.
3. Esche, S. K. & Chassapis, C., Integrating Concepts of Decision Making and Uncertainty into Engineering Design Education, *33rd ASEE/IEE Frontiers in Education Conference*, 2003.
4. Esche, S. K. & Chassapis, C., SGER: A Framework for Adapting Decision Based Scientific Principles in Engineering Design, *NSF Proposal*, 2002.
5. Kirkwood, C. W., *Strategic Decision Making, Multiobjective Decision Analysis with Spreadsheets*, 1997.
6. Chen, Y., Sharon, J. A., Esche, S. K. & Chassapis, C., A Pilot Program on Teaching Engineering Design Using Probabilistic Approaches, *ICEE*, 2004.
7. Buede, D. M., *The Engineering Design of Systems – Models and Methods*, 2000.
8. Roman, S., *Writing Excel Macros Learning to Program the Excel Object Model Using VBA*, 2002.
9. Gavin, H. P., Bicycle Wheel Spoke Patterns and Spoke Fatigue, *Journal of Engineering Mechanics*, Vol. 112, No. 8, (1996) pp. 736-742.

Biographies

Yin Chen:

Yin Chen is currently a M.S. student at the Department of Mechanical Engineering at Stevens Institute of Technology. Her research interests include stochastic processes in design engineering and manufacturing and armament design and engineering.

John Sharon:

John Sharon is currently an undergraduate student in the Department of Mechanical Engineering at Stevens Institute of Technology. His research interests include the use of applied statistics for the design of mechanical and manufacturing systems, system engineering processes and practices, and aerospace engineering.

Sven Esche:

Dr. Esche is an Associate Professor of Mechanical Engineering at Stevens Institute of Technology. His research interests include manufacturing, integrated product and process design, metal forming, prediction of microstructure development in metals, remote sensing and control and remote experimentation.

Constantin Chassapis:

Dr. Chassapis is the Director of the Department of Mechanical Engineering and a Professor of Mechanical Engineering at Stevens Institute of Technology. His research interests are in knowledge-based engineering systems; computer-aided design and manufacturing. At Stevens he has developed a number of undergraduate and graduate courses in the design and manufacturing areas.