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Developing a Quantitative Methods Course for Undergraduate Civil and Construction Engineering Students

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Developing a Quantitative Methods Course for Civil and Construction Engineering Students

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Abstract

The ability to apply quantitative methods to gather, review, analyze and draw conclusions from data to support decision making is an important skillset in the engineering profession. To develop a deeper understanding and appreciation for basic quantitative methods for construction engineering students we developed a new three-credit hour undergraduate course. The main objective of the course is to provide basic skills in quantitative methods, by familiarizing students with the critical steps in an analytical approach to decision-making. The course applies a hands on approach to problems solving and decision making using a variety of engineering themed problems that practicing engineers are likely to face. The specific methods explored include; constructing quantitative models to include break even analysis, decision trees, linear optimization, PERT/CPM schedule development and crashing, as well as Monte Carlo Simulation, and sensitivity analysis to generate and interpret problem solutions. Instruction emphasizes a hands-on approach and practical assignments to develop a logical framework for describing and solving problems. This new course emphasizes Excel software rather than hand calculations and introduces use of Excel Solver and other data analysis tools.

Keywords

Quantitative Methods, Linear Programming, Optimization.

Introduction

Expectations for graduates entering the engineering profession are changing and intensifying to meet the complex needs of society. Global issues, technological innovation, blending of discipline boundaries, and increased professional complexities are transforming how engineers analyze problems and provide effective solutions. Societal demands require engineering graduates possess strong technical knowledge and the ability to think creatively and critically, effectively communicate, and work in teams to solve challenging problems [1].

Despite their technological savvy, most students entering university lack the necessary computer skills to succeed in a quantitative analysis course, in which they are often expected to gather and analyze data and then report results. This lack of technological savvy results in increased anxiety, with students spending large amounts of time to complete the assignments and detracting from the students' learning [2]. Teachers in technical colleges are finding that traditional teaching approaches fail to provide students with the expected level of knowledge. New techniques and approaches are needed that actively engage and excite students about the material they are being introduced to. By employing new and inventive teaching methods, students gain knowledge, which has a positive and efficient effect on their academic performance and achievement [3].

Students often view quantitative methods courses as difficult due to the nature of the learning goals (i.e., applying, analyzing, evaluating, and creating) which are, in terms of Bloom's Taxonomy complex and cognitively demanding [4]. As part of the process for developing a new quantitative methods course, faculty undertook a thorough review of the Construction Engineering curriculum, ABET requirements, and current teaching approaches. The remainder of this paper provides a background of the Citadel's description of the course, goals and outcomes, and discussion of future plans for the course.

We chose to design the course around the use of Microsoft Excel which we feel is an ideal tool for teaching quantitative analysis and graphic presentation of data. It is widely available in industry and is offered at a low cost for students. Excel's robust library of built in functions and data analysis tools are easily accessible and allow students to quickly become skilled at employing it. In this paper, we present our efforts to develop a quantitative methods course incorporating Excel spreadsheet exercises that are designed to develop the ability and confidence of students to create progressively more complex quantitative models to solve a variety of problems they are likely to encounter in the practice of engineering.

Background

The Citadel is a teaching college in Charleston, SC, with a day program student body numbering about 2,200 students, and an evening program of graduate and professional studies with a student body of about 1,600. The mission of the Civil, Environmental and Construction Engineering, programs is to provide a nationally recognized student-centered learning environment for the development of principled leaders in the civil, environmental and construction engineering communities through a broad-based, rigorous curriculum, emphasizing theoretical and practical engineering concepts, strong professional values, and a disciplined work ethic. Our goal is to prepare engineers that are capable of tackling and solving difficult problems involving design, construction, and resource utilization they are likely to encounter in engineering practice. Accordingly, the Department strives to develop the skills of its engineering students in the management of resources, time, materials, money, and people through effective combination of effective academic curriculum and discipline [5].

Fall 2023 Offering

The goal of this course is to enable students to develop and use quantitative models that utilize algorithmic thinking and problem solving. To promote student learning success quantitative methods are taught in the context of engineering examples that require students apply the concepts by developing mathematical models to solve engineering themed problems. Course development was guided by learning goals based on our belief that developing practical model development skills is of limited use if one does not also develop the ability to think about problems algorithmically while developing a positive attitude towards problem solving. Students are taught how to break a complex problem into simpler steps and develop strategies to validate a specific problem-solving approach. One of the goals of teaching quantitative methods should be to focus on fostering a positive attitude towards quantitative and computational thinking while helping the students overcome their initial apprehension towards developing mathematical models. By the end of the course, we want students to be comfortable with the concepts, tools and quantitative reasoning, and to recognize their value in the practice of engineering [6].

To introduce construction engineering students to the application of quantitative methods, a pilot three-credit hour course, CIVL 453 Special Topics in Civil Engineering, was developed and offered as a technical elective to sophomores, juniors and senior construction engineering students. Lessons learned from the pilot course will be used to transition to a permanent three-credit hour course, CONE 290 Quantitative Methods for Construction Engineering. The major challenge in preparing a course of this type is in deciding how to condense abundant subject matter into allocated time constraints, while still providing significant technical content. A main consideration was that sufficient class time was allocated for practical application in developing models and using them to solve problems using excel software. For CIVL 453 the section met two days a week for 75 minutes. The permanent course will also be offered in day and evening sections, which also meet two days a week for 75 minutes. Table 1 provides a list of the course objectives, while Table 2 depicts how classroom hours are apportioned.

Table 1. CIVL 453/CONE 290 Course Learning Objectives

CIVL-453/CONE 290, Quantitative Methods for Construction Engineering **List of Course Objectives**
Analysis: Access, manipulate and analyze data using excel. Develop appropriate quantitative models that can be used to solve a (engineering themed) problem. Use probability and decision theory to construct mathematical models useful in finding optimal solutions. Apply linear programming techniques to model, analyze, and solve a variety of decision problems. Apply the concepts of deterministic project management, including PERT/CPM, transportation and network models, to calculate the probability of successful completion of a project.
Comprehension: Determine the most appropriate approach for developing a model to reach optimized results. Review and interpret the model outputs and make a recommendation for action to be taken. Know and apply the basic probability rules, the concepts of expected value and variance for discrete and continuous variables.
Synthesis: Describe a problem and determine which quantitative methods to apply in solving the problem. Develop an appropriate model to solve the problem. Collect data for model input and interpret the results of quantitative models. Report the results and recommended solution to the problem.

Course Learning Outcomes: Upon course completion, students will be able to:

1. Apply Quantitative Analysis and Optimization Techniques to model a variety of problems and solve the resulting models using Excel software.

2. Utilize probability theory to solve quantitative analysis problems.

3. Use Decision Theory to construct mathematical models useful in optimizing managerial decisions.

4. Apply linear programming techniques to model, analyze, and solve a variety of decision making problems.

5. Apply the concepts of deterministic project management, including PERT/CPM, transportation and network models, to calculate the probability of successful completion of a project.

6. Determine the most appropriate optimization model and apply that model to reach optimized results and make a recommendation based on those computations

Table 2. Course Schedule showing topic hours scheduled.

Topic	Hours
Intro to Quantitative Methods. Break Even & Make or Buy Analysis	2.5
Introduction to Decision Theory and Expected Value	1.25
Basic Rules of Probability, Decision Making Under Uncertainty, Expected Value	2.5
Decision Trees, Expected Monetary Value	2.5
Algebra Refresher	1.25
Linear Programming Models, Graphical Solutions	2.5
Intro to Excel Solver for Linear Programing	2.5
Network Models, Transportation & Assignment Problems	2.5
Integer Programming	2.5
Network models , Maximal Flow	2.5
Network models , Shortest Route	2.5
Network models, Minimal Spanning Tree	2.5
Travelling Engineer Problem	1.25
Deterministic Project Scheduling models, PERT and CPM	3.75
Schedule Duration Compression	2.5
Simulation Modeling, Monte Carlo Simulation	5
Comprehensive Final Exam	3
Course Goal Total	**43**

This course applies a hands-on approach to developing quantitative models for problem solving and decision-making using problems with engineering specific scenarios. Several examples are; a break even analysis assignment focuses on a company deciding on which of two concrete construction methods to use, precast or cast in place. An expected value assignment challenges students to calculate the expected value for the number of faulty components in an electrical system and the expected value of the voltage output for an electrical circuit. Several assignments use linear programming models to solve maximum flow, shortest route, minimum spanning tree, and critical path problems. Practical assignments like these are used to develop a logical framework for describing and solving engineering problems.

A main objective of the course is to provide basic skills in quantitative methods, by introducing students to the critical steps in an analytical approach to decision-making. Students gain experience constructing a quantitative model that can be used to address a (engineering themed) question, implementing the model in Excel, and using various built in functions and tools, such as Solver and Data Analysis to develop problem solutions. Our core philosophy is that the best way to master these topics is through a hands-on approach. A significant portion of classroom time is devoted to examining an engineering related problem and developing a quantitative model to solve it. The exercises focus on a variety of examples drawn from engineering using Excel spreadsheets.

Course Design

There are four principal aspects receiving primary emphasis within the course design: 1.) Calculations are demonstrated and exercised in practice problems prior to demonstrating how to use excel for the calculations; 2.) Problem Solving by building quantitative models, time is built into each class to discuss problem solving approaches; 3.) Higher-level practice, the homework assignments include problems requiring analysis, evaluation, and reporting; and 4.) Assessment, assessment of student learning focuses on comprehensive higher-level assignments. The course focuses on developing a deeper understanding through solving practical application problems by building quantitative models. Applicable equations are introduced, and calculations are explained and then demonstrated. Students are not expected to memorize or interpret the formulas. Rather, students are expected to develop models that they can use to analyze data, arrive at a solution, and then report results of the analysis. Excel was chosen as the course software for several reasons: 1.) most students already have and are comfortable with Excel for solving problems; and 2.) Excel is a standard software package that is available to practicing engineers making the problem-solving skills learned in this course transportable. Students are encouraged to learn more about functionality of Excel for analysis on their own as the term progresses and seek individual help from faculty when necessary.

Course Assessment

Course assessment of student performance is based on the practical application problem sets solved for homework along with quizzes and a comprehensive final exam. The course incorporates 10 homework assignments of increasing complexity requiring students to collect data; develop an appropriate quantitative model using demonstrated techniques; solve the problem; and report results and conclusions in a standard report. The report, whose sections include: statement of the problem, calculations and results, analysis and interpretation of the results and a specific solution recommendation. Simply performing calculations and providing a numerical outcome will not lead to a passing grade on these problem assignments. Students must demonstrate the ability to develop a problem-solving approach using appropriate modeling techniques and to interpret and report results. Students upload their report in the college's learning management system, CANVAS, and receive detailed feedback on each of the report areas. Students are afforded the opportunity to review the feedback and then resubmit the report for a higher grade. Figure 1 is an example of a representative student assignment report.

Figure 1. Sample Student Assignment Reports.

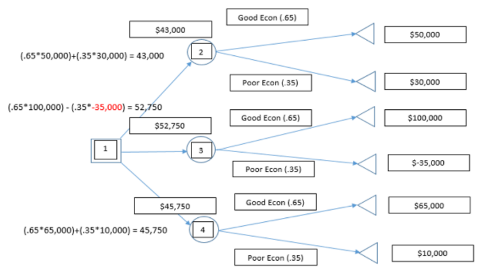
Title: Hwk 3.2 Analysis of Development Options **Name:** _______________

Problem Description. Coastal Construction Ltd. is considering three options (building a new apartment complex, building an office building, and building a warehouse). If economic conditions remain favorable, they stand to make a lot of money, if economic conditions take a turn for the worse, they stand to lose a lot of money. The following information was used or the analysis.

	States of Nature	
	Good economic Conditions	Poor economic conditions
	0.65	0.35
2. Apt Bldg	$50,000.00	$30,000.00
3. Office Bldg	$100,000.00	-$35,000.00
4. Warehouse	$65,000.00	$10,000.00

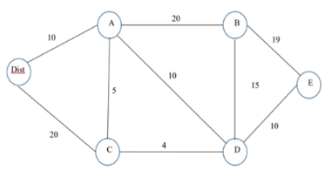
Solution/Recommendation:
Decision tree analysis was conducted with the results shown. Based on our analysis the greatest EMV is achieved by developing an office building with an expected payoff of $52,750.00. Based on my analysis I recommend building the Office Building. I do want to point out that there is an element of risk with this option and the potential of incurring a $35,000 loss. The second best option with the lowest total risk is to build a Warehouse.

Calculations:



Title: CIVL 453 Assignment #5.3

Problem Statement: Santee Cooper needs to install underground gas lines between five cities shown in the network diagram below along with the distances in miles. As the project engineer assigned to the job you have been asked to determine the routing network based on the minimum span of pipe that is needed to connect the five cities from the gas distribution center.



Objective function:

Minimize $Z = 10X_{12} + 20X_{13} + 5X_{23} + 5X_{32} + 20X_{24} + 20X_{42} + 10X_{25}$

$+ 10X_{52} + 4X_{53} + 15X_{45} + 15X_{54} + 10X_{46} + 10X_{56}$

St:

$X_{12} + X_{13} = 1$ Node 1

$X_{12} + X_{32} - X_{23} - X_{24} - X_{25} = 0$ Node 2

$X_{13} + X_{23} - X_{32} - X_{35} = 0$ Node 3

$X_{24} + X_{54} - X_{42} - X_{45} - X_{46} = 0$ Node 4

$X_{25} + X_{35} + X_{45} - X_{52} - X_{53} - X_{54} - X_{56} = 0$ Node 5

From	To	Distance	A	B	C	D	E	Paths	Link Used?	Edging Const.
Dist	A	10	1					5	1	-95
Dist	C	20			1			0	0	0
A	C	5	-1		1			4	1	-96
C	A	5	1		-1			0	0	0
A	B	20	-1	1				0	0	0
B	A	20	1	-1				0	0	0
A	D	10	-1			1		0	0	0
D	A	10	1			-1		0	0	0
C	D	4			-1	1		3	1	-97
D	C	4			1	-1		0	0	0
B	D	15		-1		1		0	0	0
D	B	15		1		-1		1	1	-99
B	E	19		-1			1	0	0	0
E	B	19		1			-1	0	0	0
D	E	10				-1	1	1	1	-99
E	D	10				1	-1	0	0	0
			1	1	1	1	1			
									44	

Solution: After completing the work in Excel as displayed on the chart below, we were able to determine that the minimum span of pipe needed to connect the five cities from the distribution center is 44 miles. Also, by observing the links used section of the chart, we see that the optimal tree consists of arcs from Dist. to A, A to C, C to D, D to B, and D to E.

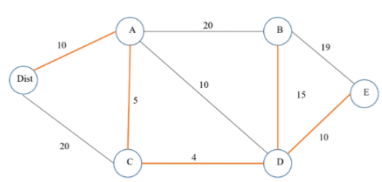


Table 3 presents a summary of the assessment course outcomes. Further analysis is intended to assess course objectives in a similar manner at the end of the Fall 2024 term, and for subsequent offerings.

Table 3. Assessment of student performance on a key course learning outcomes.

1. **Analysis**: Access, manipulate and analyze data using excel. Develop appropriate quantitative models that can be used to solve a (engineering themed) problem. Use probability and decision theory to construct mathematical models useful in finding optimal solutions. Apply linear programming techniques to model, analyze, and solve a variety of decision problems. Apply the concepts of deterministic project management, including PERT/CPM, transportation and network models, to calculate the probability of successful completion of a project.
2. **Comprehension**: Determine the most appropriate approach for developing a model to reach optimized results. Review and interpret the model outputs and make a recommendation for action to be taken. Know and apply the basic probability rules, the concepts of expected value and variance for discrete and continuous variables.
3. **Synthesis**: Describe a problem and determine which quantitative methods to apply in solving the problem. Develop an appropriate model to solve the problem. Collect data for model input and interpret the results of quantitative models. Report the results and recommended solution to the problem.

LO	1	2	3	4	5	6
Assessor	Hwk 1 Final Exam	Hwk 2.5 Quiz Final Exam	Hwk 3.1 Hwk 3.2 Final Exam	Hwk 4.2 Hwk 5.1 Hwk 5.2 Hwk 5.3 Hwk 5.4 Final Exam	Hwk 6.1 Hwk 6.2 Final Exam	Hwk 7.1 Final Exam
Performance Outcome	100% 88.00%	95.82% 88.00%	98.82% 80.59% 88.00%	96.92% 99.29% 95.59% 96.47% 97.59% 88.00%	98.82% 100% 88.00%	100% 88.00%
Performance to Standard	≥ 80%					

Conclusion

In the beginning students were apprehensive about developing quantitative models but by using a crawl, walk, run approach we were able to introduce basic modeling concepts which students could quickly master. Gaining confidence in developing decision trees and break-even analysis seems to be a good Segway into more complex models incorporating Excel Solver and the data Analysis tools in Excel. Students were able to demonstrate the ability to gather and organize data, select a quantitative technique to base a model on, develop the model, analyze the output, and to interpret results and report their conclusions in a clear and concise report format. Initially students showed a tendency to present calculations and numerical results with insufficient interpretation and explanation of what the results mean. Providing students with a report template for homework helped them to organize their thoughts and by the end of the course few students expressed any resistance to the format. At the end of the course students are introduced to a comprehensive assignment in two parts. In Part 1; Students are provided with a construction project scenario where they develop a task list, identify activity precedence and calculate the activity duration using PERT. They then develop a linear programming model to identify the critical path, construct a 95% confidence interval estimate for the project duration and construct a Gantt chart for the project schedule. In Part II, students are given an amended scope statement and asked to reduce the schedule duration by crashing the critical path using linear programming, update the project schedule and the 95% confidence interval estimate. The students enjoyed this type of comprehensive problem that combines multiple concepts. As part of the final exam for this pilot course students were asked to describe in a well written paragraph what they liked and did not like about this course and to provide two substantive recommendations for improving the course. In the future, we plan to take the course assessment data and student comments to improve the course and to develop additional practical application problems which involve the entire process of collecting, organizing, analyzing, and reporting.

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